



| | |
|---|--|
| Title: <h2 style="text-align: center;">Application of an Active Foil Propeller</h2> | Delivered: 14.6.2010 |
| | Availability: Open |
| Student: Christian Thomas Borgen | Number of pages: 70 + Appendices |

Abstract:

In this master thesis the author has investigated the potential benefits from an active foil propeller. Foils are mounted on the hull and take advantage of the heaving and pitching motion of the vessel travelling and produce thrust, similarly to the tail fin of aquatic mammals. Active foil means that the angle of the foil has been controlled to constantly maximise the thrust.

The author has investigated the potential fuel savings for three vessels, an offshore supply vessel, a coastal tanker and a purse seiner. Calculations have been done considering 9 different foil configurations and five wave headings at forward velocities of 10, 12, 15 and 18 knots. In regular waves six wave periods have been used and irregular waves are also considered.

The structural aspect and the possibility of fatigue are investigated and concepts for storing the foils when not used are suggested.

ShipX, a program developed by MARINTEK, has been used to find the motions of the vessels and other vital information needed to predict the potential fuel savings. The thrust force is calculated using MATLAB.

The results show large potential benefits. Especially for irregular waves we have calculated fuel savings of more than 60 % at 10 and 12 knots. Higher velocities are less beneficial. A large aspect ratio combined with a large foil area produces the most promising results, but if the aspect ratio becomes too large there is a danger of fatigue and the foil structure must be strengthened.

The foils are quite large and when not in use they would be stowed away. The ideal method is to store the foils in a compartment of little use, like in the collision bulkhead. There is no easy way of doing this, so the storing system would probably be costly.

Over all the potential fuel savings are large for a range of wave conditions up to a certain vessel velocity, but there are practical aspects that would reduce the total benefits.

Keyword:

Controllable foil propeller
Fuel saving
Environmentally friendly propulsion

Advisor:

Sverre Steen

MASTER THESIS IN MARINE TECHNOLOGY

SPRING 2010

FOR

STUD. TECHN. Christian Thomas Borgen

Application of an active foil propeller on an offshore vessel

The so-called foil propeller was introduced by Einar Jacobsen in the 1970-ies. It was found that under ideal circumstances, it could provide a significant additional propulsive force. However, strength and vulnerability issues lead to that the trial on the fishing vessel “Kystfangst” was not a commercial success, and since then few if any applications of the foil propeller has been realized.

Active anti-roll fin stabilizers are now common on most monohull passenger vessels. They are robust, and can be retracted to avoid added resistance when there is no need for roll stabilization. Together with passive anti-roll tanks for ships that spend much time lying still offshore, this means that roll motions is no longer a real problem for advanced ships. However, there are currently no systems in practical use to reduce pitch motions. Reducing pitch motions will in itself reduce the added resistance in waves, and thereby the fuel consumption. The idea is to use a technology for the foil propeller that is similar to that of the anti-roll fins – actively controlled angle and retractable foils. The fact that the foils are retractable means that there is practically no added resistance of the system when not in use (which is a significant difference from the “Kystfangst” case). The fact that the angle of the foils is actively controlled supposedly means that higher efficiency can be obtained.

In the spring of 2009 Ingrid Angvik, student of NTNU, wrote a thesis where she made a feasibility study of the actively controlled foil propeller, as it is described above. She made some simplifications and calculated the potential benefit in terms of reduced fuel consumption and reduced pitch motions for a typical offshore supply vessel (as function of the foil size), and pointed out potential challenges with respect to structural loads and control of the foil. The candidate has himself done a project thesis on the subject, selecting a range of suitable vessels, comparing them, and trying to see which vessels will benefit the most on having a foil propeller. This work will form a basis on which the candidate will write his master thesis.

Considering the suggested further work from this project thesis, it is recommended that the candidate shall do the following in his master thesis:

1. Give a brief overview of previous work on the foil propeller
2. Describe the principle of the foil propeller
3. Establish a model for ship motions including the effect of an actively controlled foil propeller
 - a. Verify the calculation model by comparing calculations of a fixed foil with ShipX calculations.
 - b. Check the importance of unsteady lift effects (Theodorsen functions etc. “Foil Theory” lecture note)
4. Select a range of suitable vessels, consider which speed(s) the vessels might be travelling at and make calculations to find the potential benefits gained from a foil propeller, using the method developed in point 3
5. Do the calculations using several wave headings
6. Analyse the foil propeller system in irregular waves
7. Investigate the use of fully or partly flexible foils
8. Look closer on a practical system for bow fins storing

9. Estimate the dimensioning forces on the foil
10. Make conclusions regarding the benefits and potential problems of the system

The candidate should in his report give a personal contribution to the solution of the problem formulated in this text. All assumptions and conclusions must be supported by mathematical models and/or references to physical effects in a logical manner.

The candidate should apply all available sources to find relevant literature and information on the actual problem.

In the thesis the candidate shall present his personal contribution to the resolution of problem within the scope of the thesis work.

Theories and conclusions should be based on mathematical derivations and/or logic reasoning identifying the various steps in the deduction.

The candidate should utilize the existing possibilities for obtaining relevant literature.

The thesis should be organized in a rational manner to give a clear exposition of results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work. The plan should include a budget for the use of computer and laboratory resources that will be charged to the department. Overruns shall be reported to the supervisor.

The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

The thesis shall be submitted in two copies:

- Signed by the candidate
- The text defining the scope included
- In bound volume(s)
- Drawings and/or computer prints that cannot be bound should be organized in a separate folder.
- The bound volume shall be accompanied by a CD or DVD containing the written thesis in Word or PDF format. In case computer programs have been made as part of the thesis work, the source code shall be included. In case of experimental work, the experimental results shall be included in a suitable electronic format.

Supervisor : Sverre Steen
Start : 24th of January 2010
Deadline : 14 June, 2010

Trondheim, 24th of January

Supervisor

Preface

This report is my master thesis in marine hydrodynamics written at the Department of Marine Technology at the Norwegian University of Technology and Science (NTNU) in Trondheim, Norway. It was made during the spring of 2010.

The topic of the thesis is application of an actively controlled foil propeller. The motive is to find the potential benefit of such a concept. In the fall of 2009 I did my project thesis on the same subject, mainly focusing on getting an overview of previous work. Prior to this I did not have any knowledge on the specific subject, but I was inspired by the exiting concept. After learning more on the topic I found it challenging but intriguing.

I have used the software ShipX with the plug-in VERES, MATLAB and Microsoft excel to do my calculations.

I would like to thank Edvart Ringen at MARINTEK for supplying me with the ShipX software, Dariusz Fathi for helping me understand the calculation methods used in the program and Rolls Royce for sharing their vessel data and letting me use them for my calculations.

I would also like to thank fellow students for constructive conversations and moral support during the course of my work.

Last, but not least, my thanks go to my supervisor professor Sverre Steen for guiding me in the right direction throughout the semester.

Trondheim, 18th of December 2009

Christian Thomas Borgen

Table of Contents

| | |
|--|-----|
| Preface..... | III |
| 1 Introduction..... | 1 |
| 2 Previous work on oscillating foil propulsion | 2 |
| 3 The foil propeller..... | 3 |
| 3.1 Basic foil theory | 3 |
| 3.2 Thrust force | 4 |
| 3.2.1 The relative velocity | 4 |
| 3.2.2 Actively controlled foil..... | 6 |
| 3.2.3 Forces on the foil..... | 7 |
| 3.3 Time average thrust value..... | 10 |
| 3.4 Inaccuracies | 11 |
| 3.5 Unsteady lift effect | 11 |
| 3.6 Flexible foils | 12 |
| 3.7 Reduced added resistance | 14 |
| 3.8 Fuel Savings | 14 |
| 3.9 Fatigue | 15 |
| 3.9.1 Foil structure | 16 |
| 3.9.2 Moment of inertia | 17 |
| 4 Vessel and foil dimensions | 19 |
| 4.1 Key Criteria | 19 |
| 4.2 The vessels..... | 19 |
| 4.3 Vessel speed | 19 |
| 4.4 The foils | 20 |
| 4.4.1 Foil storage | 20 |
| 4.4.2 Foil positioning | 23 |
| 4.4.3 Offshore Supply Vessel (Angvik, 2009)..... | 23 |
| 4.4.4 Coastal Tanker | 24 |
| 4.4.5 Purse Seiner..... | 25 |
| 5 Wave conditions..... | 27 |
| 5.1 Regular waves..... | 27 |
| 5.2 Irregular waves | 27 |
| 6 Computer programs | 31 |
| 6.1 ShipX and VERES..... | 31 |

| | | |
|-------|---|----|
| 6.1.1 | Vessel Description | 31 |
| 6.1.2 | Condition information | 31 |
| 6.1.3 | Foil dimensions..... | 32 |
| 6.1.4 | Method of calculation | 32 |
| 6.1.5 | Ship Speed and Powering..... | 33 |
| 6.1.6 | Assumptions | 35 |
| 6.1.7 | Computational difficulties | 35 |
| 6.2 | MATLAB | 35 |
| 6.3 | Microsoft EXCEL..... | 35 |
| 6.4 | Program organisation..... | 35 |
| 7 | Results for Regular waves | 37 |
| 7.1 | Offshore Supply vessel | 37 |
| 7.1.1 | Thrust force | 37 |
| 7.1.2 | Including unsteady lift effects and flexible foils | 40 |
| 7.1.3 | Reduced added resistance in waves..... | 41 |
| 7.1.4 | Required thrust force | 42 |
| 7.1.5 | Fuel Savings | 44 |
| 7.2 | Coastal Tanker | 45 |
| 7.2.1 | Thrust force | 45 |
| 7.2.2 | Unsteady lift effects and flexible foil..... | 46 |
| 7.2.3 | Reduced added resistance | 46 |
| 7.2.4 | Reduction in required thrust | 48 |
| 7.2.5 | Fuel Savings | 49 |
| 7.3 | Purse Seiner..... | 50 |
| 7.3.1 | Thrust force | 50 |
| 7.3.2 | Unsteady lift effects and flexible foil..... | 52 |
| 7.3.3 | Reduced added resistance | 52 |
| 7.3.4 | Reduction in required thrust | 52 |
| 7.3.5 | Fuel Savings | 53 |
| 7.4 | Comparison | 54 |
| 7.4.1 | The foils | 54 |
| 7.4.2 | The vessels..... | 54 |
| 7.4.3 | Varying speed | 55 |
| 8 | Results in irregular waves for Offshore Supply vessel | 56 |

| | | |
|--|--|--------|
| 8.1 | Thrust force | 56 |
| 8.2 | Unsteady lift effects and flexible foil..... | 57 |
| 8.3 | Reduced added resistance in waves..... | 57 |
| 8.4 | Reduction in required thrust | 58 |
| 8.5 | Fuel Savings | 59 |
| 8.6 | Comparing regular and irregular waves | 60 |
| 9 | Results of the structural analysis..... | 62 |
| 9.1 | Double Stress amplitude | 62 |
| 9.2 | Fatigue | 64 |
| 10 | Conclusion | 65 |
| 11 | Further work..... | 66 |
| 12 | List of symbols and acronyms | 67 |
| 12.1 | Acronyms..... | 67 |
| 12.2 | Symbols | 67 |
| 13 | Bibliography..... | 69 |
| Appendices | | i |
| Appendix A: Scatter diagram for North Sea and northern Atlantic | | i |
| Appendix B: Thrust force, varying wave headings, offshore supply vessel..... | | ii |
| Appendix C: Thrust force, varying wave periods, offshore supply vessel | | iv |
| Appendix D: Reduction in added resistance, offshore supply vessel..... | | vi |
| Appendix E: Percentage of required thrust covered, offshore supply vessel, irregular waves | | viii |
| Appendix F: Fuel savings, regular waves, offshore supply vessel | | xii |
| Appendix G: Reduction in added resistance, coastal tanker..... | | xvi |
| Appendix H: Fuel Savings, Coastal tanker | | xviii |
| Appendix I: Thrust force, foil 9, purse seiner | | xxv |
| Appendix J: Reduction in added resistance in waves, purse seiner | | xxvii |
| Appendix K: Reduction in required thrust force, purse seiner..... | | xxix |
| Appendix L: Fuel Savings, purse seiner | | xxxiii |
| Appendix M: Combined coefficient for unsteady flow and flexible foil..... | | xxxvii |

Figures

| | |
|---|----|
| FIGURE 2-1: EARLY VERSION OF JAKOBSEN'S FOIL PROPELLER (JAKOBSEN, 1981) | 2 |
| FIGURE 3-1: FOIL DEFINITIONS. | 3 |
| FIGURE 3-2: QUASI-STEADY 2D-ANALYSIS OF HEAVING FOIL. | 4 |
| FIGURE 3-3: THE PRINCIPLE OF AN ACTIVE FOIL PROPELLER | 7 |
| FIGURE 3-4: FLEXIBLE FOIL | 12 |
| FIGURE 3-5: QUASIPROPULSIVE EFFICIENCY..... | 13 |
| FIGURE 3-6: S-N CURVE FOR STEEL AND ALUMINIUM | 16 |
| FIGURE 3-7: FOIL CROSS-SECTION | 16 |
| FIGURE 3-8: FLEXIBLE FOIL DESIGN..... | 17 |
| FIGURE 3-9: NACA0015 FOIL CURVATURE | 17 |
| FIGURE 4-1: EXAMPLE OF ROLL DAMPING FIN (ROLLS-ROYCE MARINE, 2007). | 20 |
| FIGURE 4-2: SPACE LIMITATIONS | 21 |
| FIGURE 4-3: FRONT VIEW | 21 |
| FIGURE 4-4: VERTICAL TELESCOPIC RETRACTION..... | 22 |
| FIGURE 4-5: DIAGONAL TELESCOPIC RETRACTION | 22 |
| FIGURE 5-1: JONSWAP WAVE SPECTRUM..... | 28 |
| FIGURE 5-2: RESPONSE SPECTRUM (FATHI, 2005) | 29 |
| FIGURE 6-1: VESSEL DESCRIPTION..... | 31 |
| FIGURE 6-2: CONDITION INFORMATION | 32 |
| FIGURE 6-3: FOIL DIMENSIONS..... | 32 |
| FIGURE 6-4: FINDING THE RELATIVE VELOCITY SPECTRUM..... | 33 |
| FIGURE 6-5: IMPORTED SHIP RESISTANCE CURVE | 34 |
| FIGURE 6-6: SCHEMATIC DIAGRAM OF THE USE OF COMPUTER PROGRAMS..... | 36 |
| FIGURE 7-1: FOIL 9, HEAD SEAS - OFFSHORE SUPPLY VESSEL, REGULAR WAVES | 38 |
| FIGURE 7-2: FOIL 9, BEAM SEAS - OFFSHORE SUPPLY VESSEL, REGULAR WAVE | 38 |
| FIGURE 7-3: FOIL 9, FOLLOWING SEAS - OFFSHORE SUPPLY VESSEL, REGULAR WAVE | 39 |
| FIGURE 7-4: FOIL 9, $T_0 = 8,5s$ - OFFSHORE SUPPLY VESSEL, REGULAR WAVES | 39 |
| FIGURE 7-5: FOIL 9, $T_0 = 6,5s$ - OFFSHORE SUPPLY VESSEL, REGULAR WAVES | 40 |
| FIGURE 7-6: EFFECT OF UNSTEADY LIFT BY WAVE PERIOD AND HEADING | 40 |
| FIGURE 7-7: REDUCTION IN ADDED RESISTANCE, 10 KNOTS - OFFSHORE SUPPLY VESSEL..... | 41 |
| FIGURE 7-8: REDUCTION IN ADDED RESISTANCE, 18 KNOTS - OFFSHORE SUPPLY VESSEL..... | 42 |
| FIGURE 7-9: VARIATION OF CHOSEN THRUST FORCES..... | 43 |
| FIGURE 7-10: FOIL 9, HEAD SEAS - COASTAL TANKER, REGULAR WAVES | 45 |
| FIGURE 7-11: FOIL 9, BEAM SEAS - COASTAL TANKER, REGULAR WAVES..... | 45 |
| FIGURE 7-12: FOIL 9, FOLLOWING SEAS - COASTAL TANKER, REGULAR WAVES..... | 46 |
| FIGURE 7-13: REDUCTION IN ADDED RESISTANCE, 10 KNOTS - COASTAL TANKER..... | 46 |
| FIGURE 7-14: REDUCTION IN ADDED RESISTANCE, 18 KNOTS - COASTAL TANKER..... | 47 |
| FIGURE 7-15: REDUCTION IN ADDED RESISTANCE, 10 KNOTS - COASTAL TANKER (PRESSURE INTEGRATION)..... | 47 |
| FIGURE 7-16: REDUCTION IN ADDED RESISTANCE, 18 KNOTS - COASTAL TANKER (PRESSURE INTEGRATION)..... | 48 |
| FIGURE 7-17: FOIL 9, HEAD SEAS - PURSE SEINER, REGULAR WAVES..... | 50 |
| FIGURE 7-18: FOIL 9, BEAM SEAS - PURSE, REGULAR WAVES | 51 |
| FIGURE 7-19: FOIL 9, FOLLOWING SEAS - PURSE SEINER, REGULAR WAVES | 51 |
| FIGURE 7-20: REDUCTION IN ADDED RESISTANCE, 10 KNOTS - PURSE SEINER | 52 |
| FIGURE 7-21: REDUCTION IN ADDED RESISTANCE, 18 KNOTS - PURSE SEINER | 52 |
| FIGURE 7-22: REDUCTION IN REQUIRED POWER, FOIL 9 - OFFSHORE SUPPLY VESSEL..... | 55 |
| FIGURE 8-1: "PURE" THRUST FORCE, 10 KNOTS - IRREGULAR WAVES | 56 |
| FIGURE 8-2: "PURE" THRUST FORCE, 15 KNOTS - IRREGULAR WAVES | 56 |
| FIGURE 8-3: "PURE" THRUST FORCE, FOIL 9 - IRREGULAR WAVES | 57 |

| | |
|---|----|
| FIGURE 8-4: REDUCTION IN ADDED RESISTANCE IN IRREGULAR WAVES..... | 58 |
| FIGURE 9-1: DOUBLE STRESS AMPLITUDE - OFFSHORE SUPPLY VESSEL..... | 62 |
| FIGURE 9-2: DOUBLE STRESS AMPLITUDE - COASTAL TANKER..... | 63 |
| FIGURE 9-3: DOUBLE STRESS AMPLITUDE - PURSE SEINER | 63 |
| FIGURE 9-4: S-N DIAGRAM FOR STEEL AND ALUMINIUM | 64 |

Tables

| | |
|---|----|
| TABLE 1: PHASE ANGLES FOR LONG PERIODS (FATHI, 2005) | 5 |
| TABLE 2: MAIN CHARACTERISTICS | 19 |
| TABLE 3: DEFINITION OF FOIL CONFIGURATIONS | 23 |
| TABLE 4: FOIL INPUT OFFSHORE SUPPLY VESSEL – $s/c = 3$ | 24 |
| TABLE 5: FOIL INPUT OFFSHORE SUPPLY VESSEL – $s/c = 4$ | 24 |
| TABLE 6: FOIL INPUT OFFSHORE SUPPLY VESSEL – $s/c = 5$ | 24 |
| TABLE 7: FOIL INPUT COASTAL TANKER – $s/c = 3$ | 25 |
| TABLE 8: FOIL INPUT COASTAL TANKER – $s/c = 4$ | 25 |
| TABLE 9: FOIL INPUT COASTAL TANKER – $s/c = 5$ | 25 |
| TABLE 10: FOIL INPUT PURSE SEINER – $s/c = 3$ | 26 |
| TABLE 11: FOIL INPUT PURSE SEINER – $s/c = 4$ | 26 |
| TABLE 12: FOIL INPUT PURSE SEINER – $s/c = 5$ | 26 |
| TABLE 13: WAVE CONDITIONS | 27 |
| TABLE 14: WEIGHTED WAVE CONDITIONS..... | 37 |
| TABLE 15: REDUCTION IN REQUIRED THRUST - OFFSHORE SUPPLY VESSEL, REGULAR WAVES..... | 43 |
| TABLE 16: FUEL SAVINGS - OFFSHORE SUPPLY VESSEL, REGULAR WAVES..... | 44 |
| TABLE 17: REDUCTION IN REQUIRED THRUST, COASTAL TANKER | 49 |
| TABLE 18: FUEL SAVINGS - COASTAL TANKER, REGULAR WAVES | 50 |
| TABLE 19: REDUCTION IN REQUIRED THRUST – PURSE SEINER, REGULAR WAVES | 53 |
| TABLE 20: FUEL SAVINGS - PURSE SEINER, REGULAR WAVES | 54 |
| TABLE 21: COMPARING THE VESSELS | 55 |
| TABLE 22: ADDED RESISTANCE IN IRREGULAR WAVES, WITH AND WITHOUT FOIL | 58 |
| TABLE 23: REDUCTION IN REQUIRED THRUST, IRREGULAR WAVES..... | 59 |
| TABLE 24: FUEL SAVINGS, IRREGULAR WAVES..... | 60 |
| TABLE 25: RELATIVE DIFFERENCE BETWEEN REGULAR AND IRREGULAR WAVES | 61 |

1 Introduction

When looking to nature, there are very few – if any – examples of propulsion generated from a screw propeller. Creating forward velocity from transverse motion is by far the most common method of propulsion when considering the creatures living in the ocean. Aquatic mammals such as dolphins are also known for swimming close to a vessel and to use the waves from the vessel to increase their speed (Williams, et al. 1992). These facts have inspired the study of the oscillating foil propeller.

When a vessel travels at sea there will always be waves which cause the ship to oscillate in all degrees of freedom. Particularly interesting is the heave and pitch motion of the vessel and how this produces large relative vertical motions between the vessel and the water. This motion is comparable to the motion of the tail fin of dolphins, whales, etc.

Mounting foils on either side of the vessel will therefore give a forward thrust force that propels the vessel forward.

This thesis will look into foils controlled to optimise the thrust force. After finding the thrust force we plan to consider the effect of an unsteady lift which we suspect will reduce effective thrust. Further we will try to include the benefits from a flexible foil.

We want to investigate the impact of foils propellers on added resistance in waves. As foil propeller reduce pitch and heave motion we expect the added resistance to be reduced. This reduction will be considered as an extra thrust component. We plan to find the required thrust force from the conventional propeller and compare it to that of a vessel without foils. Finally, the potential fuel savings will be calculated.

The use of foil propeller in real life will require that the foils can be stowed away, one reason being so they do not obstruct the vessel coming alongside the quay. We will look into possible ways this can be done to minimise the resistance in calm seas.

The lift forces on the foils will give a significant bending moment at the root of the foil. The force is oscillating and we expect that there is a possibility of high cycle fatigue. The fatigue life of the foils will be investigated.

2 Previous work on oscillating foil propulsion

The first documented attempt to utilise waves to create a forward thrust force is dated back to 1895 and was made by H. F. L. Linden (NewYorkTimes, 1898).

In 1976 Chopra developed a foil propulsion system which was driven by an external energy source (MotorShip, 1983) and in the 1980s at Chalmers Technical University in Sweden a motor driven foil propeller was tested experimentally (Korbijn, 1989). In both cases high propulsive efficiencies were found.

Einar Jakobsen designed a propeller system that created a thrust force from the naturally occurring relative motion between a vessel and the water (Dybdahl, 1988). This is the concept which in this thesis is referred to as the foil propeller. He made promising model experiments (Jakobsen, 1981) and proceeded to mount foils on a full scale 7,5 m yacht, reporting fuel savings of 30 % in head seas at 6 knots. In this experiment the foil was attached to a spring system so that the angle of the foil would adjust as the direction of the incoming water changed (Figure 2-1), thus increasing the thrust force. Inspired by promising results he preformed another full scale test on an even larger vessel, a 20.4m fishing vessel (Berg, 1985).

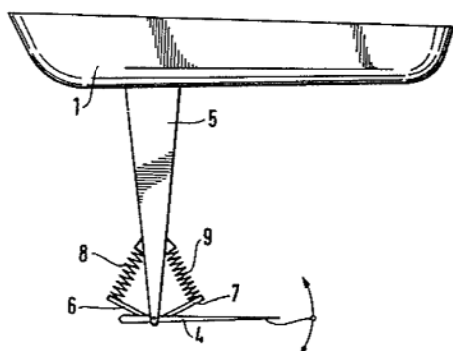


Figure 2-1: Early version of Jakobsen's foil propeller (Jakobsen, 1981).

Parallel with Jakobsen's work, experiments were preformed on a similar concept in Japan (Isshiki, et al., 1984) (Isshiki, et al., 1986a). Very promising results was reported from experiments on an 80 m long cargo vessel (Isshiki, 1994). Despite these inviting results by several independent studies any significant commercial success is yet to be seen. The drawbacks of the concepts have been added resistance in calm seas as well as cost considerations.

In the spring of 2009 Ingrid Angvik, a former student at NTNU (Norwegian University of Technology and Science), wrote her master thesis on the foil propeller (Angvik, 2009). She used state-of-the-art computer programs to investigate the benefits of mounting foils near the bow of a 93m offshore supply vessel. Calculations were preformed with varying foil-size in regular waves, varying wave direction and period. The results were again promising. For certain conditions it was found that the vessel could travel at 15 knots solely using the foil propeller. The study did not include elements such as unsteady lift effects and the use of flexible foils. Nor irregular waves were considered.

This master thesis is a continuation of the previously done work. The author wishes to look into areas and aspects of the concept of which the effects are yet to be determined.

3 The foil propeller

3.1 Basic foil theory

For a foil to create lift we need an in-flow velocity and circulation around the foil. If a foil is placed so that it is symmetric around a streamline in a uniform stream no circulation is achieved, thus no lift either. If the flow has an oscillating transverse velocity component in addition to the in-flow velocity, oscillating lift forces is obtained.

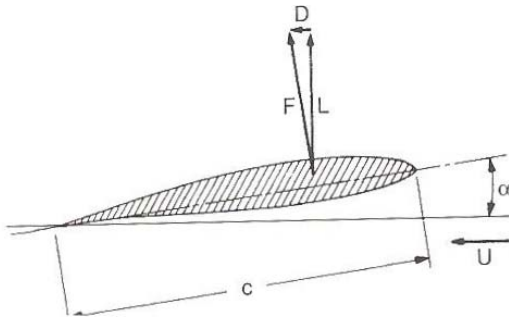


Figure 3-1: Foil definitions.

Figure 3-1 shows the transverse cross-section of a foil and its basic characteristics. L is the lift force, D is the drag force, α is the angle between the foil and the incoming flow, U is the undisturbed fluid velocity, c is the chord length and s (not shown in the figure) is the foil span in the transverse direction. By definition we have the lift (Equation 3-1) and drag (Equation 3-2) coefficients:

$$C_L = \frac{L}{\frac{\rho}{2} U^2 S}$$

Equation 3-1

$$C_D = \frac{D}{\frac{\rho}{2} U^2 S}$$

Equation 3-2

S is the planform area, or just foil area, defined as “the projected area of the foil in the direction of the lift force for zero angle of attack” (Minsaas, 2006). For a rectangular foil we have $S = c \cdot s$

Foil theory is based on the following boundary conditions.

- *The kinematic boundary condition*, which states that no fluid particle can penetrate the surface of the foil.
- *The Kutta condition*, which states that the flow must leave tangentially from the trailing edge. In other words: the foil must not be stalling
- *The far-field condition*, which says that at a point at infinity distance from the foil, the fluid velocity equals the undisturbed fluid velocity U .

3.2 Thrust force

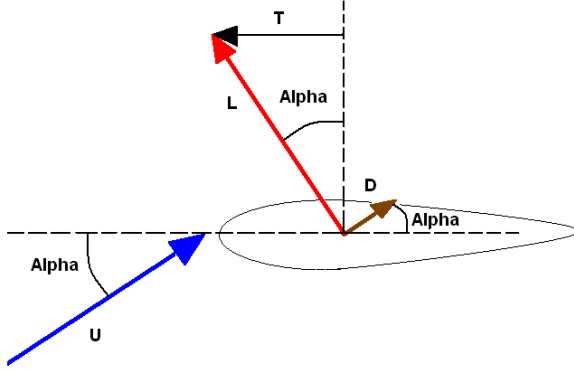


Figure 3-2: Quasi-steady 2D-analysis of heaving foil.

Initially, we will use a quasi-steady approach to analyze the forces on the foil. Figure 3-2 shows the situation at a specific time. U is the relative velocity between the foil and the fluid, being the fluid velocity that the foil “sees”. The lift force vector L will be perpendicular to the vector U , hence we have a horizontal component of the lift which becomes the thrust T . We also have a drag force D which has a horizontal component opposing the thrust, thus our total thrust is given as

$$\text{Total thrust} = L \cdot \sin(\text{Alpha}) - D \cdot \cos(\text{Alpha})$$

Equation 3-3

Because of oscillatory motion of both the vessel and the water particles, Alpha will oscillate between negative and positive values. When the angle is zero, we will have zero thrust because the lift force will be purely vertical. For a symmetric foil the lift force will be zero in this case, as we have no circulation. As the angle is increased the thrust force will increase until a certain point where stalling will occur and the lift will start to decrease.

3.2.1 The relative velocity

The relative velocity will be the difference between the foil velocity and fluid particle velocity. First we will take a look at the fluid velocity. The wave potential to an incident wave can be written in complex form as

$$\phi_I = \frac{g\zeta_a}{\omega_0} e^{kz} e^{i(\omega_0 t - k(x\cos\beta + y\sin\beta))}$$

Equation 3-4

The wave amplitude is ζ_a , k is the wave number, β is the wave heading angle, $\omega_0 = \sqrt{gk}$ is the wave frequency of the incident wave and x and y describes the position.

The vertical velocity component of the fluid particle caused by the wave is found to be

$$w_w = \frac{\partial \phi_I}{\partial z} = \omega_0 \zeta_a e^{kz} e^{i(\omega_0 t - k(x\cos\beta + y\sin\beta))} = \omega_0 \zeta_a e^{kz}$$

Equation 3-5

The horizontal component is expressed as

$$u_w = \frac{\partial \phi_I}{\partial x} = \omega_0 \zeta_a e^{kz} e^{i(\omega_0 t - k(x \cos \beta + y \sin \beta))} \cdot (-i \cos \beta)$$

Equation 3-6

Secondly we look at the foil motion. The response motions of the ship, and therefore the foil, are functions of the frequency of encounter, not the wave frequency. This frequency is (Faltinsen, 1990)

$$\omega_e = \omega_0 + \frac{\omega_0^2 U}{g} \cos \beta$$

Equation 3-7

The ship has both translatory and angular motions in all six degrees of freedom. The motion transfer functions are given by the amplitude η_0 and a phase angle ϵ .

$$\eta_{k,s}(t) = \eta_{k,s0} \cos(\omega_e t + \epsilon_k), \quad k = 1, \dots, 6.$$

Equation 3-8

The motion can be rewritten as

$$\eta_{k,s}(t) = \text{Re}[\tilde{\eta}_{k,s} e^{i\omega_e t}] = \text{Re}[(\eta_{Rk,s} + i\eta_{Ik,s})(\cos \omega_e t + i \sin \omega_e t)]$$

Equation 3-9

Where $\tilde{\eta}_{k,s}$ is the complex motion amplitude (Fathi, 2005).

By combining Equation 3-8 and Equation 3-9 the relation between the complex motion amplitude and the motion amplitude is found to be

$$\tilde{\eta}_{k,s} = \eta_{Rk,s} + i\eta_{Ik,s} = |\eta_{k,s0}| \cos \epsilon_k - i |\eta_{k,s0}| \sin \epsilon_k$$

Equation 3-10

The following table is taken from the VERES user's manual and presents the phase angles for all modes of ship motions for waves with long periods. We will also consider bow and stern quartering seas, for the first we will use the values for head sea, and for the latter we will use the values for following seas. In chapter 3.4 we will explain why this simplification is acceptable for our purpose.

| | Head sea, $\beta = 0^\circ$ | Beam sea, $\beta = 90^\circ$ | Following sea, $\beta = 180^\circ$ |
|---------------------|-----------------------------|------------------------------|------------------------------------|
| Surge, ϵ_1 | 90 | | 90 |
| Sway, ϵ_2 | | -90 | |
| Heave, ϵ_3 | 0 | 0 | 0 |
| Roll, ϵ_4 | | -90 | |
| Pitch, ϵ_5 | 90 | | -90 |
| Yaw, ϵ_6 | | | |

Table 1: Phase angles for long periods (Fathi, 2005).

The foil will be fixed to the hull, so when we consider the relative velocity between fluid particle and the foil we might as well consider the velocity at a point that is fixed to a certain coordinate relative to the centre of gravity of the vessel. The motion of any point can be written as (Faltinsen, 1990)

$$\bar{s} = (\eta_1 + z\eta_5 - y\eta_6)\bar{i} + (\eta_2 - z\eta_4 + x\eta_6)\bar{j} + (\eta_3 + y\eta_4 - x\eta_5)\bar{k}$$

Equation 3-11

From Equation 3-11 we derive the expressions for the velocities

$$w_v = \dot{\eta}_{3,s} - x_{R.C.}\dot{\eta}_5 + y_{R.C.}\dot{\eta}_4 - U\eta_5$$

Equation 3-12

$$u_v = \dot{\eta}_{1,s} - z_{R.C.}\dot{\eta}_5 + y_{R.C.}\dot{\eta}_6 - U$$

Equation 3-13

U is the velocity of the ship and $x_{R.C.}$, $y_{R.C.}$ and $z_{R.C.}$ are the coordinates of the centre of rotation of the foil.

We define the relative vertical velocity

$$w_{REL} = w_w - w_v = w_w - (\dot{\eta}_{3,s} - x_{R.C.}\dot{\eta}_{5,s} + y_{R.C.}\dot{\eta}_{4,s} - U\eta_{5,s})$$

Equation 3-14

Here w_w is taken from Equation 3-5. We assume that the vessel and foil do not disturb the fluid velocity significantly. This is a reasonable assumption when the foil is placed close to the bow.

The relative horizontal velocity is dominated by the ship velocity U, which will be much larger than the other components. Hence we simplify the expression to be

$$u_{REL} = u_w - u_v \cong U$$

Equation 3-15

3.2.2 Actively controlled foil

If the foil is constantly rotated to obtain the optimal angle for maximised thrust force we will have what we call an active foil propeller. The principle is illustrated in Figure 3-3. $\eta_{5,s}$ is the pitch angle of the ship, $\eta_{5,f}$ is the controllable pitch angle of the foil and α is the angle of attach “seen” by the foil. ϕ is the angle of the relative fluid velocity compared to fixed coordinate system moving with the ship velocity U in the positive x-direction.

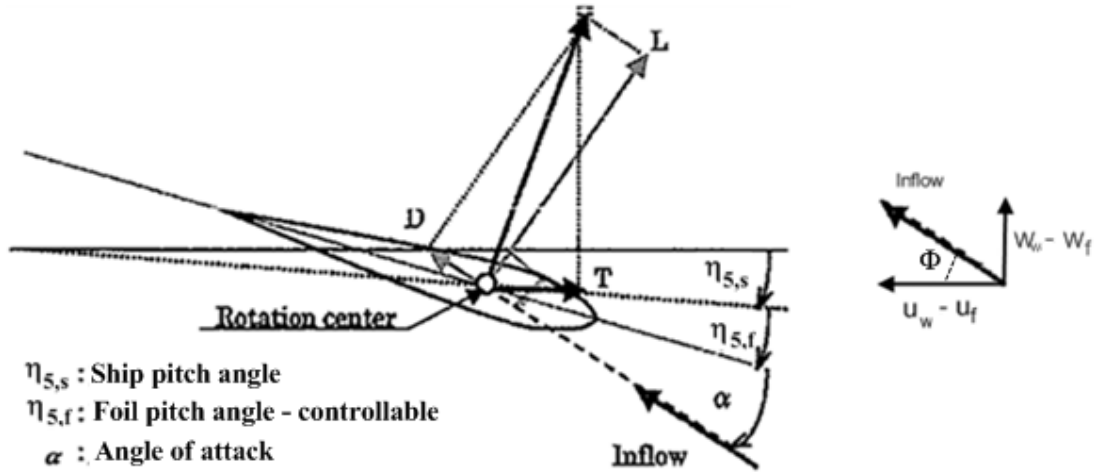


Figure 3-3: The principle of an active foil propeller

3.2.3 Forces on the foil

We recall Equation 3-3 which gives the expression for the total thrust. Both the lift and the drag force will depend on the angle of attack, α . Considering Figure 3-3 we derive the following expression. The angles are oscillating and are therefore time dependent.

$$T_{FP} = L[\alpha(t)] \sin \phi(t) - D[\alpha(t)] \cos \phi(t)$$

Equation 3-16

And similarly the vertical force is found as

$$F_V = L[\alpha(t)] \cdot \cos \phi(t) + D[\alpha(t)] \cdot \sin \phi(t)$$

Equation 3-17

Where

$$\phi(t) = \arctan \left(\frac{w_{Rel}(t)}{U} \right) \cong \frac{w_{Rel}(t)}{U}$$

Equation 3-18

The simplification is done because we assume a forward speed much larger than the relative vertical velocity.

The vertical force is of interest when we do a stress analysis with the motive of determine the structural integrity of the foil. If the foil breaks, we expect it to do so around the x-axis (defined in Figure 3-9) of the foil. Hence we are interested in the force perpendicular to this axis. The expression for the “perpendicular” force becomes

$$F_{perpendicular} = F_P = L[\alpha(t)] \cdot \cos \alpha(t) + D[\alpha(t)] \cdot \sin \alpha(t)$$

Further we can derive the following expression for α

$$\alpha(t) = \phi(t) - \eta_{5,s}(t) - \eta_{5,f}(t) \cong \frac{w_{Rel}(t)}{U} - \eta_{5,s}(t) - \eta_{5,f}(t)$$

Equation 3-19

The in-flow velocity “seen” by the foil is called the velocity of advance, V_A . From geometry we find that

$$V_A = \frac{U}{\cos\phi(t)}$$

Equation 3-20

If we rearrange Equation 3-1 and Equation 3-2, and introduce the velocity of advance we get the expressions for the lift and the drag force to be

$$L = C_L \frac{1}{2} \rho S V_A^2$$

Equation 3-21

$$D = C_D \frac{1}{2} \rho S V_A^2$$

Equation 3-22

C_L is the lift coefficient, C_D is the drag coefficient, ρ is the density of sea water and S is the projected area of the foil. In this thesis the foils will be rectangular, giving:

$$S = s \cdot c$$

Equation 3-23

Where c is the chord length of the foil and s is the foil span.

Now we need to find the lift and drag coefficients. In short the lift is proportional to the angle of attack, α , while the drag is proportional to α^2 . In this thesis we will use Prandtl’s lifting line theory which states

$$C_L = \frac{2\pi\alpha}{1 + \frac{2}{\Lambda}}$$

Equation 3-24

$$C_D = \frac{4\pi\alpha^2\Lambda}{(\Lambda + 2)^2}$$

Equation 3-25

Where the aspect ratio is defined as $\Lambda = \frac{s^2}{S} = \frac{s}{c}$. This theory gives conservative estimates and the results are most accurate for large aspect ratios. The relative error is about 20 % for aspect ratios around 4 if the foil has an elliptical shape (Faltinsen, 2005). In our calculations we will have

rectangular foils with aspect ratios of 3, 4 and 5. This will presumably make our results fairly conservative.

The effect of stalling comes into account when the angle of attack reaches about 15 degrees (Faltinsen, 2005). The actively controlled foils must be programmed so that this phenomena is avoided, keeping the angle at no more than 15 degrees all the time.

We insert Prandtl's formulas and the expression for the advance coefficients into Equation 3-21 and Equation 3-22 giving the instantaneous lift and drag force

$$L(t) \cong \frac{1}{2} \rho c s \left(\frac{U}{\cos \phi(t)} \right)^2 \frac{2\pi}{1 + \frac{2}{\Lambda}} \alpha(t)$$

Equation 3-26

$$D(t) \cong \frac{1}{2} \rho c s \left(\frac{U}{\cos \phi(t)} \right)^2 \frac{4\pi\Lambda}{(\Lambda + 2)^2} \alpha^2(t)$$

Equation 3-27

Hence the thrust and drag forces become

$$T_{FP}(t) = \frac{1}{2} \rho c s \left(\frac{U}{\cos \phi(t)} \right)^2 \frac{2\pi}{1 + \frac{2}{\Lambda}} \alpha(t) \sin \phi(t) - \frac{1}{2} \rho c s \left(\frac{U}{\cos \phi(t)} \right)^2 \frac{4\pi\Lambda}{(\Lambda + 2)^2} \alpha^2(t) \cos \phi(t)$$

Equation 3-28

$$F_V(t) = \frac{1}{2} \rho c s \left(\frac{U}{\cos \phi(t)} \right)^2 \frac{2\pi}{1 + \frac{2}{\Lambda}} \alpha(t) \cos \phi(t) + \frac{1}{2} \rho c s \left(\frac{U}{\cos \phi(t)} \right)^2 \frac{4\pi\Lambda}{(\Lambda + 2)^2} \alpha^2(t) \sin \phi(t)$$

Equation 3-29

We simplify the equations by assuming that U is much larger than w_{REL} , thus

$$\cos \left(\frac{w_{REL}}{U} \right) \rightarrow 1$$

Equation 3-30

$$\sin \left(\frac{w_{REL}}{U} \right) \rightarrow \frac{w_{REL}}{U}$$

Equation 3-31

And we get the following expressions for the forces on the foil

$$T_{FP}(t) = \frac{\pi \rho c s U^2}{1 + \frac{2}{\Lambda}} \alpha(t) \phi(t) - \frac{2\pi\Lambda \rho c s U^2}{(\Lambda + 2)^2} \alpha^2(t)$$

Equation 3-32

$$F_V(t) = \frac{\pi \rho c s U^2}{1 + \frac{2}{\Lambda}} \alpha(t) + \frac{2\pi \Lambda \rho c s U^2}{(\Lambda + 2)^2} \alpha^2(t) \phi(t)$$

Equation 3-33

3.3 Time average thrust value

We recall Equation 3-18 and Equation 3-19 and find the thrust force to be

$$T_{FP}(t) = \frac{\pi \rho c s U^2}{1 + \frac{2}{\Lambda}} \left[\frac{w_{Rel}(t)}{U} - \eta_{5,s}(t) - \eta_{5,f}(t) \right] \frac{w_{Rel}(t)}{U} - \frac{2\pi \Lambda \rho c s U^2}{(\Lambda + 2)^2} \left[\frac{w_{Rel}(t)}{U} - \eta_{5,s}(t) - \eta_{5,f}(t) \right]^2$$

Equation 3-34

To calculate the thrust gained from the foil the time average has to be calculated. We extract the six time dependent terms:

$$\left[\left(\frac{w_{Rel}(t)}{U} \right)^2 \right], \left[(\eta_{5,s}(t))^2 \right], \left[(\eta_{5,f}(t))^2 \right], \left[\frac{w_{Rel}(t)}{U} \cdot \eta_{5,s}(t) \right], \left[\frac{w_{Rel}(t)}{U} \cdot \eta_{5,f}(t) \right] \text{ and } \left[\eta_{5,s}(t) \cdot \eta_{5,f}(t) \right]$$

We use Equation 3-8 and introduce the response amplitude operators

$$\eta_{5,s}(t) = \eta_{5,s0} \cos(\omega_e t + \epsilon_{5,s}) \stackrel{\text{def}}{=} \zeta_a RAO_{\eta_{5,s}} \cos(\omega_e t + \epsilon_{5,s})$$

Equation 3-35

$$\eta_{5,f}(t) = \eta_{5,f0} \cos(\omega_e t + \epsilon_{5,f}) \stackrel{\text{def}}{=} \zeta_a RAO_{\eta_{5,f}} \cos(\omega_e t + \epsilon_{5,f})$$

Equation 3-36

$$w_{Rel}(t) = \zeta_a RAO_{w_{REL}} \sin(\omega_e t)$$

Equation 3-37

We consider our time dependent terms and find the time average values

| Time dependent value | Time average value |
|---|---|
| $\left(\frac{w_{REL}}{U} \right)^2 = \left(\frac{\zeta_a RAO_{w_{REL}} \sin(\omega_e t)}{U} \right)^2$ | $\frac{1}{2} \left(\frac{\zeta_a RAO_{w_{REL}}}{U} \right)^2$ |
| $\left(\frac{w_{REL}}{U} \cdot \eta_{5,s} \right) = - \frac{\zeta_a RAO_{w_{REL}}}{U} \sin(\omega_e t) \cdot \zeta_a RAO_{\eta_{5,s}} \cos(\omega_e t + \epsilon_{5,s})$ | $\cdot - \frac{1}{2} \frac{\zeta_a^2 RAO_{w_{REL}} \cdot RAO_{\eta_{5,s}}}{U} \sin \epsilon_{5,s}$ |
| $\left(\frac{w_{REL}}{U} \cdot \eta_{5,f} \right) = - \frac{\zeta_a RAO_{w_{REL}}}{U} \sin(\omega_e t) \cdot \zeta_a RAO_{\eta_{5,f}} \cos(\omega_e t + \epsilon_{5,f})$ | $\cdot - \frac{1}{2} \frac{\zeta_a^2 RAO_{w_{REL}} \cdot RAO_{\eta_{5,f}}}{U} \sin \epsilon_{5,f}$ |
| $(\eta_{5,s} \cdot \eta_{5,f}) = \zeta_a RAO_{\eta_{5,s}} \cos(\omega_e t + \epsilon_{5,s}) \cdot \zeta_a RAO_{\eta_{5,f}} \cos(\omega_e t + \epsilon_{5,f})$ | $\frac{1}{2} \zeta_a^2 RAO_{\eta_{5,s}} RAO_{\eta_{5,f}} (\cos \epsilon_{5,s} \cos \epsilon_{5,f} + \sin \epsilon_{5,s} \sin \epsilon_{5,f})$ |
| $\eta_{5,s}^2 = (\zeta_a RAO_{\eta_{5,s}} \cos(\omega_e t + \epsilon_{5,s}))^2$ | $\frac{1}{2} \zeta_a^2 RAO_{\eta_{5,s}}^2$ |
| $\eta_{5,f}^2 = (\zeta_a RAO_{\eta_{5,f}} \cos(\omega_e t + \epsilon_{5,f}))^2$ | $\frac{1}{2} \zeta_a^2 RAO_{\eta_{5,f}}^2$ |

The time average value of the thrust then becomes

$$\begin{aligned} \bar{T}_{FP} = & \frac{\pi \rho c s U^2 \zeta_a^2}{1 + \frac{2}{\Lambda}} \left(\frac{1}{2} \left(\frac{RAO_{W_{REL}}}{U} \right)^2 - \frac{1}{2} \frac{RAO_{W_{REL}} \cdot RAO_{\eta_{5,f}}}{U} \sin \epsilon_{5,f} - \frac{1}{2} \frac{RAO_{W_{REL}} \cdot RAO_{\eta_{5,s}}}{U} \sin \epsilon_{5,s} \right) \\ & - \frac{2\pi \Lambda \rho c s U^2 \zeta_a^2}{(\Lambda + 2)^2} \left(\frac{1}{2} \left(\frac{RAO_{W_{REL}}}{U} \right)^2 - \frac{RAO_{W_{REL}} \cdot RAO_{\eta_{5,s}}}{U} \sin \epsilon_{5,s} \right. \\ & - \frac{RAO_{W_{REL}} \cdot RAO_{\eta_{5,f}}}{U} \sin \epsilon_{5,f} + \frac{1}{2} RAO_{\eta_{5,s}}^2 + RAO_{\eta_{5,s}} RAO_{\eta_{5,f}} (\cos \epsilon_{5,s} \cos \epsilon_{5,f} \\ & \left. + \sin \epsilon_{5,s} \sin \epsilon_{5,f}) + \frac{1}{2} RAO_{\eta_{5,f}}^2 \right) \end{aligned}$$

Equation 3-38

3.4 Inaccuracies

When applying this quasi-steady 2D method, several effects are not considered. We do not take into account the continuously shed vortices from the trailing edge, which will influence the angle of attack. Free-surface effects, 3D flow effects, hull interaction with the flow close to the hull and several non-linear phenomena which are very difficult to calculate are other considerations that have been excluded in this calculation.

The actively controlled pitch angle of the foil will influence the motion of the ship. This effect is not considered in our calculation as the computer program we will use to find the response amplitude operators – ShipX – are only able to add passive foils to the hull (i.e. fixed to the ship hull). The active control will change the angle of attack with the purpose of increasing the lift and thrust force. The lift force will oppose the vertical motion of the ship at this point, hence the pitch and heave motion of the ship will be further reduced with actively controlled foils. We do not expect that this will affect the results in any significant way.

We assume the phase angle of the ship motion in heave and pitch to be as given in Table 1. The actual phase angle will differ somewhat from these values as the wave length changes. One might think that when these values become inaccurate, the resulting thrust force will be compromised. This is not the case when the foils are actively controlled because the phase angle of the foils may be adjusted to compensate for this inaccuracy, thus the in-flow angle, $\alpha(t)$, remains the same. This has been proven correct in our results, regardless of the input phase angles $\epsilon_{5,s}$, the phase angle of the foil adjusts and the thrust force remains the same.

3.5 Unsteady lift effect

We mentioned earlier that we use a quasi-steady approach in our calculations. This is a good approximation for many purposes, but as the flow around the foil oscillates between giving a lift upwards (and forward) and downwards (and forward) there is a period of time between these two states during which the lift is about to change direction. The angle will be reduced which directly affects the lift and a vortex will be shed and pass along the chord of the foil to the trailing edge and cause instability in the pressure gradient which reduces the lift further. As the lift is reduced the thrust is reduced as well. We will try to include this effect in our calculations and look to an expression from (Minsaas, 2006)

$$\frac{C_{Lu}}{C_{Lq}} = 1 - \left(\frac{k}{3}\right)^{0,35} \left[1 - 0,88 \left(\frac{Asp}{6}\right)^{0,21}\right] \cdot Asp$$

Equation 3-39

Where

Asp = aspect ratio

C_{Lu} = the mean value of the unsteady lift

C_{Lq} = the mean value of the quasi steady lift

$k = \omega_e \frac{c}{2U}$ = reduced frequency

ω_e = frequency of encounter as defined in Equation 37

c = chord length

U = Vessel velocity

From this expression we can see that the lift is reduced when the frequency of encounter increases. This is of course intuitively correct because the periods with reduced lifts become more frequent. As mentioned the vortex passing along the foil will affect the lift. The time it takes before the vortex ceases disturb the lift is proportional to the chord length and the inverse of the vessel velocity.

An actively controlled foil will be able to quickly regain a beneficial angle of attack, so there is reason to believe that the loss in thrust will be somewhat reduced for an active foil propeller.

3.6 Flexible foils

When we look to the “foils” found in nature they are with no exception flexible, meaning that the trailing edge is deflected under the action of the hydrodynamic pressure on the foil surface. This is illustrated in Figure 3-4 taken from (Bose, 2008)

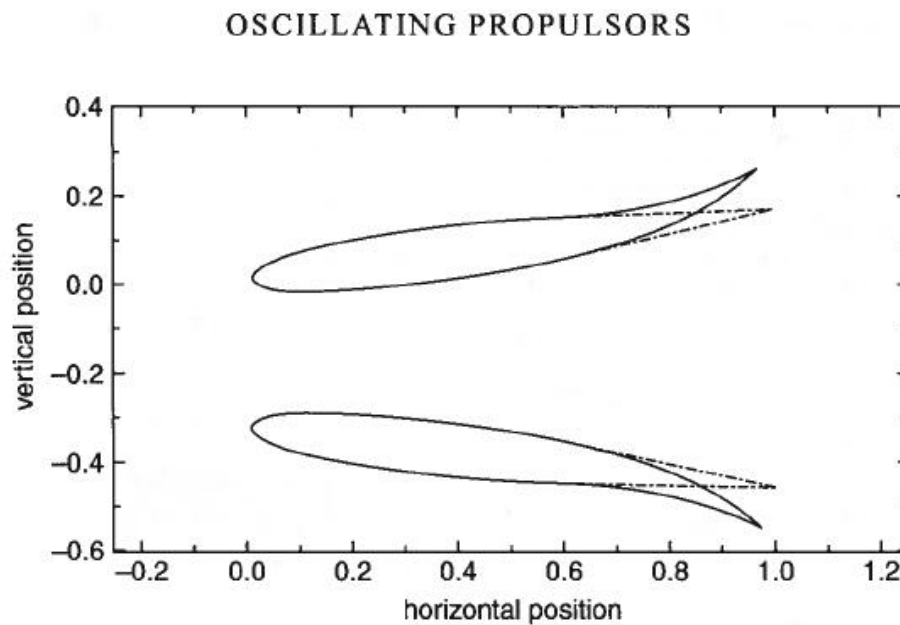


Figure 3-4: Flexible foil

Experimental research was done on a 200,000 deadweight tonnage tanker under auspices of Panel No. 200-13 of the Shipbuilding Research Association and reported in (Yamaguchi, 1992) and (Yamaguchi, et al., 1994). The vessel was equipped with a conventional screw propeller, a rigid foil propeller and a foil propeller with a flexible part from mid-chord to the trailing edge. The flexible part had an elastic Young's modulus of $3 \cdot 10^6 \text{ Nm}^{-2}$. We look to the results that compare the quasipropulsive efficiency (van Oossanen, et al., 1989) of the three propellers which is shown in Figure 3-5.

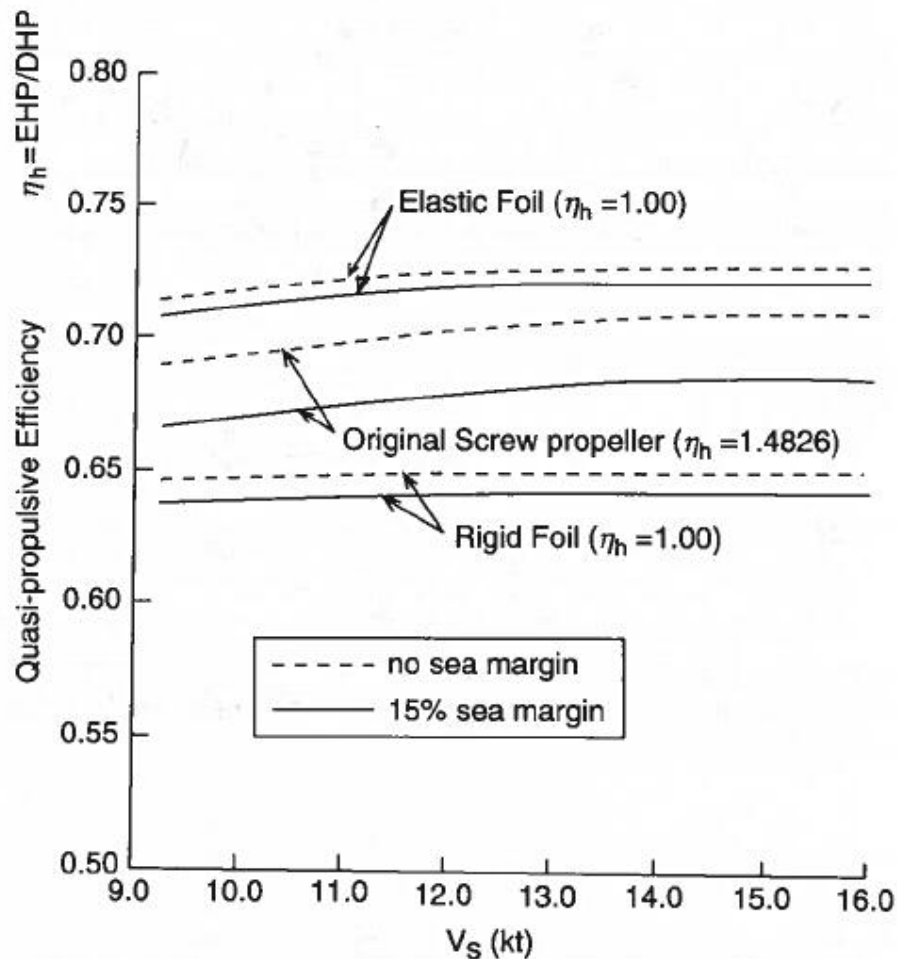


Figure 3-5: Quasipropulsive efficiency

We will apply the results including a 15 % sea margin as the idea of the foil propeller is to produce thrust from waves. It becomes clear that the flexible (elastic) foil has a significantly higher quasipropulsive efficiency than the rigid foil.

So far in this chapter our calculations have been made assuming a rigid foil. We want to investigate the potential of a flexible foil, so we will use the relative increase in quasipropulsive efficiencies in the figure to give a fair estimate of the thrust force obtained by a flexible foil. Mathematically we write

$$Thrust_{flexible} = \frac{\eta_{D_{flexible}}(U)}{\eta_{D_{rigid}}(U)} \cdot Thrust_{rigid}$$

Equation 3-40

Where

$\eta_{D_{flexible}}(U)$ = quasipropulsive efficiency of the flexible foil (dependent on U)

$\eta_{D_{rigid}}(U)$ = quasipropulsive efficiency of the rigid foil (dependent on U)

U = Vessel velocity

3.7 Reduced added resistance

One consequence of applying foil propellers onto a vessel is that they will produce a significant damping in heave, pitch and roll. This will always be welcomed as it increases the comfort for crew and passengers and reduces the probability of green water on deck. More importantly for our calculations is that it will affect the added resistance in waves. As the ship motion is reduced, we expect a reduction in the resistance. When we compare the propulsive effect of a vessel with foil propellers to one without foils, we may consider the reduced added resistance in waves as an increase in net thrust force from the foils. We express the net thrust as

$$T_{NET} = T_{FP} + (R_{waves, no\ foil} - R_{waves, with\ foil})$$

Equation 3-41

3.8 Fuel Savings

We include unsteady lift effects and the effect of a flexible foil and reach the following expression for the thrust force gained from an actively controlled flexible foil propeller

$$T_{Total} = \overline{T}_{FP} \cdot \frac{C_{Lu}}{C_{Lq}} \cdot \frac{\eta_{D_{flexible}}(U)}{\eta_{D_{rigid}}(U)}$$

Equation 3-42

Obviously, the purpose of the foil propeller will ultimately be to reduce the fuel costs for a vessel. Assuming that the fuel consumption is proportional to the delivered power from the engine, we seek to find the delivered power, P_B , for a vessel travelling with and without foils. First we find the required thrust force from the engine

$$T_{REQ, no\ foil} = R_{T, calm\ water} + R_{waves, no\ foil}$$

Equation 3-43

$$T_{REQ, with\ foil} = R_{T, calm\ water} + R_{waves, with\ foil} - T_{Total}$$

Equation 3-44

The delivered power from the engine is expressed by Equation 3-45

$$P_B = \frac{T_{REQ} \cdot U}{\eta_D(U) \cdot \eta_M}$$

Equation 3-45

Where

$\eta_D(U)$ = quasipropulsive efficiency of the screw propeller (dependent on U)
 $\eta_M = 0,97$ = assumed mechanical efficiency of the screw propeller

Finally we find the reduction in delivered power to be

$$\text{Reduction in fuel consumption} = RFC = \frac{1 - P_{B,with\ foil}}{P_{B,without\ foil}}$$

Equation 3-46

3.9 Fatigue

The forces on the foil will create bending moments and stress on the foil and the hull. A structural analysis will therefore have to be done to address this issue. The largest bending moment will occur at the root of the foil, closest to the hull. The maximum bending moment is given as

$$M = F_p \cdot s/2$$

Equation 3-47

Where F_p is found from Equation 3-19. The maximum bending stress at the root of the foil will be

$$\sigma = \frac{M}{I_{44}} \cdot t_f/2$$

Equation 3-48

Where I_{44} is the moment of inertia and t_f is the maximum foil thickness. The force on the foil will be periodically, so even if the foil does support a very large force once, we need to consider the possibility of fatigue. We will consider the S-N-curve (also known as Wöhler-diagram) to determine N_f . The S-N curve for 1045 steel and 2014-T6 aluminium is shown in Figure 2-1

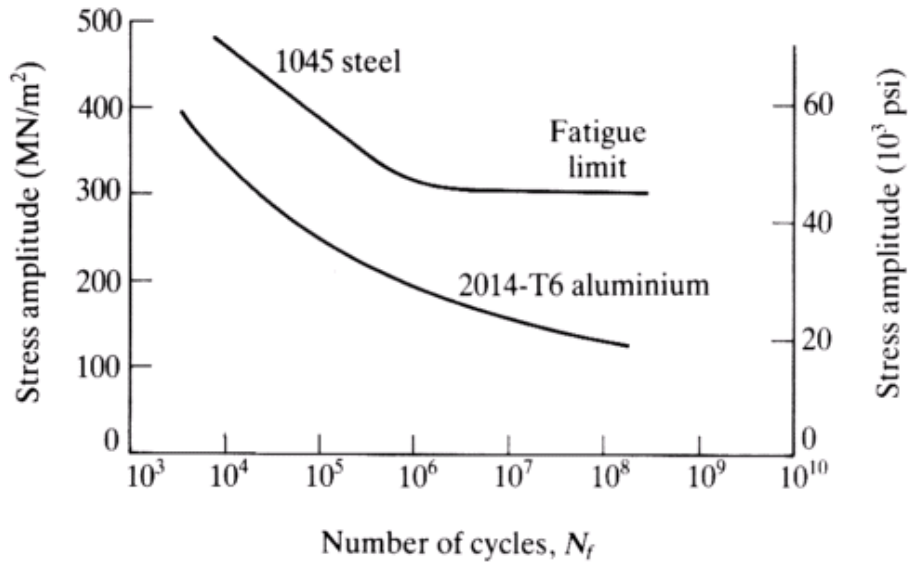


Figure 3-6: S-N curve for steel and aluminium

The foil itself will have a certain weight, but this will not affect the double stress amplitude, only shift the mean stress value away from zero. A non-zero mean stress value may cause more fatigue than if the mean value was zero, but in this thesis we will neglect this plausible effect, thus we will not consider the weight of the foil in our calculations.

3.9.1 Foil structure

We may design the structure of the foil to maximise strength and still try to keep the weight to a minimum. One way to increase the strength is to reinforce the foil hull with struts. A suggested cross-section of the foil structure reinforced with struts is shown in Figure 3-7

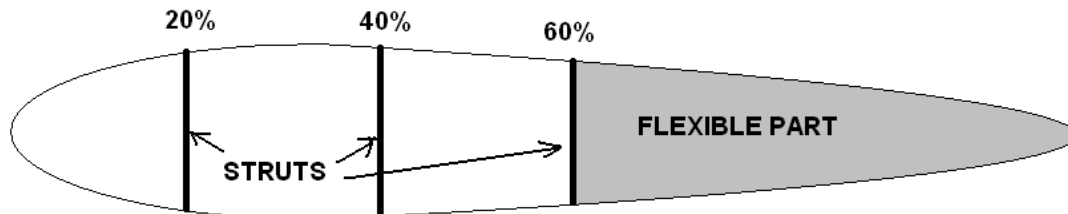


Figure 3-7: Foil cross-section

We have added the struts at 20, 40 and 60 % of the chord length. If the foil is flexible, this part of the structure will contribute very little to the structural strength of the foil. As the bending moment will be largest at the root of the foil we can imagine a design close to the one shown in Figure 3-8, where the gray area is flexible.

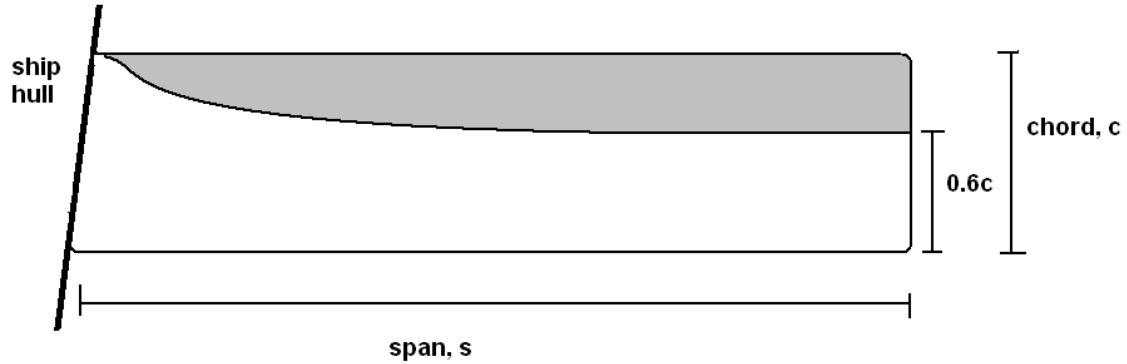


Figure 3-8: Flexible foil design

This design will decrease the gained thrust from the flexible part close to the hull, but we assume that the effect is small enough to be neglected.

3.9.2 Moment of inertia

The moment of inertia of the foil I_{44} has to be calculated to find the bending stress at the root of the foil as stated in Equation 3-48. First we take a closer look at the design of the foil. In this thesis we use a symmetric NACA0015 foil profile. The curvature is given by Equation 3-49 (Aerospaceweb.org) and shown in Figure 3-9.

$$\pm y(x) = \frac{t}{0,2} \cdot c \left(0,2969 \sqrt{\frac{x}{c}} - 0,1260 \left(\frac{x}{c}\right) - 0,3516 \left(\frac{x}{c}\right)^2 + 0,2843 \left(\frac{x}{c}\right)^3 - 0,1015 \left(\frac{x}{c}\right)^4 \right)$$

Equation 3-49

Where

$$t = 0,15 \cdot \text{chord length} = \text{maximum foil thickness} = 2 \cdot y_{max}$$

$$x = \text{position in chord direction}$$

$$y(x) = \text{half thickness of the foil at position } x$$

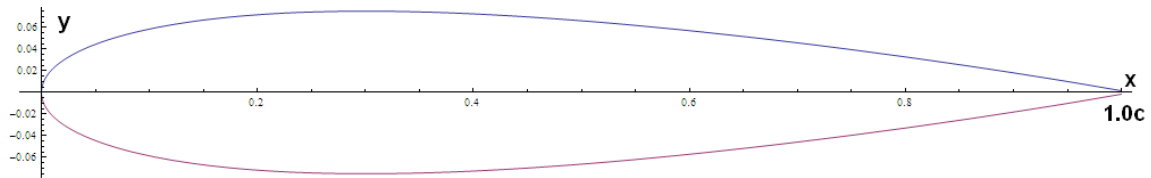


Figure 3-9: NACA0015 foil curvature

The moment of inertia from the outer wall of the foil is found by integrating along the chord length:

$$I_{wall} = 2 \int_0^c \frac{t_w^3}{12} dx + t_w \cdot \left(y(x) - \frac{t_w}{2} \right)^2 dx$$

Equation 3-50

Where

$t_w = \text{foil wall thickness}$

The moment of inertia of the struts are given by Equation 3-51

$$I_{strut} = \frac{t_{strut} \cdot (2 \cdot y(x_{strut}))^3}{12}$$

Equation 3-51

Where

$t_{strut} = \text{strut thickness}$
 $x_{strut} = x \text{ position of strut}$

The total moment of inertia for the foil will be

$$I_{44} = I_{wall} + \sum_{i=1}^n I_{strut, i}$$

Equation 3-52

Where n is the number of struts.

4 Vessel and foil dimensions

4.1 Key Criteria

We wish to compare the potential benefits of an active foil propeller applied on different ships.

We have some key criteria which we intuitively assume will enhance the probability of the vessel having a large potential benefit if equipped with foil propellers:

- **The vessel operates in relatively rough sea states** – this increases the relative vertical velocity of the foil and the water. As the lift force from a foil is proportional to the square of this velocity it is evident that this is an important criterion.
- **The motions of the ship are large** – the consequences are basically the same as the above-mentioned.

4.2 The vessels

The first vessel considered is the vessel used in the master thesis «Application of an active foil propeller on an offshore vessel» (Angvik, 2009). This is a 93 meter long offshore supply vessel. The second vessel is an 89.9m long coastal tanker and the third vessel a 71 meter long purse seiner.

The three vessels have the following main dimensions

| Vessel | | | Offshore supply vessel | Coastal Tanker | Purse Seiner |
|-------------------------------|----------|-------------------|---------------------------|-------------------|-----------------|
| Length over all | L_{OA} | [m] | 86.9 | 88.5 | 71 |
| Length on water line | L_{WL} | [m] | 93 | 89.9 | 69.2 |
| Length between perpendiculars | L_{PP} | [m] | 80.8 | 81.5 | 63 |
| Breadth | B | [m] | 21 | 16.5 | 14.4 |
| Depth | D | [m] | 8.2 | 12.5 | 8.2 |
| Draught | T | [m] | 6.8 | 6.2 | 5.3 |
| Water plane area | A_{WL} | [m ²] | 1585 | 1251 | 762 |
| Volume displacement | ∇ | [m ³] | 8722 | 6138 | 2720 |
| Distance from AP to CG | LCG | [m] | 36.9 | 37.591 | 29.918 |
| Distance from base line to CG | VCG | [m] | 6.6 | 6 | 5.3 |
| Radius of gyration in roll | r_{44} | [m] | 8 | 8 | 5 |
| Radius of gyration in pitch | r_{55} | [m] | 20.375 | 20.375 | 15.75 |
| Radius of gyration in yaw | r_{66} | [m] | 20.375 | 20.375 | 15.75 |

Table 2: Main characteristics

4.3 Vessel speed

We will consider several vessel velocities in our calculations in an effort to find out which forward velocities shows the best potential. We have chosen four velocities: 10, 12 15 and 18 knots. Although the considered vessels may not be designed to travel at all these velocities we will still perform the calculation to be able to compare the results from one vessel to another.

4.4 The foils

The foil profile used in our calculations is a NACA 0015 profile shown in Figure 3-9. This foil profile has no camber – meaning it is symmetrical – and a thickness to chord ratio of 15 %. We have chosen to make our calculation on 9 different foil configurations for each vessel. All of them will have a rectangular planform area.

4.4.1 Foil storage

If a ship is equipped with foils it will be necessary to be able to stow away the foils, primarily because the vessel will need to come alongside the quay, and the foils will be in the way. Secondly because when the vessel is travelling in calm seas the foil will produce more drag than thrust, so it will be better to stow the foils away.

Ideally the foils should be embedded into the hull in a manner that gives as small hydrodynamic drag as possible. There are several ways to do this and we would like to illustrate those that seem most beneficial. One can fold the foil into the hull by swinging them forward, backward or upwards, or one could retract them in a telescopic manner directly into the hull.

4.4.1.1 Backwards retractable

The first idea that comes to mind is to fold the fins backwards and into the hull in a purely horizontal motion. This concept already is in use for roll damping fins and is illustrated in Figure 4-1: Example of roll damping fin ..

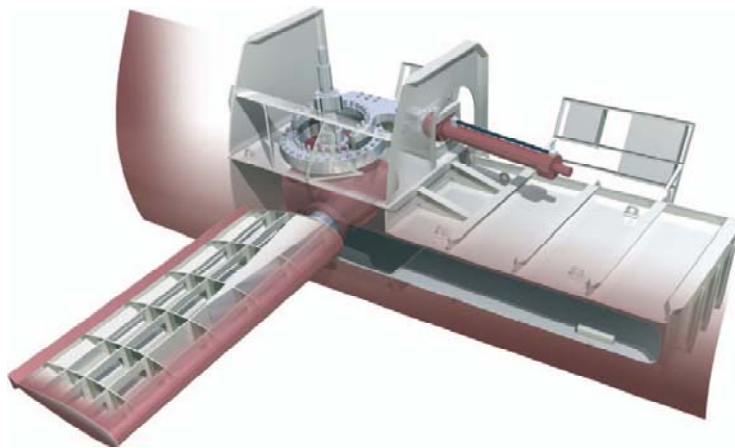


Figure 4-1: Example of roll damping fin (Rolls-RoyceMarine, 2007).

The benefit of this concept will primarily be that it is relatively easy to design and already has been proven possible. The drawback is that it takes up a large space that otherwise would be used for other purposes. Later we will prove that the foils will ideally be placed as close to bow as possible, but as shown in Figure 4-2: Space limitations the foils cannot be placed closer to the bow than where the breadth of the hull is two times the chord length.

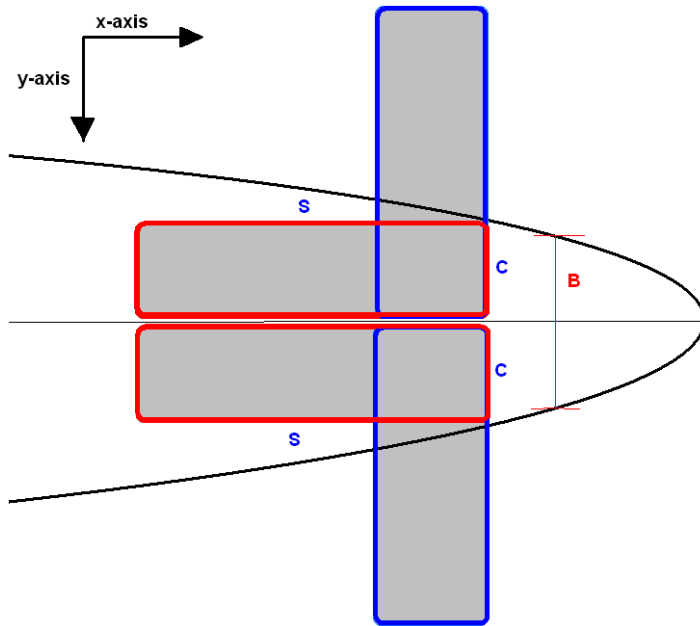


Figure 4-2: Space limitations

We also realize that there is a structural aspect to consider. This is illustrated better in the front view in Figure 4-3. We can see a structural weakness in the hull that would have to be addressed if this method of foil storage is adapted.

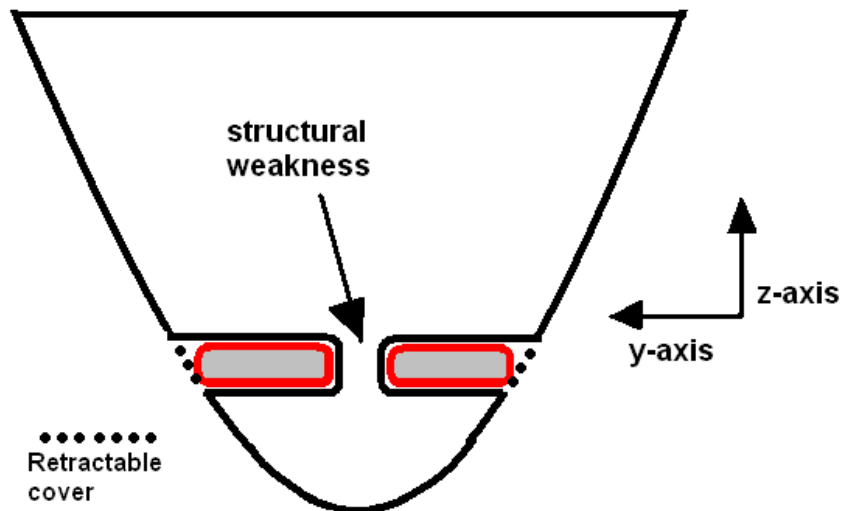


Figure 4-3: Front view

4.4.1.2 Vertical telescopic retraction

Another way to stow the fins is to retract them telescopically in the span-wise direction into the hull. This may not be done along the y-axis because the span of the foil is too large. As shown in Figure 4-4 the foils could be bent downwards and then retracted vertically and telescopically into the hull.

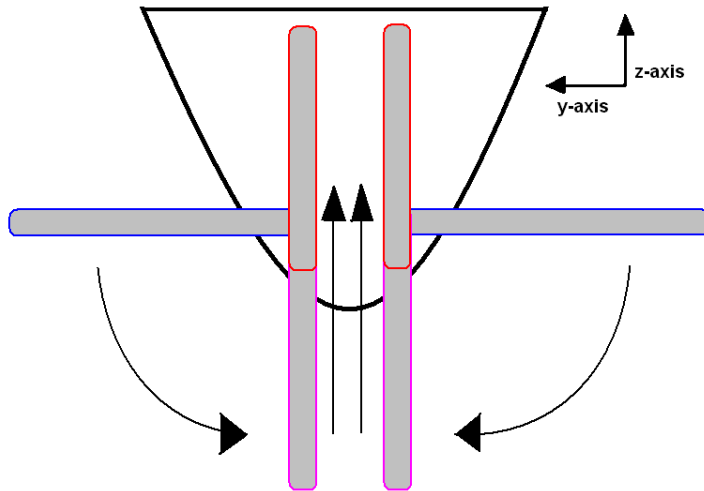


Figure 4-4: Vertical telescopic retraction

A benefit from this concept would be that the foils could easily be extracted from the ship by a crane if they were in need of maintenance. The foils could also be placed closer to the bow of the ship compared with the previous patent. A drawback would obviously be that it would be more difficult to construct.

4.4.1.3 Diagonal telescopic retraction

If one uses the imagination there are no limits for how the foil may be folded into the hull. A rather complicated manner would be to retract them not purely vertically, but diagonally forward, into the bulkhead compartment of the hull which normally is pretty inapplicable. This concept is illustrated in Figure 4-5.

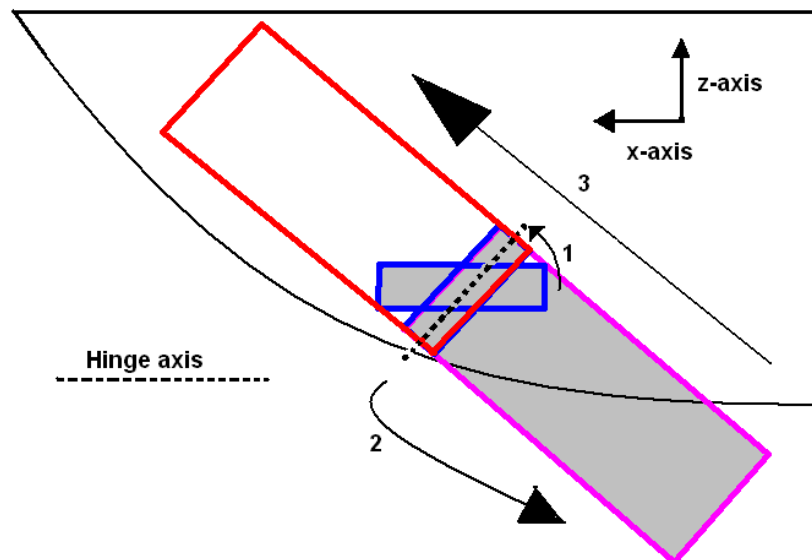


Figure 4-5: Diagonal telescopic retraction

First the foil is twisted around the y-axis so that the chord direction is parallel to the hinge-axis in the figure. As the foil already has a controllable pitch, this would not complicate the construction. Second

the foil is bent downwards, similarly to Figure 4-4, only around the hinge-axis from Figure 4-5. Thirdly the foil is retracted telescopically into the hull. This concept would be the most challenging to construct, but if space considerations are paramount this design would be of interest.

Common for all retractable foil concepts is that a retractable cover as shown in Figure 4-3 should be applied to protect the foil compartment and decrease hull resistance.

4.4.2 Foil positioning

When we mount the foil on the hull we look to where the largest potential for thrust generation lies, i.e. where we find largest relative vertical velocities. As we assume that the waves are undisturbed by the presence of the vessel, we look to the location where the vessel has largest vertical motions, that is obviously as close to the bow as possible.

In deciding the vertical position of the foils, there are limitations as well. Ideally the foils are located as close to the free water surface as possibly where the orbital velocities, i.e. the relative velocities are largest. But if the foil exits and re-enters the water there will be large slamming forces on the foil in certain wave conditions, this may lead to large structural damage and should be avoided. On the other hand, if the foils are located too close to the keel space limitations come into consideration again. This depends on the chosen foil storage design, but as the foil is placed deeper the breadth will decrease, limiting the space available for the retraction machinery.

In this thesis the foils are placed at 80 % of the draught amidships below the design water surface and as close to the bow as possible according to the limitations of the backwards retractable foil design shown in Figure 4-2. The foils have varying cord length, so the horizontal position limit differs from one configuration to another, but we assume that if a ship is equipped with foils, some modification of the hull shape will be done and the breadth can be increased at the position of the foils if required. Thus, we have placed the inner tip at the same location for all the foil configurations for each ship.

The foil dimensions for all three ships are chosen according to Table 3

| | S = 3 % of A_{WL} | S = 4 % of A_{WL} | S = 5 % of A_{WL} |
|-----------|---------------------|---------------------|---------------------|
| s/c = 3.0 | Foil #1 | Foil #2 | Foil #3 |
| s/c = 4.0 | Foil #4 | Foil #5 | Foil #6 |
| s/c = 5.0 | Foil #7 | Foil #8 | Foil #9 |

Table 3: Definition of foil configurations

When applying these dimensions to our vessels we get the following configurations

4.4.3 Offshore Supply Vessel (Angvik, 2009)

| | | | Foil #1 | Foil #2 | Foil #3 |
|-----------|--|-------|---------|---------|---------|
| Inner tip | Longitudinal position Relative to AP | x [m] | 70 | 70 | 70 |
| | Transverse position Relative to centre line | y [m] | 3.194 | 3.194 | 3.194 |
| | Vertical position Above base line | z [m] | 1.36 | 1.36 | 1.36 |
| Outer tip | Longitudinal position | x [m] | 70 | 70 | 70 |

| Relative to AP | | | | |
|-------------------------|-------|-------|-------|-------|
| Transverse position | y [m] | | | |
| Relative to centre line | | 15.14 | 16.99 | 18.62 |
| Vertical position | z [m] | | | |
| Above base line | | 1.36 | 1.36 | 1.36 |
| Chord length | c [m] | 3.983 | 4.599 | 5.141 |
| Span | s [m] | 11.95 | 13.80 | 15.42 |

Table 4: Foil input Offshore supply vessel – $s/c = 3$.

| | | | Foil #4 | Foil #5 | Foil #6 |
|--------------|-------------------------|-------|---------|---------|---------|
| Inner tip | Longitudinal position | x [m] | | | |
| | Relative to AP | | 70 | 70 | 70 |
| | Transverse position | y [m] | | | |
| | Relative to centre line | | 3.194 | 3.194 | 3.194 |
| Outer tip | Vertical position | z [m] | | | |
| | Above base line | | 1.36 | 1.36 | 1.36 |
| | Longitudinal position | x [m] | | | |
| | Relative to AP | | 70 | 70 | 70 |
| Outer tip | Transverse position | y [m] | | | |
| | Relative to centre line | | 16.99 | 19.12 | 21.00 |
| | Vertical position | z [m] | | | |
| | Above base line | | 1.36 | 1.36 | 1.36 |
| Chord length | c [m] | 3.449 | 3.983 | 4.453 | |
| Span | s [m] | 13.80 | 15.93 | 17.81 | |

Table 5: Foil input Offshore supply vessel – $s/c = 4$.

| | | | Foil #7 | Foil #8 | Foil #9 |
|--------------|-------------------------|-------|---------|---------|---------|
| Inner tip | Longitudinal position | x [m] | | | |
| | Relative to AP | | 70 | 70 | 70 |
| | Transverse position | y [m] | | | |
| | Relative to centre line | | 3.194 | 3.194 | 3.194 |
| Outer tip | Vertical position | z [m] | | | |
| | Above base line | | 1.36 | 1.36 | 1.36 |
| | Longitudinal position | x [m] | | | |
| | Relative to AP | | 70 | 70 | 70 |
| Outer tip | Transverse position | y [m] | | | |
| | Relative to centre line | | 18.62 | 21.00 | 23.11 |
| | Vertical position | z [m] | | | |
| | Above base line | | 1.36 | 1.36 | 1.36 |
| Chord length | c [m] | 3.085 | 3.562 | 3.983 | |
| Span | s [m] | 15.42 | 17.81 | 19.91 | |

Table 6: Foil input Offshore supply vessel – $s/c = 5$.

4.4.4 Coastal Tanker

| | | | Foil #1 | Foil #2 | Foil #3 |
|-----------|-------------------------|-------|---------|---------|---------|
| Inner tip | Longitudinal position | x [m] | | | |
| | Relative to AP | | 66.5 | 66.5 | 66.5 |
| | Transverse position | y [m] | | | |
| Outer tip | Relative to centre line | | 4.007 | 4.007 | 4.007 |
| | Vertical position | z [m] | | | |
| | | | 1.24 | 1.24 | 1.24 |

| Above base line | | | | |
|-----------------|-------------------------|-------|-------|-------|
| Outer tip | Longitudinal position | x [m] | | |
| | Relative to AP | | 66.5 | 66.5 |
| | Transverse position | y [m] | | |
| | Relative to centre line | | 14.62 | 16.26 |
| | Vertical position | z [m] | | |
| | Above base line | | 1.24 | 1.24 |
| | Chord length | c [m] | 3.538 | 4.086 |
| | Span | s [m] | 10.61 | 12.26 |
| | | | 13.70 | |

Table 7: Foil input Coastal tanker – s/c = 3.

| | | | Foil #4 | Foil #5 | Foil #6 |
|-----------|-------------------------|-------|---------|---------|---------|
| Inner tip | Longitudinal position | x [m] | | | |
| | Relative to AP | | 66.5 | 66.5 | 66.5 |
| | Transverse position | y [m] | | | |
| | Relative to centre line | | 4.007 | 4.007 | 4.007 |
| | Vertical position | z [m] | | | |
| | Above base line | | 1.24 | 1.24 | 1.24 |
| Outer tip | Longitudinal position | x [m] | | | |
| | Relative to AP | | 66.5 | 66.5 | 66.5 |
| | Transverse position | y [m] | | | |
| | Relative to centre line | | 16.26 | 18.16 | 19.83 |
| | Vertical position | z [m] | | | |
| | Above base line | | 1.24 | 1.24 | 1.24 |
| | Chord length | c [m] | 3.064 | 3.538 | 3.956 |
| | Span | s [m] | 12.26 | 14.15 | 15.82 |

Table 8: Foil input Coastal tanker – s/c = 4.

| | | | Foil #7 | Foil #8 | Foil #9 |
|-----------|-------------------------|-------|---------|---------|---------|
| Inner tip | Longitudinal position | x [m] | | | |
| | Relative to AP | | 66.5 | 66.5 | 66.5 |
| | Transverse position | y [m] | | | |
| | Relative to centre line | | 4.007 | 4.007 | 4.007 |
| | Vertical position | z [m] | | | |
| | Above base line | | 1.24 | 1.24 | 1.24 |
| Outer tip | Longitudinal position | x [m] | | | |
| | Relative to AP | | 66.5 | 66.5 | 66.5 |
| | Transverse position | y [m] | | | |
| | Relative to centre line | | 17.71 | 19.83 | 21.70 |
| | Vertical position | z [m] | | | |
| | Above base line | | 1.24 | 1.24 | 1.24 |
| | Chord length | c [m] | 2.741 | 3.165 | 3.538 |
| | Span | s [m] | 13.70 | 15.82 | 17.69 |

Table 9: Foil input Coastal tanker – s/c = 5.

4.4.5 Purse Seiner

The purse seiner has a certain design trim angle. Because of this we have lifted the vertical position of the foils with a distance corresponding to the trim at the longitudinal position of the foils.

| | Foil #1 | Foil #2 | Foil #3 |
|--|---------|---------|---------|
|--|---------|---------|---------|

| | | | | | |
|------------------|---|--------------|-------|-------|--------|
| Inner tip | Longitudinal position Relative to AP | x [m] | 50.4 | 50.4 | 50.4 |
| | Transverse position Relative to centre line | y [m] | 2.5 | 2.5 | 2.5 |
| | Vertical position Above base line | z [m] | 1.56 | 1.56 | 1.56 |
| Outer tip | Longitudinal position Relative to AP | x [m] | 50.4 | 50.4 | 50.4 |
| | Transverse position Relative to centre line | y [m] | 10.78 | 12.06 | 13.19 |
| | Vertical position Above base line | z [m] | 1.56 | 1.56 | 1.56 |
| | Chord length | c [m] | 2.761 | 3.188 | 3.564 |
| | Span | s [m] | 8.282 | 9.563 | 10.692 |

Table 10: Foil input Purse seiner – $s/c = 3$.

| | | | Foil #4 | Foil #5 | Foil #6 |
|------------------|---|--------------|----------------|----------------|----------------|
| Inner tip | Longitudinal position Relative to AP | x [m] | 50.4 | 50.4 | 50.4 |
| | Transverse position Relative to centre line | y [m] | 2.5 | 2.5 | 2.5 |
| | Vertical position Above base line | z [m] | 1.56 | 1.56 | 1.56 |
| Outer tip | Longitudinal position Relative to AP | x [m] | 50.4 | 50.4 | 50.4 |
| | Transverse position Relative to centre line | y [m] | 12.06 | 13.54 | 14.85 |
| | Vertical position Above base line | z [m] | 1.56 | 1.56 | 1.56 |
| | Chord length | c [m] | 2.391 | 2.761 | 3.087 |
| | Span | s [m] | 9.563 | 11.043 | 12.346 |

Table 11: Foil input Purse seiner – $s/c = 4$.

| | | | Foil #7 | Foil #8 | Foil #9 |
|------------------|---|--------------|----------------|----------------|----------------|
| Inner tip | Longitudinal position Relative to AP | x [m] | 50.4 | 50.4 | 50.4 |
| | Transverse position Relative to centre line | y [m] | 2.5 | 2.5 | 2.5 |
| | Vertical position Above base line | z [m] | 1.56 | 1.56 | 1.56 |
| Outer tip | Longitudinal position Relative to AP | x [m] | 50.4 | 50.4 | 50.4 |
| | Transverse position Relative to centre line | y [m] | 13.19 | 14.85 | 16.30 |
| | Vertical position Above base line | z [m] | 1.56 | 1.56 | 1.56 |
| | Chord length | c [m] | 2.138 | 2.469 | 2.761 |
| | Span | s [m] | 10.692 | 12.346 | 13.803 |

Table 12: Foil input Purse seiner – $s/c = 5$.

5 Wave conditions

5.1 Regular waves

To determine the wave conditions the vessels will be travelling in we look to the Scatter diagram in Appendix A: Scatter diagram for North Sea and northern Atlantic. This is the combined scatter diagram for the North Sea and northern Atlantic. We examine the most frequent zero-crossing periods which are from 4,5 to 9,5 seconds. This covers more than 97 % of the time. Outside this range we assume that the foils will be stowed away. The wave characteristics are shown in Table 13: Wave conditions.

| Wave condition | Zero-crossing period (T0) | Av. Significant Wave amplitude (zetaa) | Wave frequency(W0) | Wave length (lambda) | Time in % of the total time |
|---|---------------------------|--|--------------------|----------------------|-----------------------------|
| wc1 | 4,5 | 0,5888 | 1,3963 | 31,6165 | 8,9 % |
| wc2 | 5,5 | 0,8711 | 1,1424 | 47,23 | 21,7 % |
| wc3 | 6,5 | 1,1741 | 0,9666 | 65,97 | 27,3 % |
| wc4 | 7,5 | 1,4707 | 0,8378 | 87,82 | 21,6 % |
| wc5 | 8,5 | 1,7642 | 0,7392 | 112,80 | 12,0 % |
| wc6 | 9,5 | 2,0913 | 0,6614 | 140,91 | 5,1 % |
| Total percentage of time covered | | | | | <u>97 %</u> |

Table 13: Wave conditions

We choose to perform the calculations for regular waves with wave periods corresponding to the zero-crossing periods from Table 13: Wave conditions and wave height corresponding to the average significant wave height for the zero-crossing period in question.

5.2 Irregular waves

Our calculation model is able to take regular waves into account, but in the open seas there are no purely regular waves, one always encounter a wave spectrum. From the scatter diagram in Appendix A: Scatter diagram for North Sea and northern Atlantic we find the most probable significant wave height and zero-crossing period. They are

$$H_s = 2,51m$$

$$T_p = 6,77s$$

We will use the JONSWAP spectrum (Joint North Sea Wave Project) were the peakedness parameter γ will be defined by

$$\gamma = \begin{cases} 5 & \text{for } T_p / \sqrt{H_s} \leq 3,6 \\ e^{5,75 - 1,15 T_p / \sqrt{H_s}} & \text{for } 3,6 \leq T_p / \sqrt{H_s} \leq 5 \\ 1 & \text{for } 5 \leq T_p / \sqrt{H_s} \end{cases}$$

Equation 5-1

With our values we will get a peakedness parameter, $\gamma = 2,307$. Our wave spectrum is shown in Figure 5-1.

Wave spectrum JONSWAP
Hs = 2.51 m Tp = 6.8 sec

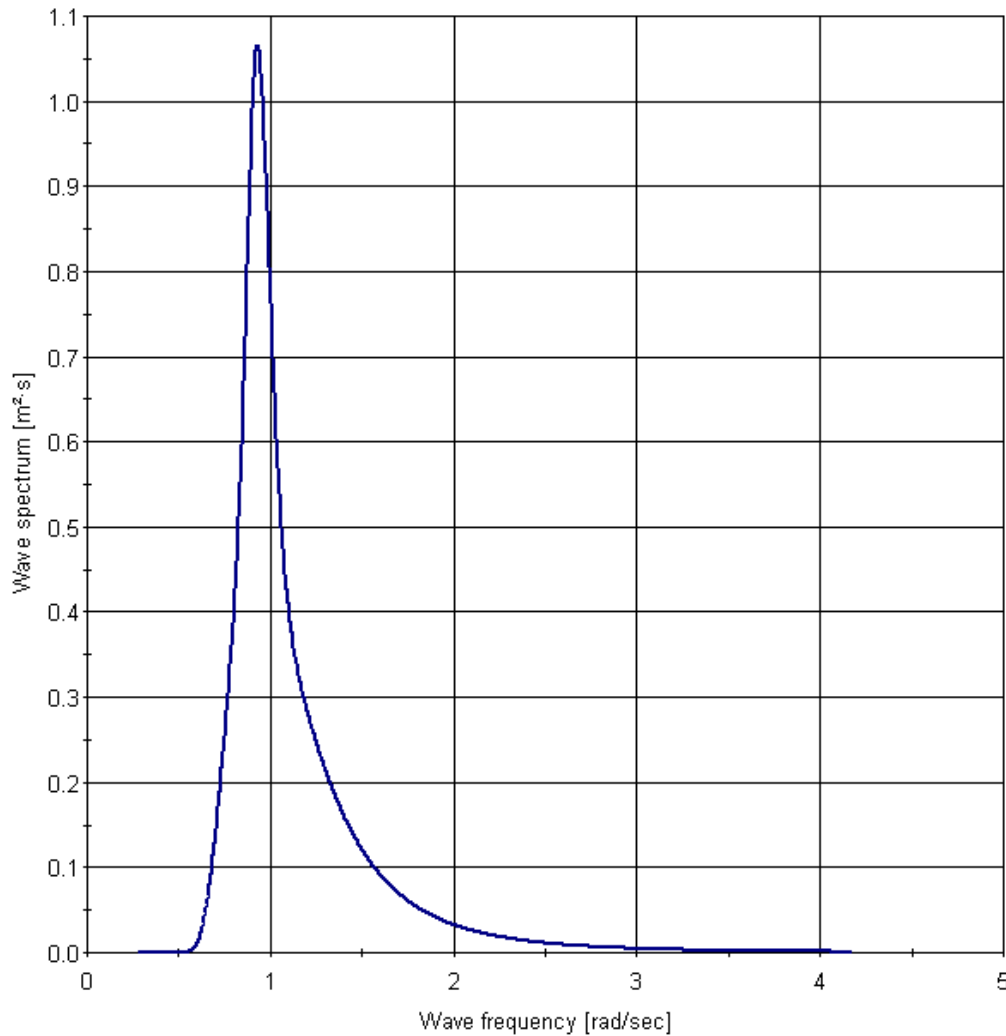


Figure 5-1: JONSWAP wave spectrum

To find the thrust we need to find the relative vertical velocities $w_{Rel}(t)$, i.e. we need a relative vertical velocities spectrum from our wave spectrum. This is found from Equation 5-2:

$$S_{Rel.vel.}(\omega) = S(\omega) \cdot |H_{Rel.vel.}(\omega)|^2$$

Equation 5-2

Where

$S(\omega)$ = wave spectrum

$H_{Rel.vel.}(\omega)$ = transfer function for relative velocities

The principle of how a transfer function and a wave spectrum give the response spectrum is shown in Figure 5-2.

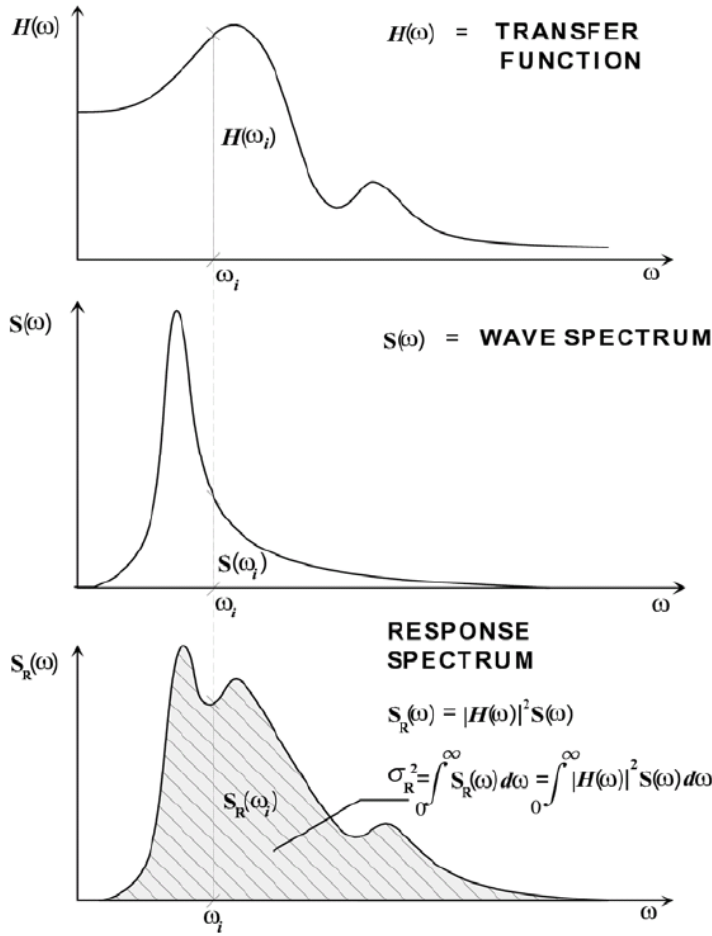


Figure 5-2: Response spectrum (Fathi, 2005)

Now that we have the relative velocity spectrum we go back to Equation 3-34.

$$T_{FP}(t) = \frac{\pi \rho c s U^2}{1 + \frac{2}{\Lambda}} \left[\frac{w_{Rel}(t)}{U} - \eta_{5,s}(t) - \eta_{5,f}(t) \right] \frac{w_{Rel}(t)}{U} - \frac{2\pi \Lambda \rho c s U^2}{(\Lambda + 2)^2} \left[\frac{w_{Rel}(t)}{U} - \eta_{5,s}(t) - \eta_{5,f}(t) \right]^2$$

Equation 5-3

We assume that we have a perfect motion control system to control the foil angle $\eta_{5,f}(t)$. This means that the term $\left[\frac{w_{Rel}(t)}{U} - \eta_{5,s}(t) - \eta_{5,f}(t) \right]$ is controllable and we replace it to simplify the equation. We also introduce the constants a and b.

$$T_{FP}(t) = a \cdot \alpha_{attack} \cdot \frac{w_{Rel}(t)}{U} - b \cdot \alpha_{attack}^2$$

Equation 5-4

Where

$$\alpha_{attack} = \text{the angel of attack, which may not exceed } \frac{\pi}{12} = 15 \text{ deg}$$

$$a = \frac{\pi \rho c s U^2}{1 + \frac{2}{\Lambda}}$$

$$b = \frac{2\pi \Lambda \rho c s U^2}{(\Lambda + 2)^2}$$

$U = \text{vessel velocity}$

To find the optimal angle of attack which maximises the thrust we derivate Equation 5-5, set it equal to zero and solve the equation for α_{attack} :

$$\frac{\delta T_{FP}(t)}{\delta \alpha_{attack}} = a \cdot \frac{w_{Rel}(t)}{U} - 2 b \cdot \alpha_{attack} = 0$$

Equation 5-5

$$\alpha_{attack} = \begin{cases} \frac{\pi}{12} & \text{for } \frac{a \cdot w_{Rel}(t)}{2U \cdot b} < \frac{\pi}{12} \\ \frac{a \cdot w_{Rel}(t)}{2U \cdot b} & \text{for } \frac{\pi}{12} \leq \frac{a \cdot w_{Rel}(t)}{2U \cdot b} \leq \frac{\pi}{12} \\ \frac{\pi}{12} & \text{for } \frac{\pi}{12} < \frac{a \cdot w_{Rel}(t)}{2U \cdot b} \end{cases}$$

Equation 5-6

To find the thrust force we will need to create irregular waves numerically and calculate the average thrust force over a very long period of time to get an accurate result. This is a very time consuming calculation, so this will only be done for the offshore supply vessel, considering four foils (number 3, 6, 7 and 9) at forward velocities of 10 and 15 knots. In addition we will consider foil 9 at 12 and 18 knots.

6 Computer programs

6.1 ShipX and VERES

ShipX is a computer program developed by MARINTEK. Once a ship hull has been imported to the program, many important characteristics can be found by using a range of pre-programmed applications.

For our calculation we need the relative vertical velocities between the water and the foil at the centre of gravity of the foil and the response amplitude operators. After finding these we can calculate the thrust force from an active foil. Secondly, we need to find the added resistance in waves for our vessels, with and without foils. Thirdly, we need to find the calm water resistance as well as the quasipropulsive efficiency of the screw propeller for the chosen speeds and corresponding required thrusts as defined in Equation 3-43 and Equation 3-44. To find all this, a plug-in to ShipX called VERES (Vessel Responses) is needed.

6.1.1 Vessel Description

To make calculations on a hull in ShipX using VERES we need to input some basic data. The dimensions of the hull are already known from the hull geometry file, but we still need to set the position of the centre of gravity, the mass displacement and the radii of gyration.

Vessel Description

Main Dimensions :

Lpp 81.500 m
Breadth 16.500 m
Draught 6.000 m
Sinkage 0.000 m
Trim aft 0.000 deg

Metacentric Heights :

Calculate GM

Vessel Mass Distribution :

LCG rel. AP 37.591 m
VCG 6.000 m
Mass 6322.480 tonnes

Radii of Gyration :

R 44 8.000 m
R 55 20.375 m
R 66 20.375 m
R 64 0.000 m

Coefficients for datacheck :

Block Coefficient, Cb : 0.7607
Waterplane Area Coeff., Cw : 0.855
Mid Section Coefficient, Cm : 0.9937

Please note the following definitions: Longitudinal center of gravity, LCG, is given relative to AP (positive forwards). Vertical center of gravity, VCG, is given relative to the baseline.

VERES

OK
Cancel
Help...

Figure 6-1: Vessel description

6.1.2 Condition information

In the condition information box we decide what kind of waves the vessel is exposed to. We may choose a range of wave periods and headings and we also set the desired vessel velocities.

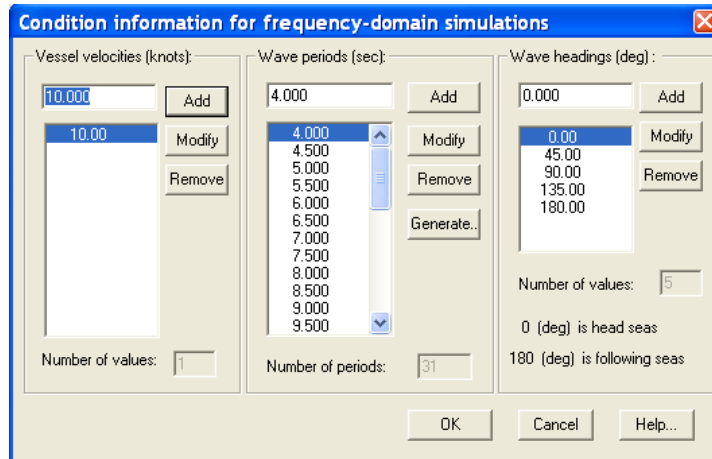


Figure 6-2: Condition information

When considering irregular waves we need a transfer function. VERES calculates this from the wave periods selected in this box. It is paramount that the range of periods covers the entire wave spectrum for the transfer function to be correct.

6.1.3 Foil dimensions

We may add foils to the hull at specified coordinates with the desired dimensions.

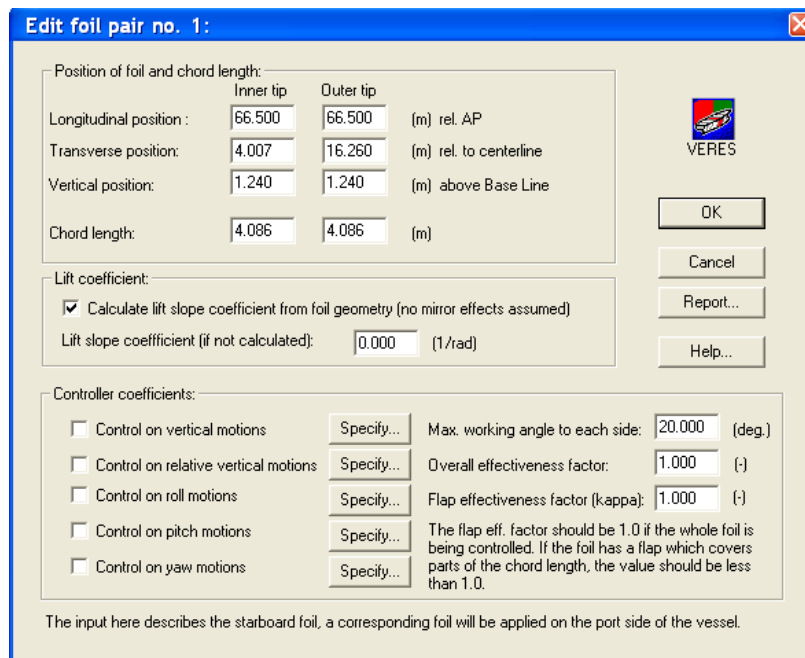


Figure 6-3: Foil dimensions

6.1.4 Method of calculation

Before starting the calculation we need to choose which method of calculation to use, we select ordinary strip theory. To calculate the added resistance we initially selected the default Gerritsma & Beukelman method. This method is efficient and reduces computational time compared to the other option: direct pressure integration. Unfortunately this method may give some unreliable results in

following seas. Therefore the calculation of the added resistance calculations for stern quartering and following seas were redone with direct pressure integration.

6.1.4.1 Post processing

After the full calculation has been done in VERES, we create a “Vessel Response Postprocessor Project”. Here we find the motions and relative velocities at any location relative to the centre of gravity of the vessel. Thus we find the relative velocities at the rotation centre of the foil. We also find the relative velocities spectrum by selecting “short term stat.”, input our selected JONSWAP spectrum and plot the results as a function of wave frequency. This is shown in the red ring in Figure 6-4: Finding the relative velocity spectrum. The relative velocity response spectrum is used to find the thrust force for irregular seas by writing the spectrum to a text file and using MATLAB do the further calculations.

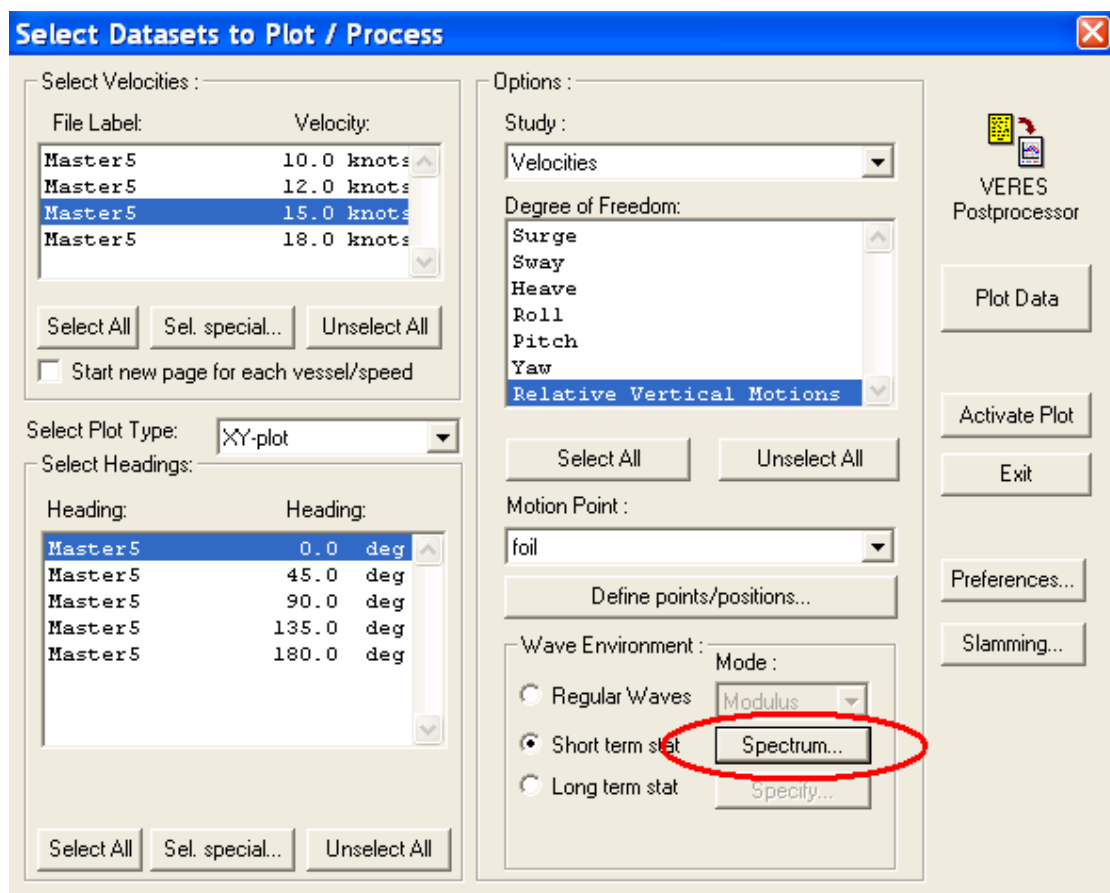


Figure 6-4: Finding the relative velocity spectrum

Further we can create an “Added Resistance Postprocessor Project” and get the added resistance for the ship in the chosen conditions and compare them to results made with a hull without foils.

6.1.5 Ship Speed and Powering

Ship speed and powering is another plug-in to Ship X and is used to make calculations on the calm water performance of the hull. We use the HOLTROP method which is based on a regression analysis from approximately 300 ships with varying form and main dimensions (Holtrop, et al., 1982). This

method may not give accurate results for modern designs, but we assume it to be adequate for our purposes. We also use the “optimum propeller wizard” to find a suitable screw propeller that is optimized for the vessel without foils and travelling at 15 knots.

From Equation 3-43 and Equation 3-44 we find the required thrust force needed from the screw propeller to maintain the forward velocity used in the calculation of interest. To find the required engine power we select “specify ship resistance R (t) curve”. Then we import a resistance table (the resistance varies with the speed) from EXCEL which gives the required thrust force for the vessel with foils. This is shown in Figure 6-5: Imported ship resistance curve . We then do another calm water calculation with the same screw propeller as above and find the quasipropulsive efficiency. The procedure is repeated for the vessel without foils. We then continue the calculation according to Equation 3-45.

The quasipropulsive efficiency does not vary very from one resistance table to another and due to the amount of calculations we perform and time-consuming work of importing the data and doing the calculations we make a simplification: We find an average resistance table for all the foils and import this instead of the individual tables, thus reducing the number of calculations with a factor 9.

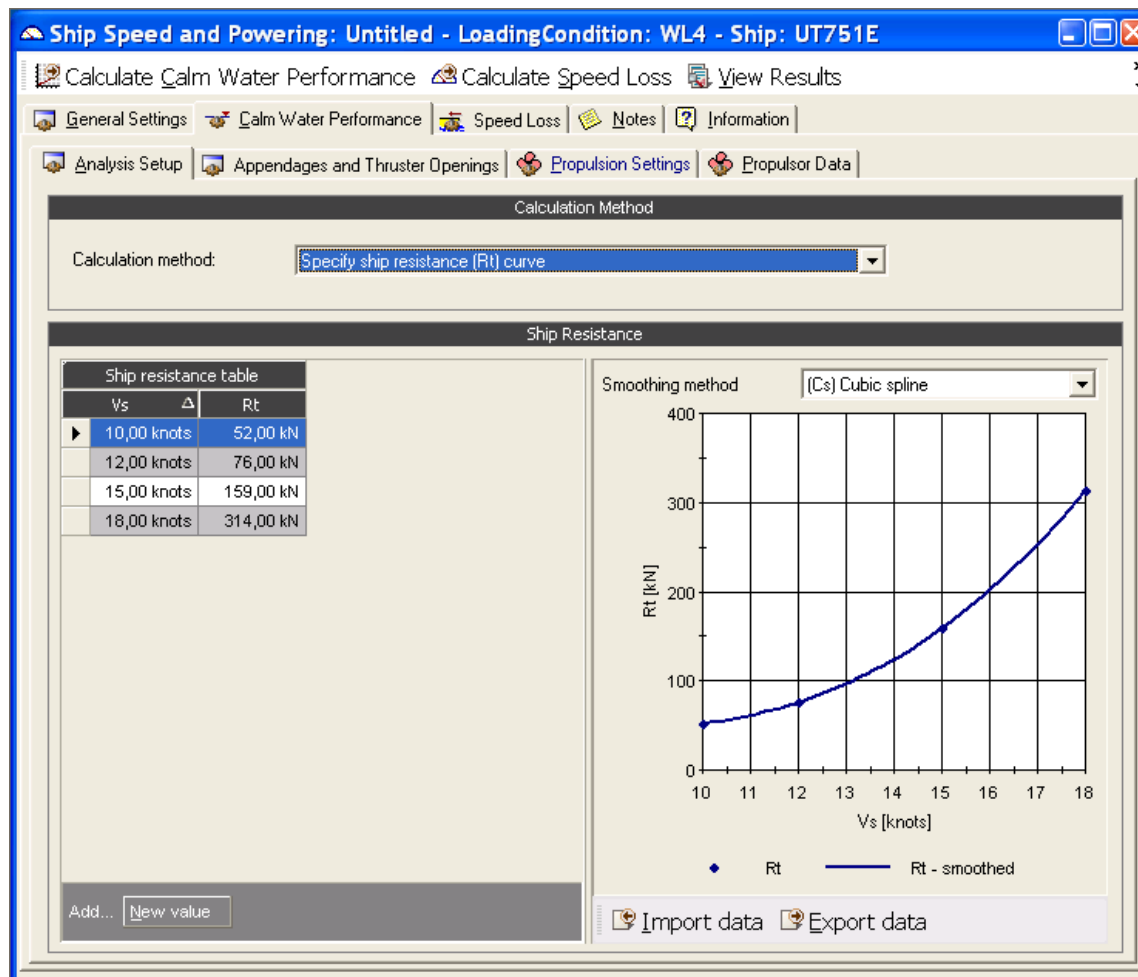


Figure 6-5: Imported ship resistance curve

6.1.6 Assumptions

In VERES potential theory is used, i.e. the fluid is homogeneous, incompressible, irrotational and non-viscid and the velocity potential exists.

Slender body theories are applied, and the hydrodynamic coefficients are assumed to be correctly calculated using strip theory. Interaction between the strips is not taken into account, and 3D-effects are neglected.

The response calculations are based on linear theory, meaning the wave-induced motion amplitudes are linearly proportional to the wave amplitude.

ShipX does not consider slamming and green water on deck and no transient or hydro-elastic effects are accounted for.

6.1.7 Computational difficulties

As we have mentioned ShipX normally uses the method developed by Gerritsma and Beukelman to calculate the added resistance in waves for the vessels. This method was originally used for head seas, but has been expanded to other wave headings when imported to ShipX. In following seas this method has some weaknesses and may produce very wrong results. This was initially the case in this thesis and the results in following and stern-quartering seas had to be redone using pressure integration. This error proved time consuming as most of the saved data was lost due to a problem with the ShipX-license at the time resulting in ShipX needing to be reinstalled. Therefore the new and modified calculations were done only for vessels without foils and vessels with the mean foil size (foil 5). The results from the latter calculation were used for all foil configurations for the mentioned wave headings. We consider the error in the results to be too small to affect the results significantly as the added resistance in waves does not differ much from foil to foil, the point of interest is the reduced added resistance in waves compared to a vessel without foil. For head, bow quartering and beam seas results based on the method by Gerritsma and Beukelman still applies.

6.2 MATLAB

After doing the necessary calculations in ShipX, we use a MATLAB script to do the calculations described in chapter 3.2 until and including Equation 3-38. We also do the fatigue calculations from chapter 3.9. Another script is made to perform the thrust calculation for irregular waves described chapter 5.2.

6.3 Microsoft EXCEL

EXCEL is used for all other calculations and to organise the results and produce the tables and figures shown in the results.

6.4 Program organisation

To make it more clear how the programs have been used and combined to give us the results we make a schematic diagram (Figure 6-6: Schematic diagram of the use of computer programs) illustrating the procedure.

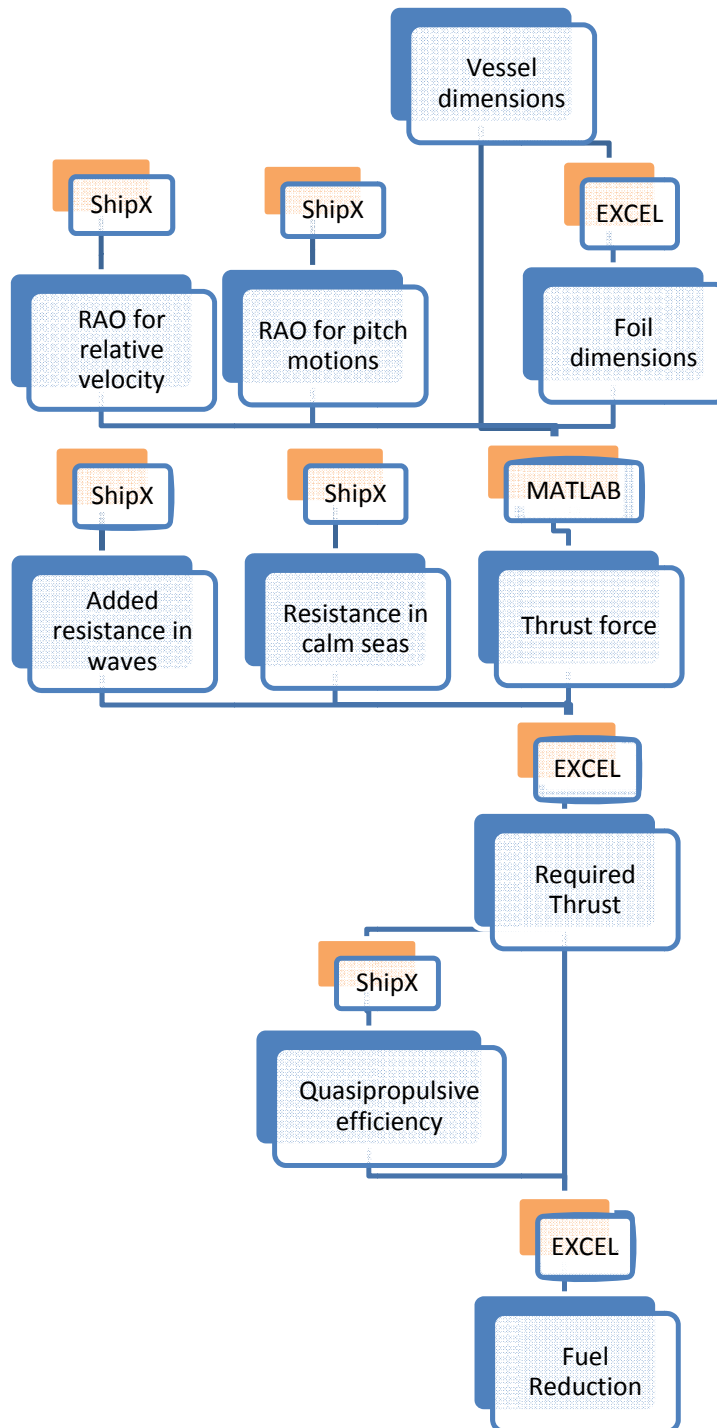


Figure 6-6: Schematic diagram of the use of computer programs

7 Results for Regular waves

The results for regular waves are a substantial amount of information. We consider three vessels, each exposed to six wave periods with five wave headings each travelling at four different velocities. All these results are then produced for nine different foil configurations. This gives a total of $5 \cdot 6 \cdot 4 \cdot 9 = 1080$ thrust forces and corresponding fuel savings for each vessel. It is a challenge to reduce the amount data to a more comprehensible size without losing vital information. But in an effort to do this we combine the results for the six wave periods into a weighted average where we multiply the result for each wave period with percentage of the total time the wave period is expected according to Table 14: Weighted wave conditions. This will also give us an idea of the expected results from a calculation for irregular waves, even though the method is based on reasoning more than scientific facts.

| Wave condition number | Wave period | Wave amplitude | Time in % of the total time |
|-----------------------|-------------|----------------|-----------------------------|
| Wave condition 1 | 4,5 | 0,5888 | 8,9 % |
| Wave condition 2 | 5,5 | 0,8711 | 21,7 % |
| Wave condition 3 | 6,5 | 1,1741 | 27,3 % |
| Wave condition 4 | 7,5 | 1,4707 | 21,6 % |
| Wave condition 5 | 8,5 | 1,7642 | 12,0 % |
| Wave condition 6 | 9,5 | 2,0913 | 5,1 % |

Table 14: Weighted wave conditions

These values correspond to the values from Table 13.

7.1 Offshore Supply vessel

7.1.1 Thrust force

When presenting the data the purpose will be to find larger trends in the material and be able to draw conclusions from it. Therefore we will show some graphics which demonstrates the general tendencies of the result material.

7.1.1.1 Variation with wave conditions and velocities

First we look at just foil 9 in head seas. In Figure 7-1 we can see how the thrust force (including the including unsteady lift and flexible foil effects) varies with speed and wave condition.

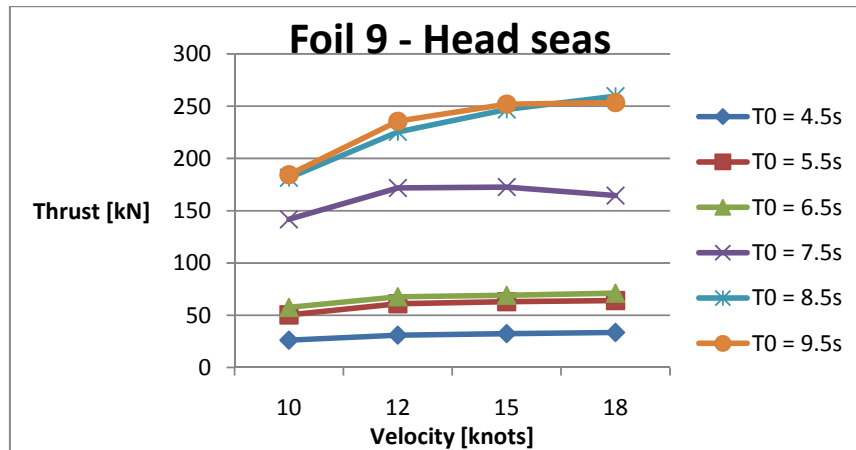


Figure 7-1: Foil 9, Head seas - Offshore supply vessel, regular waves

The largest thrust forces are found for the largest wave period. The thrust increases somewhat for the largest waves when the velocity increases. For the smaller waves the thrust is almost constant. When we move on to beam seas (Figure 7-2) the variation with respect to speed is still very small. If anything, the thrust force decreases with increasing speed. The thrust forces are generally small in beam seas.

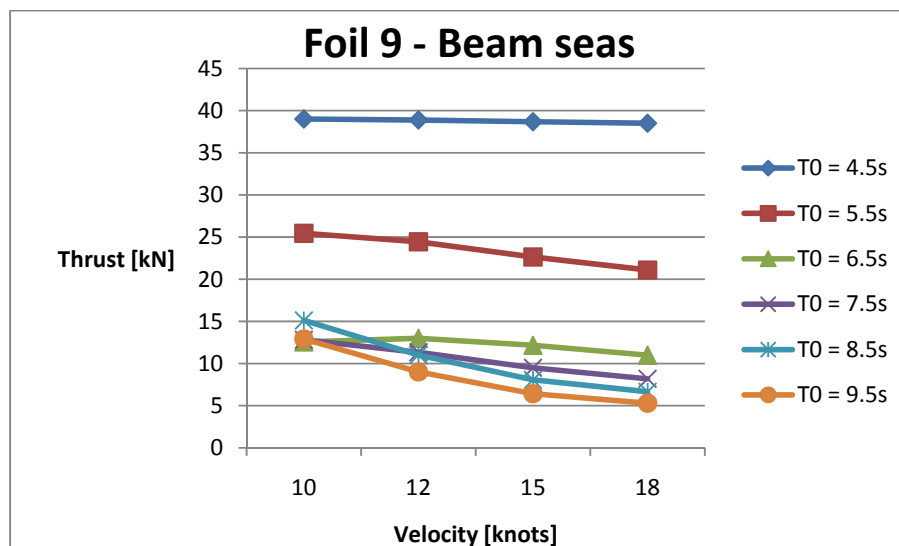


Figure 7-2: Foil 9, Beam seas - Offshore supply vessel, regular wave

In following seas (Figure 7-3) the trend is that wave periods around 8 seconds give the largest thrust forces, this corresponds to a wave length close to the length of the vessel. As mentioned, beam seas give very small thrust forces, for all other wave directions a wave period of 8,5 seconds generally gives the largest thrust force, while the smaller wave periods give relatively small thrust values. This trend applies for all the foils and all three vessels.

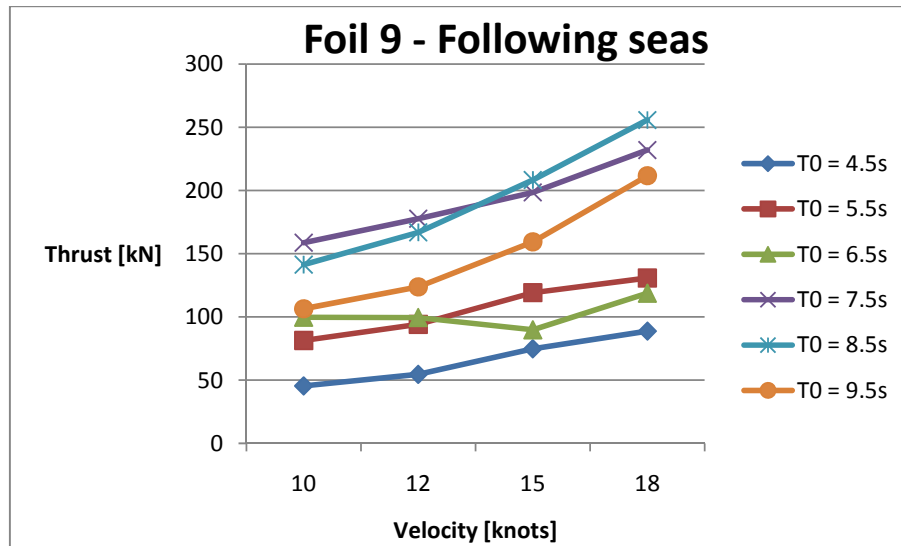


Figure 7-3: Foil 9, Following seas - Offshore supply vessel, regular wave

The results for all wave headings are found in Appendix B: Thrust force, varying wave headings, offshore supply vessel.

7.1.1.2 Variation with wave headings

We wish to compare the results for the different wave headings as well, so we select one wave period and plot the thrust force in Figure 7-4. 45 deg means bow quartering seas, 90 deg is beam seas, 135 deg is stern quartering seas and 180 deg is following seas.

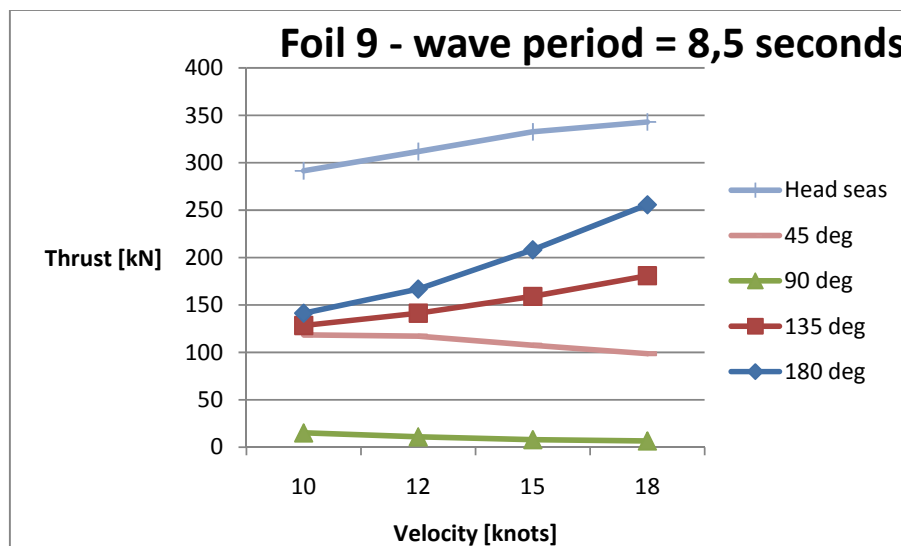


Figure 7-4: Foil 9, T0 = 8,5s - Offshore supply vessel, regular waves

Head seas give the largest thrust force followed by following seas. Stern quartering seas gives more promising results than bow quartering seas, while beam seas hardly produce any thrust force. When decreasing the wave period to 6,5 seconds (Figure 7-5) and decreasing the wave amplitude as well according to Table 14, we see that the largest thrust forces are obtained for stern and bow quartering seas.

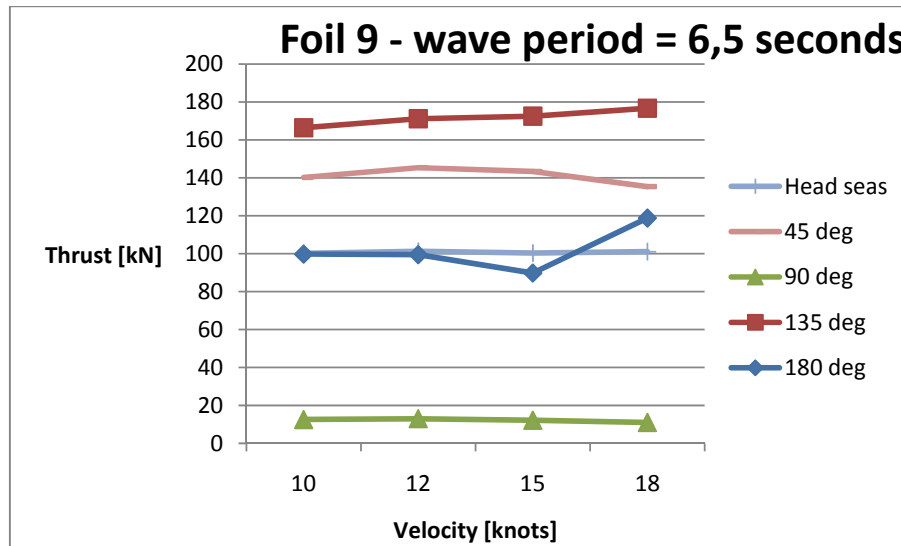


Figure 7-5: Foil 9, T0 = 6,5s - Offshore supply vessel, regular waves

A likely reason for this is that the heave and pitch motion of the ship are reduced considerably, but a roll motion increases the relative vertical velocities at the centre of the foils and consequently the thrust force is increased. Even so, pure roll motion is still very unfavourable for our foil propeller according to these results. The results for all six wave periods can be found in Appendix C: Thrust force, varying wave periods, offshore supply vessel

7.1.2 Including unsteady lift effects and flexible foils

The effect of an oscillating – and consequently unsteady – flow depends on the wave encounter frequency, i.e. the wave frequency and wave heading. We illustrate this in Figure 7-6.

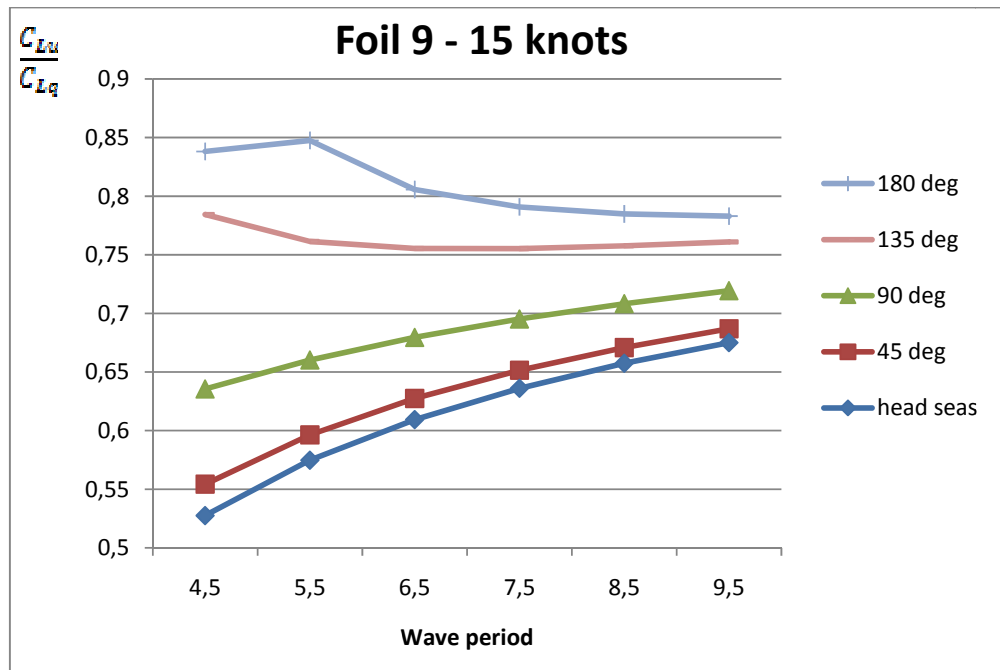


Figure 7-6: Effect of unsteady lift by wave period and heading

In addition the coefficient $\frac{C_{Lu}}{C_{Lq}}$ depends on the chord length. A larger chord length decreases the coefficient, i.e. the thrust force is reduced.

As shown in Figure 3-5 the application of flexible foils will increase the thrust force according to Equation 3-40 by approximately 13% for all velocities.

7.1.3 Reduced added resistance in waves

As mentioned earlier a reduction in the added resistance in waves as a consequence of equipping a vessel with foils is equivalent with an increase in the thrust force. In Figure 7-7 the reduction in added resistance is plotted as a function of wave period for the different wave headings.

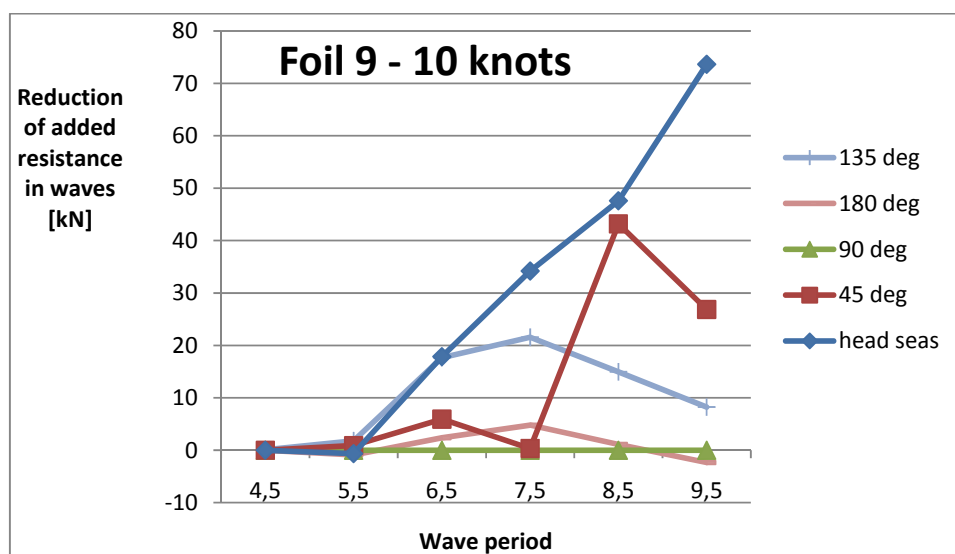


Figure 7-7: Reduction in added resistance, 10 knots - Offshore supply vessel

Naturally, the added resistance in waves increases with increasing wave period (and amplitude). At 10 knots the reduction in added resistance is quite significant for head seas and partly so for bow quartering seas too. However, the picture becomes more undefined when the speed is increased. The graphs gradually alter until they reach the values illustrated in Figure 7-8. For several wave conditions the added resistance in waves actually increases when the vessel is equipped with foils. The figures for 12 knots and 15 knots are found in Appendix D: Reduction in added resistance, offshore supply vessel.

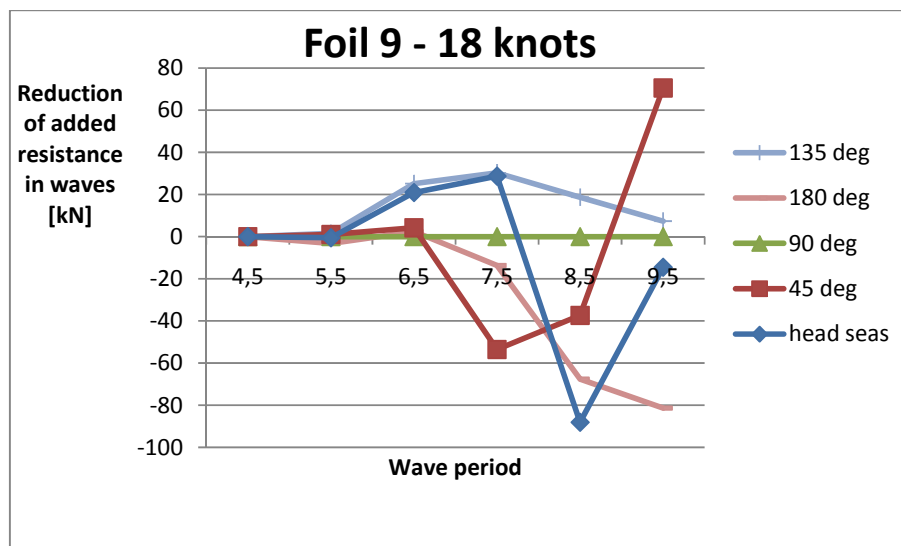


Figure 7-8: Reduction in added resistance, 18 knots - Offshore supply vessel

7.1.4 Required thrust force

The relative reduction in required thrust force gained from an active foil propeller including the effect of unsteady lift, flexible foils and reduction (or in some cases increase) of added resistance in waves are shown in Table 15. We have used the method explained in the beginning of this chapter to reduce the amount of data so that each value is a weighted average of all the wave periods. The complete results with each wave period considered separately can be found in Appendix E: Percentage of required thrust covered, offshore supply vessel, irregular waves. We have used a colouring system to make it easier to see where the best results are found.

| | Red | < | 15 % | < | Yellow | < | 30 % | < | Green |
|----------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| <u>10kt</u> | Foil 1 | Foil 2 | Foil 3 | Foil 4 | Foil 5 | Foil 6 | Foil 7 | Foil 8 | Foil 9 |
| Head seas | 26 % | 30 % | 34 % | 31 % | 37 % | 41 % | 35 % | 42 % | 48 % |
| 45 deg | 14 % | 16 % | 18 % | 16 % | 19 % | 21 % | 18 % | 22 % | 24 % |
| 90 deg | 5 % | 5 % | 5 % | 6 % | 6 % | 5 % | 7 % | 6 % | 5 % |
| 135 deg | 18 % | 22 % | 26 % | 21 % | 25 % | 28 % | 23 % | 27 % | 31 % |
| 180 deg | 13 % | 17 % | 21 % | 16 % | 20 % | 25 % | 19 % | 24 % | 30 % |
| Average | 15 % | 18 % | 21 % | 18 % | 21 % | 24 % | 20 % | 24 % | 28 % |
| <u>12kt</u> | Foil 1 | Foil 2 | Foil 3 | Foil 4 | Foil 5 | Foil 6 | Foil 7 | Foil 8 | Foil 9 |
| Head seas | 24 % | 28 % | 32 % | 29 % | 34 % | 39 % | 33 % | 40 % | 46 % |
| 45 deg | 13 % | 15 % | 16 % | 15 % | 18 % | 20 % | 18 % | 21 % | 23 % |
| 90 deg | 4 % | 4 % | 4 % | 5 % | 5 % | 4 % | 5 % | 5 % | 4 % |
| 135 deg | 17 % | 20 % | 23 % | 19 % | 23 % | 26 % | 22 % | 25 % | 29 % |
| 180 deg | 11 % | 15 % | 19 % | 14 % | 19 % | 24 % | 17 % | 23 % | 28 % |
| Average | 14 % | 17 % | 19 % | 16 % | 20 % | 22 % | 19 % | 23 % | 26 % |
| <u>15kt</u> | Foil 1 | Foil 2 | Foil 3 | Foil 4 | Foil 5 | Foil 6 | Foil 7 | Foil 8 | Foil 9 |
| Head seas | 15 % | 18 % | 20 % | 18 % | 22 % | 24 % | 21 % | 26 % | 29 % |
| 45 deg | 8 % | 9 % | 10 % | 10 % | 11 % | 12 % | 11 % | 13 % | 14 % |
| 90 deg | 2 % | 2 % | 2 % | 3 % | 3 % | 2 % | 3 % | 3 % | 2 % |

| | | | | | | | | | |
|------------------|------|------|------|------|------|------|------|------|------|
| 135 deg | 11 % | 14 % | 15 % | 13 % | 16 % | 18 % | 15 % | 18 % | 20 % |
| 180 deg | 7 % | 10 % | 12 % | 10 % | 13 % | 16 % | 12 % | 16 % | 20 % |
| Average | 9 % | 10 % | 12 % | 11 % | 13 % | 15 % | 13 % | 15 % | 17 % |
| 18kt | | | | | | | | | |
| Head seas | 6 % | 7 % | 8 % | 8 % | 9 % | 11 % | 9 % | 11 % | 13 % |
| 45 deg | 3 % | 4 % | 4 % | 4 % | 5 % | 5 % | 5 % | 6 % | 6 % |
| 90 deg | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % |
| 135 deg | 6 % | 8 % | 9 % | 8 % | 9 % | 10 % | 9 % | 11 % | 12 % |
| 180 deg | 4 % | 5 % | 7 % | 5 % | 7 % | 10 % | 7 % | 9 % | 12 % |
| Average | 4 % | 5 % | 6 % | 5 % | 6 % | 7 % | 6 % | 8 % | 9 % |

Table 15: Reduction in required thrust - Offshore supply vessel, Regular waves

The first notable trend we see is that the potential benefit from a foil propeller is significantly decreased with increasing speed. This seems logical as the resistance increases with the square of the velocity, while the thrust force does not. In Figure 7-9 we have plotted the thrust force for some selected foils with varying wave period and heading. T0 is the wave period.

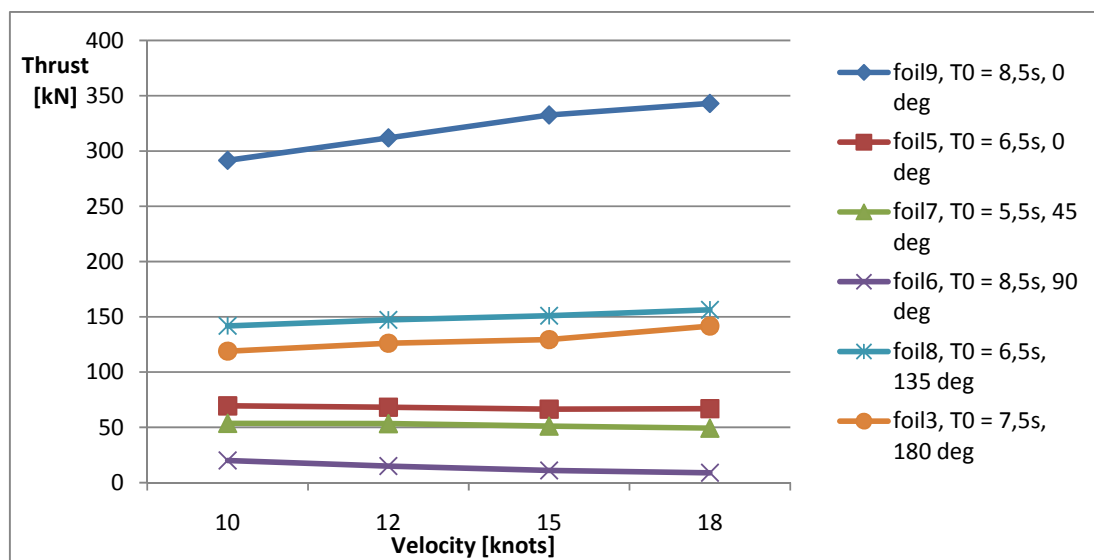


Figure 7-9: Variation of chosen thrust forces

On average there is a slight increase in the thrust with increasing velocity, but obviously not nearly enough to compensate for the increased resistance.

Another clear trend from Table 15: Reduction in required thrust - Offshore supply vessel, Regular waves is that foil 9 has the largest potential for reducing the required thrust. This is not surprising as it has the largest aspect ratio ($s/c = 5$) and the largest area (5% of water plane area). Closely behind follows foil 8 and 7 with only a reduction in the foil area (4 and 3%) and foil 6 and 3 where only the aspect ratio is reduced (to 4 and 3) compared to foil 9.

When comparing the wave headings we see that head seas are the most beneficial by far. Following seas and stern quartering seas gives better results than bow quartering seas, while beam seas is not a very suitable wave heading for foils propulsion based on these results.

7.1.5 Fuel Savings

Finally the potential fuel savings are calculated as described in Equation 3-45 and Equation 3-46. Again we combine the wave periods as we did in Table 15: Reduction in required thrust - Offshore supply vessel, Regular waves and present the results in Table 16

| <i>Regular waves</i> | Red | < | 15 % | < | Yellow | < | 30 % | < | Green |
|----------------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| 10 knots | Foil 1 | Foil 2 | Foil 3 | Foil 4 | Foil 5 | Foil 6 | Foil 7 | Foil 8 | Foil 9 |
| Head seas | 36 % | 40 % | 43 % | 40 % | 45 % | 49 % | 44 % | 50 % | 55 % |
| 45 deg | 24 % | 26 % | 28 % | 26 % | 29 % | 31 % | 28 % | 31 % | 34 % |
| 90 deg | 12 % | 12 % | 12 % | 13 % | 12 % | 12 % | 14 % | 13 % | 12 % |
| 135 deg | 21 % | 25 % | 28 % | 23 % | 27 % | 31 % | 26 % | 30 % | 33 % |
| 180 deg | 19 % | 23 % | 26 % | 22 % | 26 % | 31 % | 24 % | 30 % | 35 % |
| Average | 22 % | 25 % | 27 % | 25 % | 28 % | 31 % | 27 % | 31 % | 34 % |
| 12 knots | | | | | | | | | |
| Head seas | 35 % | 39 % | 42 % | 39 % | 43 % | 47 % | 43 % | 48 % | 53 % |
| 45 deg | 23 % | 25 % | 26 % | 25 % | 28 % | 29 % | 27 % | 30 % | 32 % |
| 90 deg | 11 % | 11 % | 11 % | 12 % | 11 % | 11 % | 12 % | 12 % | 11 % |
| 135 deg | 19 % | 23 % | 26 % | 22 % | 25 % | 28 % | 24 % | 28 % | 31 % |
| 180 deg | 18 % | 21 % | 25 % | 21 % | 25 % | 29 % | 23 % | 29 % | 34 % |
| Average | 21 % | 24 % | 26 % | 24 % | 27 % | 29 % | 26 % | 29 % | 32 % |
| 15 knots | | | | | | | | | |
| Head seas | 27 % | 29 % | 31 % | 30 % | 33 % | 35 % | 32 % | 36 % | 39 % |
| 45 deg | 19 % | 20 % | 21 % | 20 % | 22 % | 23 % | 22 % | 24 % | 25 % |
| 90 deg | 9 % | 9 % | 9 % | 10 % | 10 % | 9 % | 10 % | 10 % | 9 % |
| 135 deg | 14 % | 16 % | 18 % | 16 % | 19 % | 20 % | 18 % | 21 % | 22 % |
| 180 deg | 14 % | 16 % | 19 % | 16 % | 19 % | 22 % | 18 % | 22 % | 26 % |
| Average | 17 % | 18 % | 20 % | 18 % | 20 % | 22 % | 20 % | 22 % | 24 % |
| 18 knots | | | | | | | | | |
| Head seas | 20 % | 21 % | 21 % | 21 % | 22 % | 23 % | 22 % | 24 % | 25 % |
| 45 deg | 15 % | 16 % | 16 % | 16 % | 16 % | 17 % | 17 % | 17 % | 18 % |
| 90 deg | 8 % | 8 % | 8 % | 8 % | 8 % | 8 % | 8 % | 8 % | 8 % |
| 135 deg | 9 % | 11 % | 12 % | 11 % | 12 % | 13 % | 12 % | 13 % | 15 % |
| 180 deg | 11 % | 12 % | 14 % | 12 % | 14 % | 16 % | 13 % | 16 % | 19 % |
| Average | 13 % | 13 % | 14 % | 14 % | 15 % | 16 % | 15 % | 16 % | 17 % |

Table 16: Fuel Savings - Offshore supply vessel, regular waves

The results are promising for a vessel travelling at 10 and 12 knots, saving up to more than 50 % with the largest foil and travelling at head seas. Although it seems like travelling in beam seas is somewhat of an Achilles' heel for the foil propeller travelling in regular waves. The complete table where each wave frequency is kept separate is found in Appendix F: Fuel savings, regular waves, offshore supply vessel and here we find savings up to 99 % a wave frequency of 8,5 seconds. This is not very relevant though, since such perfect waves will never be found in the ocean.

7.2 Coastal Tanker

7.2.1 Thrust force

Not surprisingly the same trends found from the study of the offshore supply vessel are present for the coastal tanker. This fact is demonstrated in Figure 7-10, Figure 7-11 and Figure 7-12 which have almost the exact same characteristics as Figure 7-1, Figure 7-2 and Figure 7-3.

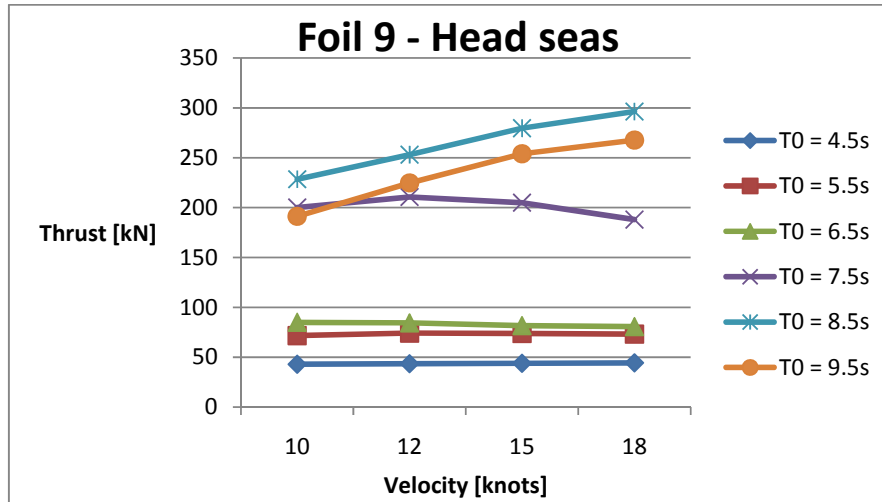


Figure 7-10: Foil 9, Head seas – Coastal Tanker, regular waves

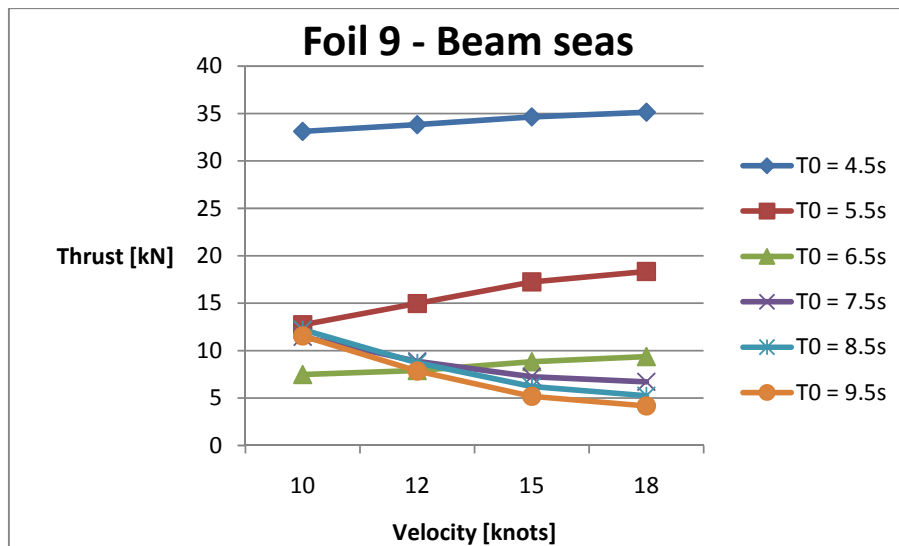


Figure 7-11: Foil 9, Beam seas – Coastal Tanker, regular waves

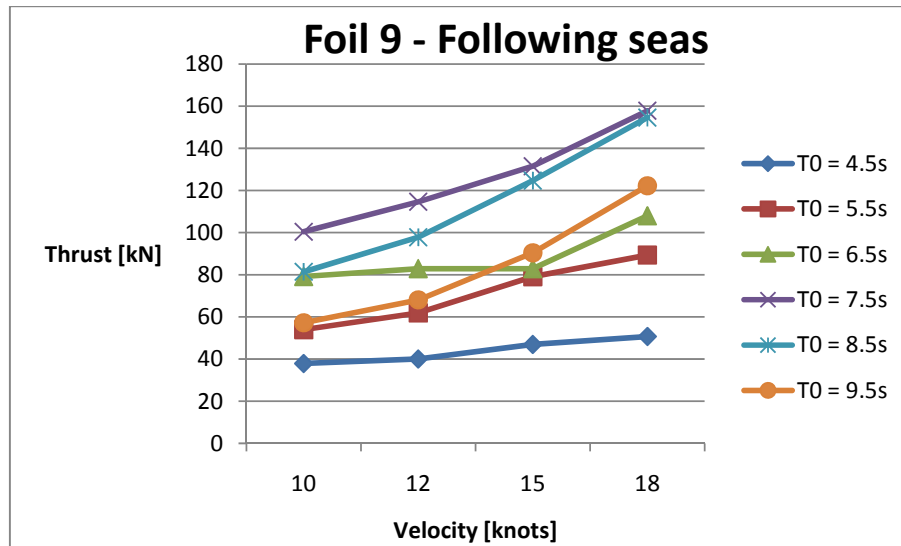


Figure 7-12: Foil 9, Following seas – Coastal Tanker, regular waves

7.2.2 Unsteady lift effects and flexible foil

The effect of flexible foils is exactly the same for all the vessels when applying our method of calculation. The unsteady lift coefficient slightly differs from those obtained for the offshore supply vessel because of the altered foil configuration, but the trends are all the same.

7.2.3 Reduced added resistance

We recall that the reduction in added resistance was quite chaotic for the offshore supply vessel, so we will try to make more sense of the results for the coastal tanker. In Figure 7-13 we consider the vessel equipped with foil 9 travelling at 10 knots and in Figure 7-14 we have increased the speed to 18 knots.

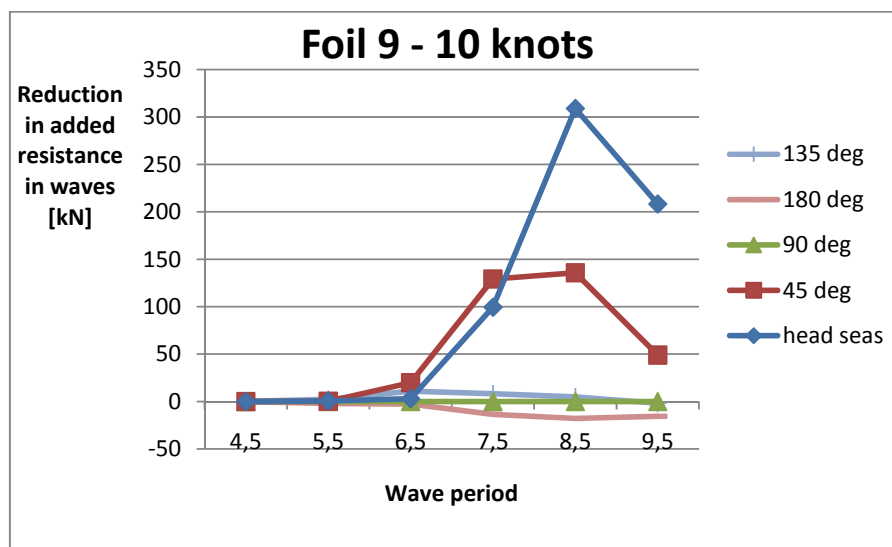


Figure 7-13: Reduction in added resistance, 10 knots – Coastal Tanker

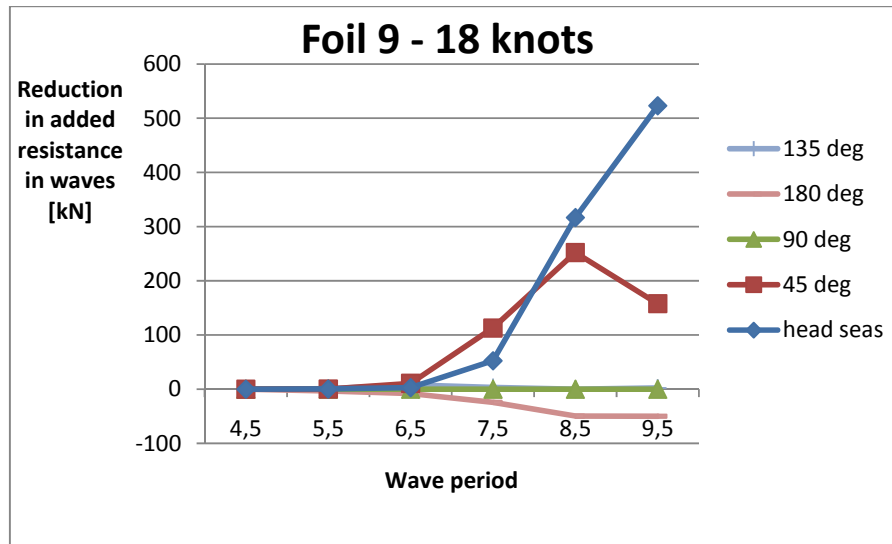


Figure 7-14: Reduction in added resistance, 18 knots – Coastal Tanker

Here we observe a significant deviation from the offshore supply vessel as the values are much larger. We remember that the main dimensions of these two vessels are quite similar, meaning that the hull shape has become an important factor. The hull of the coastal tanker is probably not designed for velocities up to 18 knots, and perhaps the general design is just not very modern.

We also notice that it is for head seas and bow-quartering seas that the values become very large. We remember from chapter 6.1.4 that the calculation method for head and bow quartering seas (Gerritsma and Beukelman) was not the same as for following and stern quartering seas (Direct pressure integration). Beam seas do not produce any added resistance. One might think that this may contribute to the differences between the results, so we did another calculation using direct pressure integration for head and bow quartering seas as well.

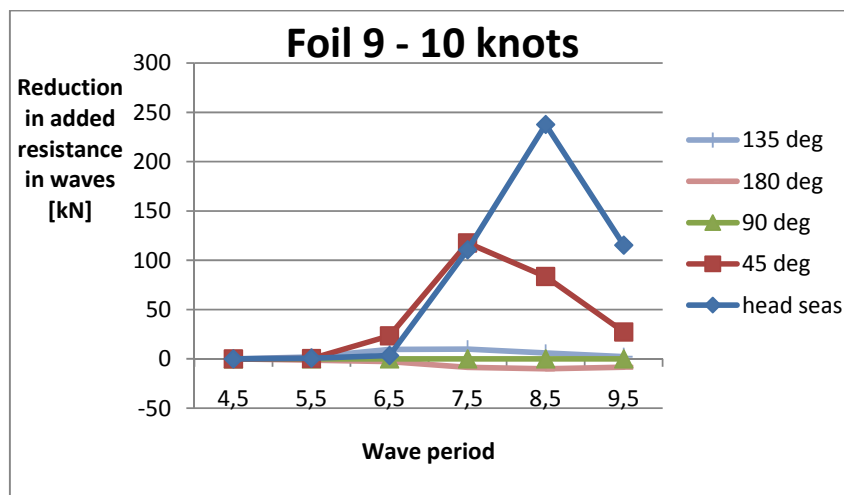


Figure 7-15: Reduction in added resistance, 10 knots – Coastal Tanker (pressure integration)

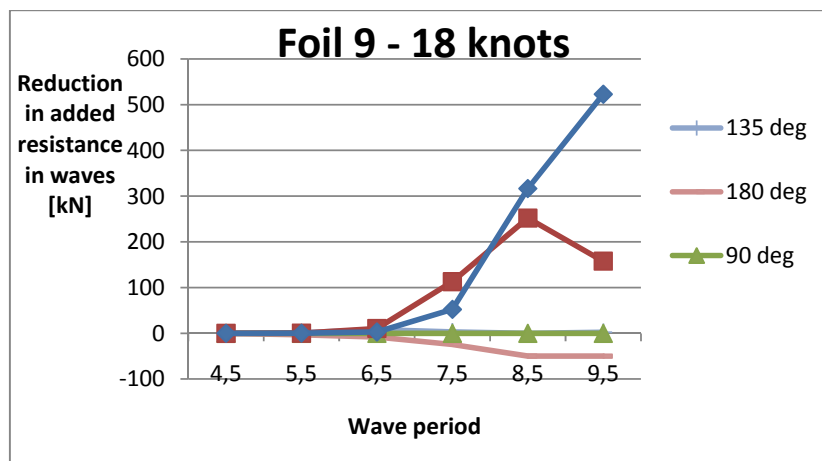


Figure 7-16: Reduction in added resistance, 18 knots – Coastal Tanker (pressure integration)

Figure 7-15 and Figure 7-16 tells us that the difference is marginal, and the results still does not compare to the added resistance for the offshore supply vessel. All the reductions added resistance in waves for the coastal tanker are found in Appendix G: Reduction in added resistance, coastal tanker.

7.2.4 Reduction in required thrust

We present the reduction in the required thrust force from the conventional screw propeller for the coastal tanker in Table 17.

| <i>Regular waves</i> | Red | < | 15 % | < | Yellow | < | 30 % | < | Green |
|----------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 10kt | Foil 1 | Foil 2 | Foil 3 | Foil 4 | Foil 5 | Foil 6 | Foil 7 | Foil 8 | Foil 9 |
| Head seas | 25 % | 30 % | 34 % | 29 % | 35 % | 39 % | 33 % | 39 % | 45 % |
| 45 deg | 16 % | 19 % | 22 % | 18 % | 22 % | 25 % | 21 % | 24 % | 28 % |
| 90 deg | 2 % | 3 % | 3 % | 4 % | 5 % | 5 % | 5 % | 6 % | 6 % |
| 135 deg | 19 % | 23 % | 26 % | 22 % | 27 % | 30 % | 25 % | 30 % | 33 % |
| 180 deg | 11 % | 16 % | 20 % | 15 % | 20 % | 26 % | 18 % | 25 % | 31 % |
| Average | 15 % | 18 % | 21 % | 18 % | 22 % | 25 % | 20 % | 25 % | 29 % |
| 12kt | | | | | | | | | |
| Head seas | 23 % | 28 % | 32 % | 28 % | 33 % | 38 % | 31 % | 38 % | 43 % |
| 45 deg | 16 % | 19 % | 22 % | 19 % | 22 % | 25 % | 21 % | 25 % | 28 % |
| 90 deg | 2 % | 2 % | 3 % | 3 % | 4 % | 4 % | 4 % | 5 % | 5 % |
| 135 deg | 15 % | 18 % | 20 % | 18 % | 21 % | 23 % | 20 % | 23 % | 25 % |
| 180 deg | 10 % | 14 % | 18 % | 13 % | 19 % | 24 % | 17 % | 24 % | 30 % |
| Average | 13 % | 16 % | 19 % | 16 % | 20 % | 23 % | 19 % | 23 % | 26 % |
| 15kt | | | | | | | | | |
| Head seas | 17 % | 21 % | 24 % | 20 % | 24 % | 28 % | 23 % | 28 % | 32 % |
| 45 deg | 13 % | 15 % | 17 % | 15 % | 18 % | 20 % | 17 % | 20 % | 22 % |
| 90 deg | 1 % | 2 % | 2 % | 2 % | 2 % | 2 % | 2 % | 3 % | 3 % |
| 135 deg | 7 % | 8 % | 10 % | 8 % | 10 % | 12 % | 10 % | 12 % | 14 % |
| 180 deg | 6 % | 9 % | 12 % | 9 % | 13 % | 17 % | 12 % | 16 % | 21 % |

| | | | | | | | | | |
|------------------|------|------|------|------|------|------|------|------|------|
| Average | 9 % | 11 % | 13 % | 11 % | 13 % | 16 % | 13 % | 16 % | 19 % |
| 18kt | | | | | | | | | |
| Head seas | 11 % | 13 % | 15 % | 13 % | 15 % | 17 % | 15 % | 17 % | 20 % |
| 45 deg | 9 % | 10 % | 11 % | 10 % | 12 % | 13 % | 11 % | 13 % | 15 % |
| 90 deg | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 2 % |
| 135 deg | 5 % | 5 % | 6 % | 5 % | 6 % | 8 % | 6 % | 8 % | 9 % |
| 180 deg | 3 % | 5 % | 7 % | 5 % | 8 % | 11 % | 7 % | 10 % | 14 % |
| Average | 6 % | 7 % | 8 % | 7 % | 8 % | 10 % | 8 % | 10 % | 12 % |

Table 17: Reduction in required thrust, coastal tanker

The basic trend is the same as for the offshore supply vessel: larger foils give larger thrust force from the foil propeller and head seas and low velocity is beneficial. Over the whole range of foils, velocities and wave condition the numbers are quite similar for these two vessels.

7.2.5 Fuel Savings

We move on to the fuel savings and as expected the results are very similar to those of the offshore supply vessel. We have again reduced the amount of data and the complete table is in Appendix H: .

| <i>Regular waves</i> | Red | < | 15 % | < | Yellow | < | 30 % | < | Green |
|----------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 10kt | Foil 1 | Foil 2 | Foil 3 | Foil 4 | Foil 5 | Foil 6 | Foil 7 | Foil 8 | Foil 9 |
| Head seas | 38 % | 42 % | 46 % | 41 % | 46 % | 50 % | 45 % | 50 % | 55 % |
| 45 deg | 30 % | 33 % | 35 % | 32 % | 35 % | 37 % | 34 % | 37 % | 40 % |
| 90 deg | 14 % | 15 % | 15 % | 15 % | 16 % | 16 % | 17 % | 18 % | 18 % |
| 135 deg | 24 % | 28 % | 31 % | 28 % | 32 % | 35 % | 31 % | 35 % | 38 % |
| 180 deg | 20 % | 24 % | 28 % | 23 % | 28 % | 33 % | 26 % | 32 % | 38 % |
| Average | 25 % | 28 % | 31 % | 28 % | 31 % | 34 % | 30 % | 34 % | 38 % |
| 12kt | | | | | | | | | |
| Head seas | 37 % | 41 % | 44 % | 41 % | 45 % | 49 % | 44 % | 49 % | 53 % |
| 45 deg | 30 % | 33 % | 35 % | 32 % | 35 % | 38 % | 34 % | 38 % | 40 % |
| 90 deg | 14 % | 14 % | 15 % | 15 % | 15 % | 16 % | 16 % | 16 % | 17 % |
| 135 deg | 21 % | 24 % | 26 % | 24 % | 26 % | 28 % | 26 % | 29 % | 31 % |
| 180 deg | 19 % | 22 % | 26 % | 22 % | 27 % | 31 % | 25 % | 31 % | 37 % |
| Average | 24 % | 27 % | 29 % | 27 % | 30 % | 32 % | 29 % | 32 % | 36 % |
| 15kt | | | | | | | | | |
| Head seas | 32 % | 35 % | 37 % | 35 % | 38 % | 41 % | 37 % | 41 % | 44 % |
| 45 deg | 28 % | 30 % | 31 % | 29 % | 32 % | 33 % | 31 % | 33 % | 35 % |
| 90 deg | 13 % | 13 % | 14 % | 14 % | 14 % | 14 % | 14 % | 15 % | 15 % |
| 135 deg | 13 % | 15 % | 16 % | 15 % | 17 % | 18 % | 16 % | 19 % | 21 % |
| 180 deg | 15 % | 18 % | 21 % | 18 % | 21 % | 25 % | 20 % | 25 % | 29 % |
| Average | 20 % | 22 % | 24 % | 22 % | 24 % | 26 % | 24 % | 26 % | 29 % |
| 18kt | | | | | | | | | |
| Head seas | 27 % | 29 % | 30 % | 29 % | 31 % | 32 % | 30 % | 32 % | 34 % |
| 45 deg | 24 % | 26 % | 27 % | 25 % | 27 % | 28 % | 26 % | 28 % | 29 % |
| 90 deg | 13 % | 13 % | 13 % | 13 % | 13 % | 13 % | 13 % | 13 % | 13 % |
| 135 deg | 11 % | 12 % | 13 % | 12 % | 13 % | 14 % | 13 % | 14 % | 16 % |

| | | | | | | | | | |
|----------------|------|------|------|------|------|------|------|------|------|
| 180 deg | 13 % | 15 % | 16 % | 14 % | 17 % | 19 % | 16 % | 19 % | 22 % |
| Average | 18 % | 19 % | 20 % | 19 % | 20 % | 21 % | 20 % | 21 % | 23 % |

Table 18: Fuel Savings - Coastal Tanker, regular waves

As seen from Table 18 that the highest value found in the top right corner is the same as for the offshore supply vessel. Overall though, there is a slight increase in almost all of the values, especially for high velocities. We trace this back to the large reduction in added resistance for the coastal tanker.

7.3 Purse Seiner

7.3.1 Thrust force

The main dimensions of the Purse Seiner are quite different compared to the two previous vessels. The length is reduced by approximately 20%, and consequently the vessel has less than half the displacement of the coastal tanker and about a third of the offshore supply vessel.

First we consider the thrust force from foil 9 in head seas shown in Figure 7-17.

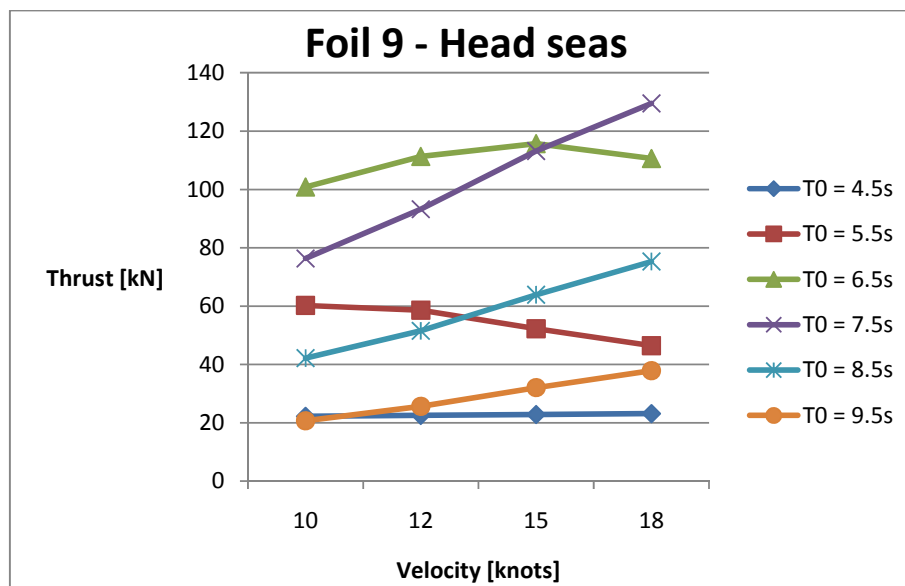


Figure 7-17: Foil 9, Head seas – Purse Seiner, regular waves

Opposing the results from the two previous vessels, the largest values are found for wave periods of 6,5 and 7,5 seconds. We continue to beam seas and following seas in Figure 7-18 and Figure 7-19.

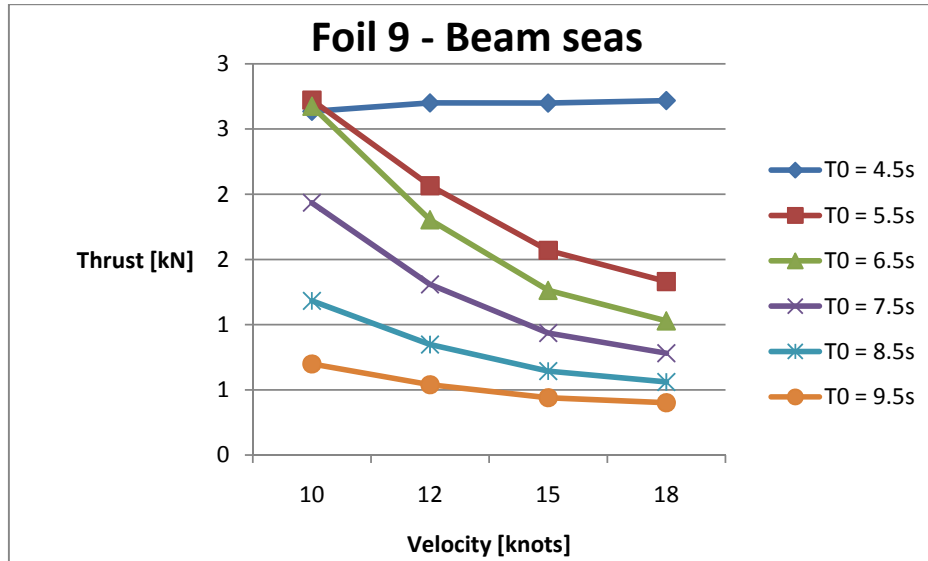


Figure 7-18: Foil 9, Beam seas – Purse, regular waves

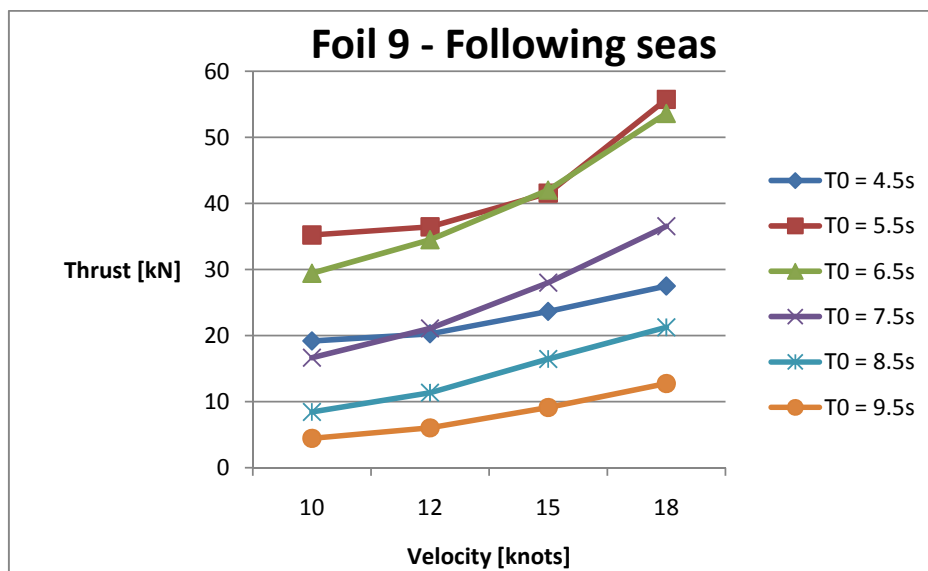


Figure 7-19: Foil 9, Following seas – Purse Seiner, regular waves

When comparing the three figures above Figure 7-1, Figure 7-2 and Figure 7-3 for the offshore supply vessel and Figure 7-10, Figure 7-11 and Figure 7-12 for the coastal tanker we notice that the highest thrust forces are found for wave periods close to 6 seconds. This corresponds to a wave length equal to the length of the vessel. In other words, the trend from the two previous vessels continues.

Other than this the graphs are very similar in shape – one average giving a slight increase in thrust with increasing velocity. This last effect is a bit more prominent for the Purse Seiner, indicating that the thrust force is more sensitive to changes in the vessel velocity. The results for all wave headings are placed in Appendix I: Thrust force, foil 9, purse seiner.

7.3.2 Unsteady lift effects and flexible foil

For reasons mentioned in chapter 7.2.2 the effect of an unsteady flow and flexible foils, further commenting on the subject is redundant.

7.3.3 Reduced added resistance

The reduced added resistance in waves for the Purse Seiner is shown in Figure 7-20 and Figure 7-21. The figures for 12 and 15 knots are found in Appendix J: Reduction in added resistance in waves, purse seiner.

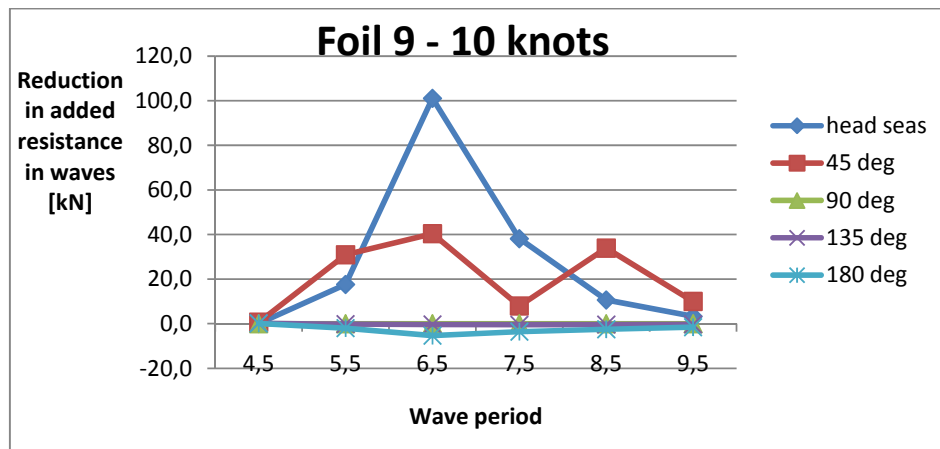


Figure 7-20: Reduction in added resistance, 10 knots – Purse Seiner

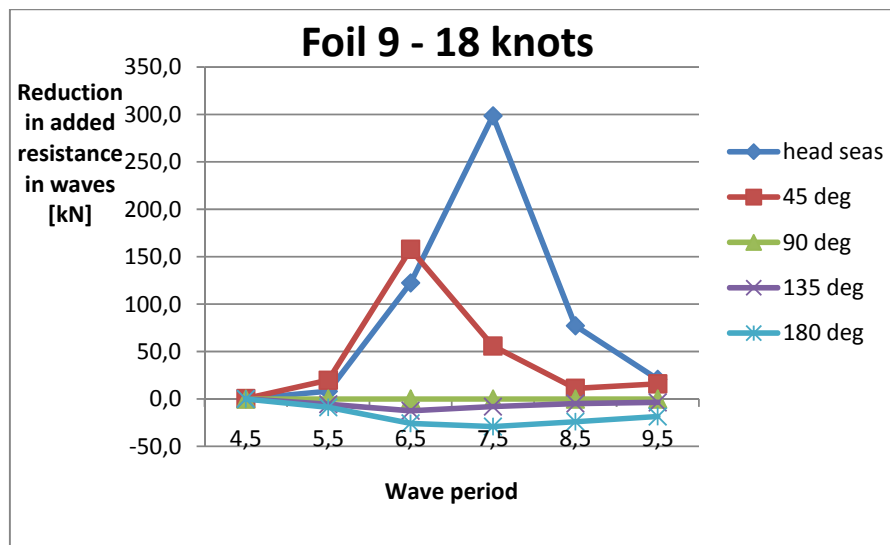


Figure 7-21: Reduction in added resistance, 18 knots – Purse Seiner

As for the two previous vessels we consider foil 9 at 10 and 18 knots. We note that the largest values are found near the wave periods that produce the largest thrust force. In other words: where the wave length is close to the length of the vessel. This relation between thrust force and reduction in added resistance in waves was also present for the two previous vessels, but not as obvious as in the case of the purse seiner.

7.3.4 Reduction in required thrust

The reduction in the required thrust force from the conventional propeller is shown in Table 19.

| <i>Regular waves</i> | Red | < | 15 % | < | Yellow | < | 30 % | < | Green |
|----------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 10kt | Foil 1 | Foil 2 | Foil 3 | Foil 4 | Foil 5 | Foil 6 | Foil 7 | Foil 8 | Foil 9 |
| Head seas | 30 % | 36 % | 41 % | 35 % | 41 % | 46 % | 38 % | 45 % | 51 % |
| 45 deg | 18 % | 20 % | 21 % | 19 % | 21 % | 23 % | 21 % | 23 % | 24 % |
| 90 deg | 8 % | 6 % | 4 % | 8 % | 5 % | 3 % | 7 % | 4 % | 3 % |
| 135 deg | 9 % | 11 % | 12 % | 11 % | 12 % | 13 % | 12 % | 14 % | 15 % |
| 180 deg | 6 % | 9 % | 12 % | 9 % | 13 % | 17 % | 12 % | 17 % | 22 % |
| Average | 14 % | 16 % | 18 % | 16 % | 18 % | 20 % | 18 % | 21 % | 23 % |
| 12kt | | | | | | | | | |
| Head seas | 31 % | 36 % | 40 % | 35 % | 41 % | 45 % | 39 % | 45 % | 50 % |
| 45 deg | 18 % | 19 % | 21 % | 19 % | 21 % | 22 % | 20 % | 22 % | 24 % |
| 90 deg | 4 % | 3 % | 2 % | 4 % | 3 % | 2 % | 4 % | 2 % | 1 % |
| 135 deg | 7 % | 9 % | 10 % | 9 % | 10 % | 11 % | 10 % | 12 % | 13 % |
| 180 deg | 3 % | 7 % | 10 % | 6 % | 10 % | 14 % | 9 % | 14 % | 19 % |
| Average | 13 % | 15 % | 17 % | 15 % | 17 % | 19 % | 17 % | 19 % | 21 % |
| 15kt | | | | | | | | | |
| Head seas | 25 % | 29 % | 32 % | 28 % | 32 % | 35 % | 31 % | 35 % | 38 % |
| 45 deg | 14 % | 16 % | 17 % | 16 % | 17 % | 18 % | 17 % | 18 % | 20 % |
| 90 deg | 2 % | 1 % | 1 % | 2 % | 1 % | 1 % | 1 % | 1 % | 1 % |
| 135 deg | 3 % | 4 % | 5 % | 4 % | 5 % | 6 % | 5 % | 6 % | 7 % |
| 180 deg | 0 % | 2 % | 4 % | 2 % | 5 % | 8 % | 4 % | 7 % | 11 % |
| Average | 9 % | 11 % | 12 % | 10 % | 12 % | 14 % | 12 % | 14 % | 15 % |
| 18kt | | | | | | | | | |
| Head seas | 19 % | 22 % | 24 % | 22 % | 24 % | 26 % | 23 % | 26 % | 28 % |
| 45 deg | 11 % | 12 % | 13 % | 12 % | 13 % | 14 % | 13 % | 14 % | 15 % |
| 90 deg | 1 % | 1 % | 0 % | 1 % | 0 % | 0 % | 1 % | 0 % | 0 % |
| 135 deg | 1 % | 2 % | 2 % | 2 % | 3 % | 3 % | 3 % | 3 % | 4 % |
| 180 deg | -2 % | 0 % | 1 % | 0 % | 2 % | 4 % | 1 % | 4 % | 6 % |
| Average | 6 % | 7 % | 8 % | 7 % | 8 % | 10 % | 8 % | 10 % | 11 % |

Table 19: Reduction in required thrust – Purse Seiner, Regular waves

The results found for the purse seiner travelling in head seas are the most promising results we have seen so far, but when the wave turns towards the stern the reduction in required thrust is smaller for the purse seiner than for the two other vessels. Beam seas are still very unfavourable. The complete table with wave frequencies considered separately are found in Appendix K: Reduction in required thrust force, purse seiner

7.3.5 Fuel Savings

When looking at the fuel saving in Table 20 the conclusion is the same as for the reduction in the required thrust force. There lies a significant potential for reducing the fuel consumption if the vessel is travelling in waves close to head seas, but with waves coming from behind the prospect looks more doubtful. Especially beam seas do not give very good results.

| <i>Regular waves</i> | Red | < | 15 % | < | Yellow | < | 30 % | < | Green |
|----------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 10kt | Foil 1 | Foil 2 | Foil 3 | Foil 4 | Foil 5 | Foil 6 | Foil 7 | Foil 8 | Foil 9 |
| Head seas | 40 % | 45 % | 49 % | 44 % | 49 % | 53 % | 47 % | 53 % | 58 % |
| 45 deg | 29 % | 31 % | 32 % | 30 % | 32 % | 33 % | 31 % | 33 % | 35 % |
| 90 deg | 18 % | 16 % | 15 % | 18 % | 15 % | 14 % | 18 % | 15 % | 13 % |
| 135 deg | 17 % | 19 % | 20 % | 18 % | 20 % | 21 % | 20 % | 21 % | 23 % |
| 180 deg | 12 % | 15 % | 18 % | 15 % | 19 % | 22 % | 17 % | 22 % | 27 % |
| Average | 23 % | 25 % | 27 % | 25 % | 27 % | 29 % | 27 % | 29 % | 31 % |
| 12kt | | | | | | | | | |
| Head seas | 40 % | 45 % | 48 % | 44 % | 49 % | 53 % | 47 % | 52 % | 57 % |
| 45 deg | 29 % | 30 % | 31 % | 30 % | 32 % | 33 % | 31 % | 33 % | 34 % |
| 90 deg | 15 % | 14 % | 13 % | 15 % | 14 % | 13 % | 15 % | 13 % | 12 % |
| 135 deg | 15 % | 17 % | 18 % | 17 % | 18 % | 19 % | 18 % | 19 % | 21 % |
| 180 deg | 10 % | 13 % | 16 % | 12 % | 16 % | 20 % | 15 % | 20 % | 24 % |
| Average | 22 % | 24 % | 25 % | 24 % | 26 % | 27 % | 25 % | 28 % | 30 % |
| 15kt | | | | | | | | | |
| Head seas | 35 % | 39 % | 41 % | 38 % | 41 % | 44 % | 40 % | 44 % | 47 % |
| 45 deg | 26 % | 27 % | 28 % | 27 % | 28 % | 29 % | 28 % | 29 % | 31 % |
| 90 deg | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 11 % |
| 135 deg | 12 % | 13 % | 13 % | 13 % | 14 % | 14 % | 14 % | 15 % | 15 % |
| 180 deg | 7 % | 9 % | 11 % | 9 % | 11 % | 14 % | 10 % | 14 % | 17 % |
| Average | 18 % | 20 % | 21 % | 20 % | 21 % | 23 % | 21 % | 23 % | 24 % |
| 18kt | | | | | | | | | |
| Head seas | 30 % | 33 % | 34 % | 32 % | 35 % | 36 % | 34 % | 36 % | 38 % |
| 45 deg | 23 % | 24 % | 25 % | 24 % | 25 % | 26 % | 25 % | 26 % | 27 % |
| 90 deg | 12 % | 11 % | 11 % | 12 % | 11 % | 11 % | 12 % | 11 % | 11 % |
| 135 deg | 10 % | 10 % | 11 % | 10 % | 11 % | 12 % | 11 % | 12 % | 12 % |
| 180 deg | 5 % | 7 % | 8 % | 6 % | 8 % | 10 % | 8 % | 10 % | 12 % |
| Average | 16 % | 17 % | 18 % | 17 % | 18 % | 19 % | 18 % | 19 % | 20 % |

Table 20: Fuel Savings - Purse Seiner, regular waves

The complete table is found in Appendix L: Fuel Savings, purse seiner

7.4 Comparison

7.4.1 The foils

From the results presented above we look for general trends. Most obvious is it that foil 9, having the largest area and span to chord length ratio, produces the best results. Foil 8 and foil 6 produces very similar results and so too do foil 7 and 3. This indicates that reducing the foil area from 5% of the water plane area to 4% or 3% has about the same effect as reducing the aspect ratio from 5 to 4 or 3, i.e. increasing the span while decreasing the chord length.

7.4.2 The vessels

The purse seiner seems to be best suited when the waves comes towards the bow, while the coastal tanker looks like it takes best advantage of waves towards the stern of the vessel. In general the

differences are not very large. As the amount of data still is very large – even after we have taken the weighted average of the wave periods – we compress the fuel saving data further to compare the vessels.

| | Red | < | 22 % | < | Yellow | < | 26 % | < | Green | |
|-------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|-------------|
| Regular waves | | | | | | | | | | |
| Vessel | Foil 1 | Foil 2 | Foil 3 | Foil 4 | Foil 5 | Foil 6 | Foil 7 | Foil 8 | Foil 9 | Average |
| Offshore supply vessel | 18 % | 20 % | 22 % | 20 % | 22 % | 24 % | 22 % | 25 % | 27 % | <u>22 %</u> |
| Coastal Tanker | 22 % | 24 % | 26 % | 24 % | 26 % | 29 % | 26 % | 29 % | 31 % | <u>26 %</u> |
| Purse Seiner | 20 % | 21 % | 23 % | 21 % | 23 % | 24 % | 23 % | 25 % | 26 % | <u>23 %</u> |

Table 21: Comparing the vessels

The coastal tanker gives slightly better results than the two other, which on average are very equal.

7.4.3 Varying speed

From all the tables shown in this chapter we have seen that the largest potential for fuel saving – as a percentage of the total fuel consumption – lies at the low speeds. However, this is of course closely related to the fact that the required propeller power increases with the square of the velocity. The thrust force increases with the velocity as well, but not at the same rate. Henceforth, even if the relative fuel savings are largest for low velocities, the absolute fuel saving are largest for the largest vessel velocity as shown in Figure 7-22

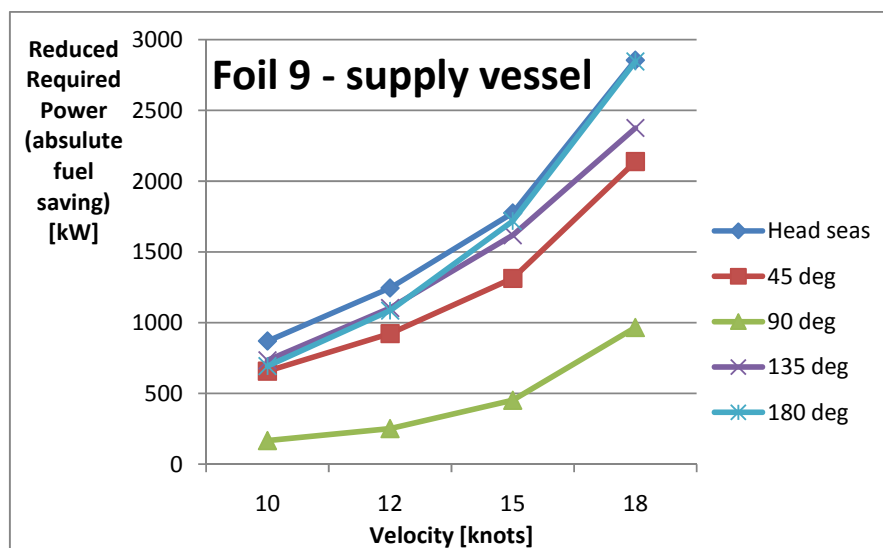


Figure 7-22: Reduction in required power, foil 9 - offshore supply vessel

8 Results in irregular waves for Offshore Supply vessel

Due to the computational time when doing the calculations for irregular waves, they are only preformed on the offshore supply vessel. We have considered foil number 9 travelling at 10, 12, 15 and 18 knots, as well as foil number 3, 6 and 7 travelling at 10 and 15 knots.

8.1 Thrust force

The "pure" thrust forces in irregular waves (excluding the effects of unsteady lift and flexible foils) at 10 and 15 knots are shown in Figure 8-1 and Figure 8-2.

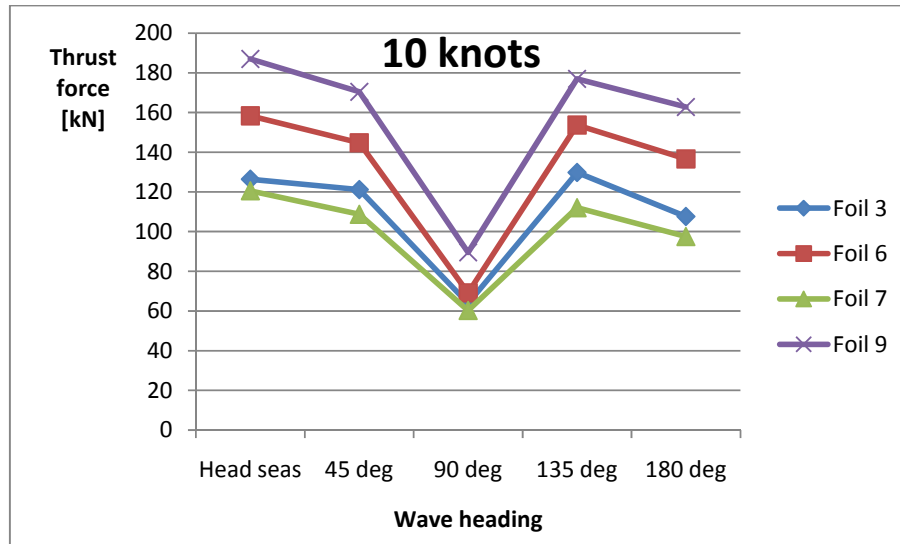


Figure 8-1: "Pure" Thrust force, 10 knots - Irregular waves

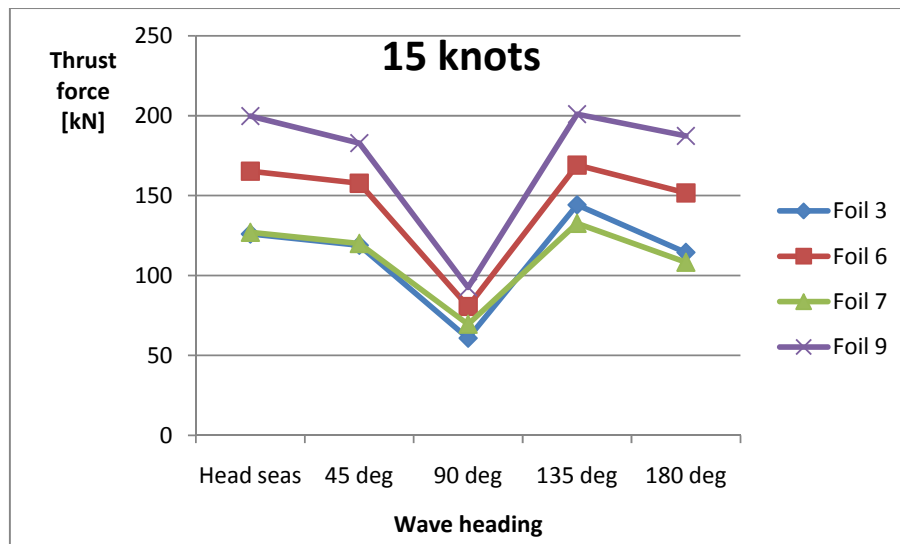


Figure 8-2: "Pure" Thrust force, 15 knots - Irregular waves

We see that the thrust forces in irregular waves are almost equal for all wave headings except beam seas, and even for beam seas they are not as small as for regular waves.

In Figure 8-3 we are just considering foil 9, and we see that although the thrust force increases with increasing velocity, the effect is not that prominent.

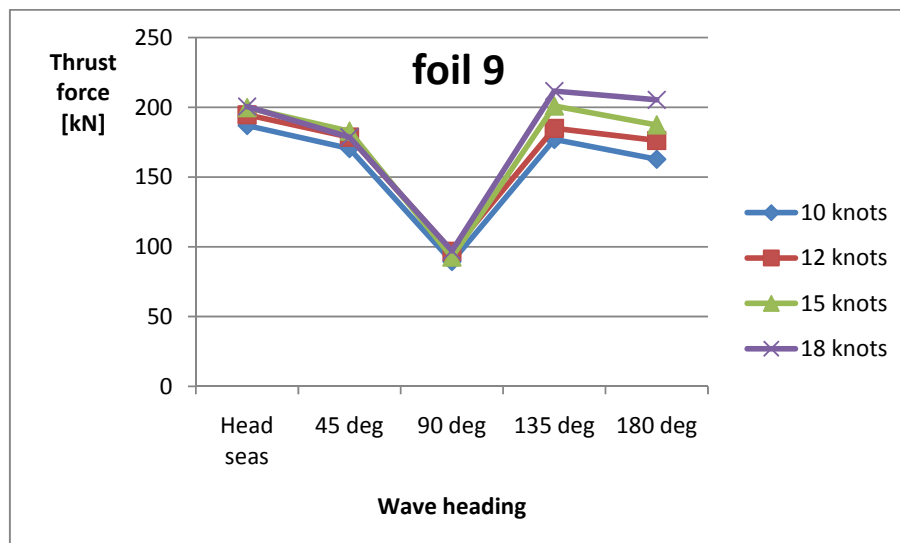


Figure 8-3: "Pure" Thrust force, foil 9 - Irregular waves

8.2 Unsteady lift effects and flexible foil

Our calculations on the effect of a flexible foil are not influenced by what kind of waves we are travelling in. The increase is still considered to be around 13 %.

The effect of unsteady lift is closely related to the frequency of encounter, but for irregular waves there is no defined frequency. In an effort to get any kind of results from this we take the mean value of the unsteady lift coefficient from the periods considered in regular waves. We could have used the zero-crossing period for the wave spectrum, but in following seas the coefficient proved to be very large in this case due to the frequency of encounter approaching zero. We have therefore chosen the more conservative path and use the mean value.

The table showing the combined unsteady lift and flexible foil coefficient for the purse seiner are found in Appendix M: Combined coefficient for unsteady flow and flexible foil.

8.3 Reduced added resistance in waves

We look at the reduction in added resistance in irregular waves in Figure 8-4 and see that the values are very small. This is because the added resistances in waves are quite similar with and without foils, and – as we see in Table 22 – are not very large.

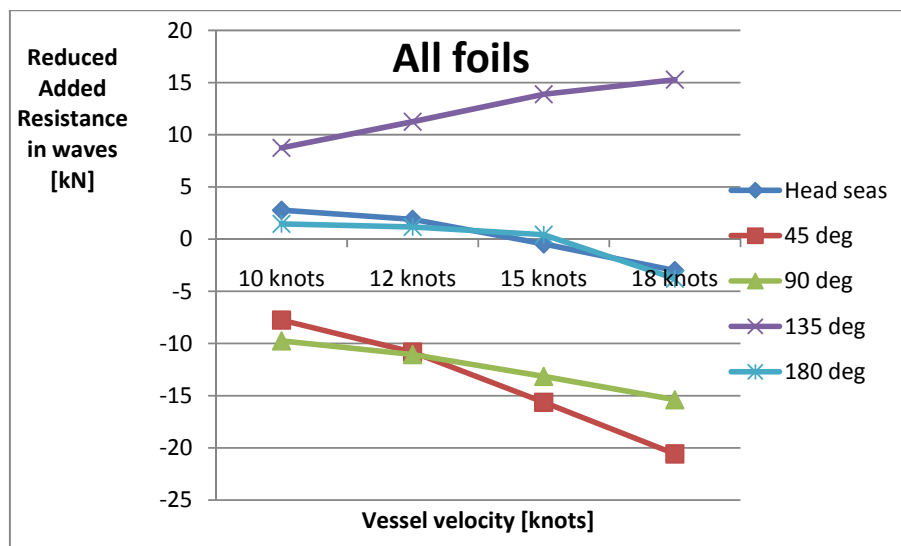


Figure 8-4: Reduction in added resistance in irregular waves

| | | <u>Added resistance</u> | | | | <u>Added resistance</u> | | | |
|-------------|-----------|-------------------------|-----------|---------|-------------|-------------------------|--------|-----------|---------|
| | | [in N] | with foil | no foil | | | [in N] | with foil | no foil |
| <u>10kt</u> | Head seas | | 27978 | 30755 | <u>15kt</u> | Head seas | 21340 | 20876 | |
| | 45 deg | | 81619 | 73866 | | 45 deg | 78597 | 62964 | |
| | 90 deg | | 52120 | 42379 | | 90 deg | 64579 | 51431 | |
| | 135 deg | | 54684 | 63428 | | 135 deg | 77569 | 91445 | |
| | 180 deg | | 37057 | 38519 | | 180 deg | 51199 | 51621 | |
| <u>12kt</u> | Head seas | [in N] | with foil | no foil | <u>18kt</u> | Head seas | [in N] | with foil | no foil |
| | 45 deg | | 80113 | 69286 | | 45 deg | | 79340 | 58769 |
| | 90 deg | | 56971 | 45914 | | 90 deg | | 72594 | 57208 |
| | 135 deg | | 62631 | 73886 | | 135 deg | | 97965 | 113242 |
| | 180 deg | | 41672 | 42848 | | 180 deg | | 56963 | 53175 |

Table 22: Added resistance in irregular waves, with and without foil

8.4 Reduction in required thrust

We combine the results from the three previous sub-chapters and find the reduction in required thrust from the conventional propeller in Table 23.

| <u>Irregular waves</u> | Red | 15 % | Yellow | 30 % | Green |
|------------------------|-----|--------|--------|--------|--------|
| | | Foil 3 | Foil 6 | Foil 7 | Foil 9 |
| <u>10kt</u> | | | | | |
| Head seas | | 39 % | 48 % | 40 % | 58 % |
| 45 deg | | 27 % | 32 % | 26 % | 40 % |
| 90 deg | | 15 % | 16 % | 15 % | 23 % |
| 135 deg | | 43 % | 50 % | 40 % | 58 % |
| 180 deg | | 39 % | 49 % | 37 % | 59 % |
| <u>Average</u> | | 33 % | 39 % | 31 % | 48 % |

| <u>12kt</u> | Foil 3 | Foil 6 | Foil 7 | Foil 9 |
|--------------------|---------------|---------------|---------------|---------------|
| Head seas | | | | 51 % |
| 45 deg | | | | 37 % |
| 90 deg | | | | 22 % |
| 135 deg | | | | 52 % |
| 180 deg | | | | 55 % |
| Average | | | | 43 % |

| <u>15kt</u> | Foil 3 | Foil 6 | Foil 7 | Foil 9 |
|--------------------|---------------|---------------|---------------|---------------|
| Head seas | 19 % | 24 % | 20 % | 30 % |
| 45 deg | 14 % | 19 % | 15 % | 23 % |
| 90 deg | 7 % | 10 % | 9 % | 12 % |
| 135 deg | 26 % | 30 % | 25 % | 36 % |
| 180 deg | 21 % | 28 % | 21 % | 35 % |
| Average | 17 % | 22 % | 18 % | 27 % |

| <u>18kt</u> | Foil 3 | Foil 6 | Foil 7 | Foil 9 |
|--------------------|---------------|---------------|---------------|---------------|
| Head seas | | | | 15 % |
| 45 deg | | | | 11 % |
| 90 deg | | | | 6 % |
| 135 deg | | | | 20 % |
| 180 deg | | | | 19 % |
| Average | | | | 14 % |

Table 23: Reduction in required thrust, irregular waves

The results are very promising, especially for the two slowest velocities. It is worth noting that the values for following and stern quartering seas are as high as those for head seas.

8.5 Fuel Savings

From Table 24 we see that the fuel saving potential is very large across the board. Again we point out that the values in following seas and stern quartering seas are equal to, if not larger, than in head seas. All four foils show good potential, and the trend from regular waves continues with respect to the relations between the foils: foil 9 is the best, while foil 3 and 7 produce very similar results.

| <u>Irregular waves</u> | Red | 15 % | Yellow | 30 % | Green |
|-------------------------------|------------|-------------|---------------|-------------|--------------|
| <u>10kt</u> | | | | | |
| Head seas | | 49 % | 56 % | 50 % | 65 % |
| 45 deg | | 35 % | 40 % | 34 % | 47 % |
| 90 deg | | 20 % | 21 % | 20 % | 28 % |
| 135 deg | | 53 % | 59 % | 50 % | 66 % |
| 180 deg | | 44 % | 53 % | 42 % | 62 % |
| Average | | 40 % | 46 % | 39 % | 53 % |

| <u>12kt</u> | Foil 3 | Foil 6 | Foil 7 | Foil 9 |
|--------------------|---------------|---------------|---------------|---------------|
| Head seas | | | | 59 % |
| 45 deg | | | | 45 % |
| 90 deg | | | | 27 % |
| 135 deg | | | | 62 % |

| | | | | | |
|----------------|---------------|---------------|---------------|---------------|-------------|
| 180 deg | | | | | 64 % |
| Average | | | | | 51 % |
| 15kt | Foil 3 | Foil 6 | Foil 7 | Foil 9 | |
| Head seas | 25 % | 30 % | 27 % | 36 % | |
| 45 deg | 19 % | 24 % | 20 % | 28 % | |
| 90 deg | 10 % | 12 % | 11 % | 15 % | |
| 135 deg | 34 % | 37 % | 33 % | 42 % | |
| 180 deg | 29 % | 35 % | 28 % | 41 % | |
| Average | 23 % | 28 % | 24 % | 32 % | |
| 18kt | Foil 3 | Foil 6 | Foil 7 | Foil 9 | |
| Head seas | | | | | 19 % |
| 45 deg | | | | | 15 % |
| 90 deg | | | | | 8 % |
| 135 deg | | | | | 26 % |
| 180 deg | | | | | 25 % |
| Average | | | | | 19 % |

Table 24: Fuel Savings, irregular waves

8.6 Comparing regular and irregular waves

We have already mentioned that the results for irregular waves are better than for regular waves. Especially the potential fuel savings in stern quartering and following seas are much better.

We try to illustrate the difference in another table (Table 25), showing the relative increase in potential fuel savings in irregular waves compared to regular waves

| | Green | 20% | Yellow | 40% | Red |
|----------------|-------------|-------------|-------------|-------------|-------------|
| 10kt | | | | | |
| Head seas | 12 % | 14 % | 12 % | 17 % | |
| 45 deg | 26 % | 30 % | 21 % | 39 % | |
| 90 deg | 71 % | 77 % | 46 % | 129 % | |
| 135 deg | 90 % | 93 % | 96 % | 98 % | |
| 180 deg | 66 % | 73 % | 71 % | 80 % | |
| Average | 46 % | 50 % | 44 % | 58 % | |
| 12kt | | | | | |
| Head seas | | | | | 12 % |
| 45 deg | | | | | 40 % |
| 90 deg | | | | | 148 % |
| 135 deg | | | | | 99 % |
| 180 deg | | | | | 91 % |
| Average | | | | | 60 % |
| 15kt | | | | | |
| Head seas | -19 % | -13 % | -18 % | -8 % | |
| 45 deg | -9 % | 5 % | -8 % | 12 % | |
| 90 deg | 3 % | 34 % | 16 % | 59 % | |

| | | | | |
|------------------|------|------|------|-------|
| 135 deg | 86 % | 83 % | 82 % | 88 % |
| 180 deg | 54 % | 57 % | 54 % | 59 % |
| Average | 18 % | 27 % | 19 % | 33 % |
| 18kt | | | | |
| Head seas | | | | -24 % |
| 45 deg | | | | -17 % |
| 90 deg | | | | 4 % |
| 135 deg | | | | 75 % |
| 180 deg | | | | 35 % |
| Average | | | | 10 % |

Table 25: Relative difference between regular and irregular waves

To be clear: 15 % in this table means that the calculated fuel saving is 15 % larger in irregular waves than regular waves. The green values means that the results correspond very well (less than 20 % difference).

We notice that the largest difference is found in beam seas where our calculation in irregular waves gives approximately twice the fuel savings. The fuel savings are of course very small in beam seas for regular waves, so the absolute increase is not as large as one might get the impression of.

In stern quartering and following seas the increase is also very large compared to regular waves, especially for low velocities.

We must remember that our results from regular waves are combined results of all wave periods. The manner this was done in is does not necessarily compare to irregular waves. We have to look to the complete results in Appendix F: Fuel savings, regular waves, offshore supply vessel , Appendix H: Fuel Savings, Coastal tanker and Appendix L: Fuel Savings, purse seiner where the fuel savings are found separately for all wave periods.

9 Results of the structural analysis

For our calculations we will need to choose a wall thickness as well as a strut thickness. This can of course be changed if the strength of the structure proves to be insufficient or exaggerated. We chose a wall thickness of 30mm and a strut thickness of 100 mm. Standing alone one might argue that these values are very large, but we keep in mind that we have simplified the foil structure. If the foils are to be constructed, they would most certainly have a range of stiffeners, bracket plates, etc. to strengthen them.

The structural analysis is based on an angle of attack equal to 15 degrees. This gives the largest bending moment and will be a very conservative estimate as we do not expect this angle to be reached for every oscillation of the lift.

9.1 Double Stress amplitude

For each vessel we find the double stress amplitude for each foil and vessel velocity. The wave condition does not affect the results in our calculation method as we look at the “worst case scenario”, giving an angle of attack of 15 degrees.

The double stress amplitude for the offshore supply vessel, coastal tanker and purse seiner are shown in Figure 9-1, Figure 9-2 and Figure 9-3 respectively.

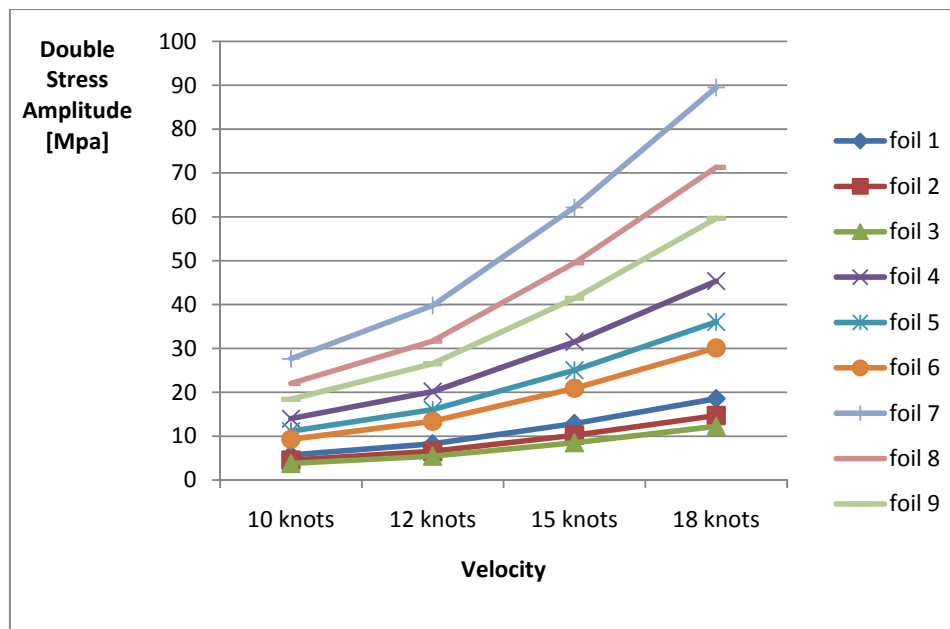


Figure 9-1: Double stress amplitude - Offshore Supply vessel

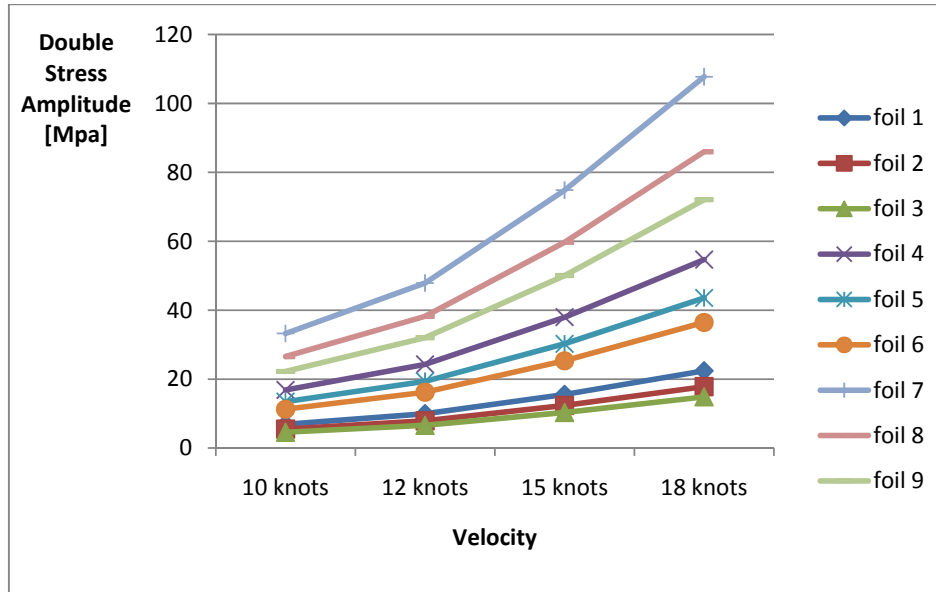


Figure 9-2: Double stress amplitude - Coastal Tanker

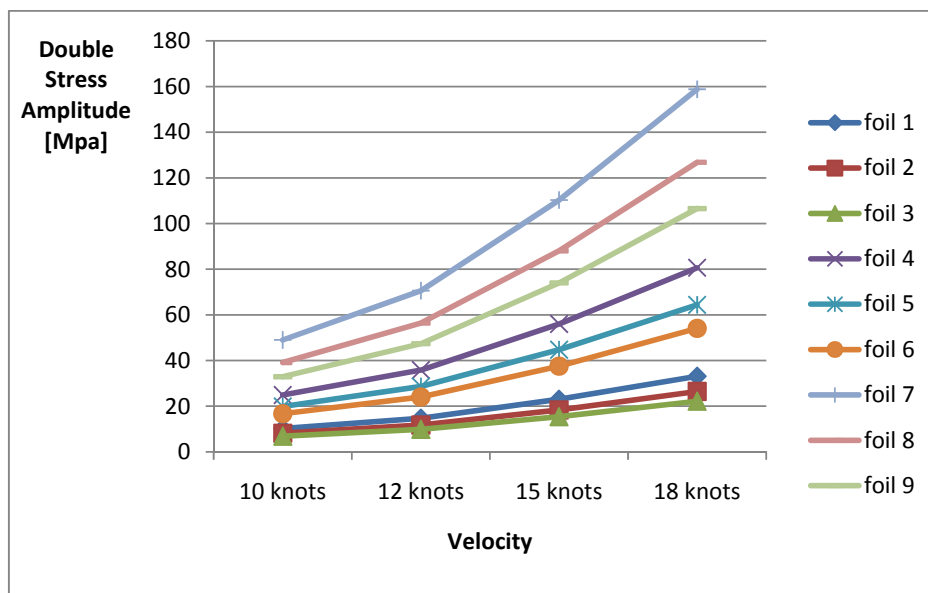


Figure 9-3: Double stress amplitude - Purse Seiner

As expected the stress increases with the velocity. The largest stresses are found from foil 7, 8 and 9, not surprisingly as they have an aspect ratio of 5. Foil 7 has the largest values because the area of this foil is the smallest. A small area gives a small foil thickness since the thickness of the foil is 15 % of the chord length, which again is proportional to the area. We know from Equation 3-50 and Equation 3-51 that the second moment of inertia is proportional to the square of the foil thickness. This means that even though the bending moment decreases with decreasing foil area, the double stress amplitude will increase.

9.2 Fatigue

Depending on the material of the foils, the results may be satisfying or worrying. We recall the S-N diagram from chapter 3.9:

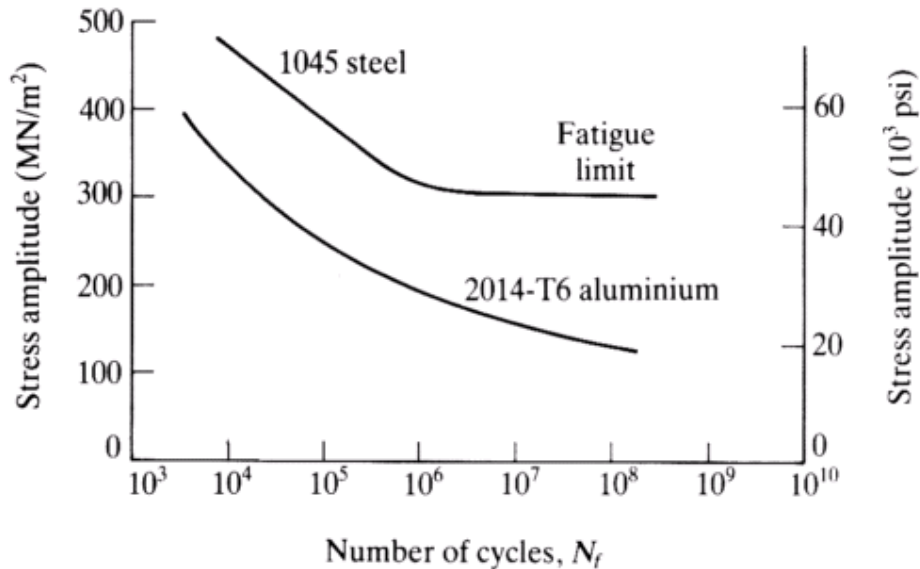


Figure 9-4: S-N diagram for Steel and Aluminium

We clearly see that if the foils are made of steel, there will be no problems with fatigue and the strut and wall thickness may be reduced to reduce weight and costs.

If the foils are made of aluminium we note that for the largest value in our result – foil 7 at 18 knots for the purse seiner – the number of cycles until fatigue will be approximately $5 \cdot 10^6$. We assume that the period is 8 seconds and convert the number to years.

$$\text{number of years} = \frac{5 \cdot 10^6 \text{ cycles} \cdot 8 \frac{\text{cycles}}{\text{second}}}{3600 \frac{\text{seconds}}{\text{hour}} \cdot 24 \frac{\text{hours}}{\text{day}} \cdot 365,25 \frac{\text{days}}{\text{year}}} = 1,27 \text{ years}$$

These estimates are of course very conservative. A vessel will obviously not be travelling continuously as it will spend time at the dock and in the calm seas in and around the harbour. Even when the vessel is sailing it will not produce the maximum double stress amplitude – which we have used in our calculation – during every oscillation. Still, just above one year is not an adequate results, and another foil configuration or material would be recommended. If we move to foil 8 – which gives the second largest value – the number of cycles until fatigue is increased to more at than $10^8 \text{ cycles} = 25,4 \text{ years}$. This result would probably be satisfying.

10 Conclusion

With regard to the different foil configurations. A large foil area and aspect ratio (span divided by chord length) produces the best potential fuel saving. If the aspect ratio is reduced by 20 % the potential is reduced by approximately 10 %. Reducing the area gives equivalent results.

The domination force will be the bending moment causing oscillating stress and fatigue at the root of the foil. If the area of the foil is decreased the foil thickness decreases and the structure becomes weaker. With an aspect ratio of 5 and foil area equal to 3 % of the water plane area, fatigue in the structure becomes an issue for the structural design in this thesis.

Considering regular waves the largest thrust forces are found when the wave length are close to the length of the vessel (L_{pp}). Keeping to regular waves, a vessel travelling in head seas has the largest potential benefit of a foil propeller followed by bow quartering seas. When we consider irregular waves the potential in stern quartering and following seas are at least equally promising to those in head seas. Beam seas generally give poor results, especially in regular waves.

The effect of unsteady lift is quite large and relates closely to the frequency of encounter. In head seas the loss in thrust force can be large, up to 50 % for the worst combinations of foil configuration, and wave condition and vessel velocity. Long wave periods reduces this effect significantly and in following seas the wave encounter frequency may approach zero – making the effect of unsteady lift very small. Flexible foil we estimate will a 13 % increase in the thrust force.

The added resistance in waves is not easy to predict, but we have found that wave periods close to those producing most thrust gives the largest values. This force changes when foils are mounted on the hull. A reduction in this force gives an increase in the net gained thrust from the foil propeller system. In head and bow quartering seas it proves to be quite significant, especially with regards to the coastal tanker and purse seiner. In irregular seas the effect is quite small.

Potential fuel savings up to around 50 % is found for regular waves in head seas. In beam seas the potential is very low, around 10 %. When studying the performance in irregular waves the fuel savings improves significantly – especially in stern quartering and following seas – and we get fuel saving peaking at more than 60 %. We must keep in mind that the results in regular waves are computed from a time-average of several wave periods. The variation with respect to wave period is often very large.

The thrust force increase with increasing speed, but the relative fuel savings decrease because the total required thrust for the vessel increase faster. For a vessel travelling at 10 or 12 knots the potential savings are quite similar and especially irregular waves gives good results at these velocities. When we increase the velocity to 15 knots the potential is reduced and 18 knots seems to be too fast for the foil propeller.

There must be a way to store the foils when they are not needed or simply in the way. We have proposed several ways to do this, but the common factor is that significant changes in the hull structures have to be made. The storing system will also take up large volumes inside the hull which would force a rearrangement of the interior. The combined cost of the rearrangement, the storing system and a system to actively control the foil pitch to optimize the thrust force may become large.

11 Further work

In continuing work on the foil propeller the author would recommend the following:

Do the calculations in irregular waves for the four foils already considered at a range of vessel velocities with a shorter interval and repeat the process for the purse seiner.

Consider more than five wave headings to be able to detect potential critical wave headings for the foil propeller.

Use elliptical or other non-rectangular shaped foils. In other areas where foils play a part (aviation etc.) one normally does not use rectangular foils, so there is reason to believe that the foil propeller would benefit from another configuration.

Increase the accuracy of the unsteady lift effects calculation, the author recommends to study (Faltinsen, 2005) chapter 6.11.2 - "2D flat foil oscillating harmonically in heave and pitch".

Evaluate the conventional propeller system closer because the thrust provided will not be constant. A system that is able to produce varying thrust with high quasi-propulsive efficiency is ideal. The author recommends a controllable pitch propeller.

Do a model test.

12 List of symbols and acronyms

12.1 Acronyms

| | |
|-------|--|
| 2D | Two dimensional |
| 3D | Three dimensional |
| AP | Aft Perpendicular |
| RAO | Response Amplitude Operator – response amplitude per unit wave |
| VERES | VEssel RESponses |

12.2 Symbols

| | |
|----------------------------------|---|
| α , Alpha | Angle of attack |
| β | Wave heading angle |
| ϵ | phase angle |
| ϕ_I | Wave potential to an incident wave |
| η_x | Motion in a selected degree of freedom |
| $\eta_{5,f}$ | Foil pitch |
| η_1 | Ship surge |
| η_2 | Ship sway |
| η_3 | Ship heave |
| η_4 | Ship roll |
| η_5 | Ship pitch |
| η_6 | Ship yaw |
| $\dot{\eta}_j$ | Velocity of motion of mode j , $\frac{\partial \eta_j}{\partial t}$ |
| λ | Wave length |
| ρ | Density |
| ω_0 | Frequency of incident wave |
| ω_ϵ | Frequency of encounter |
| ζ_a | Wave amplitude |
| Λ | Aspect ratio = s^2/S |
| C | Chord length |
| G | Gravitational acceleration |
| I | $\sqrt{-1}$ |
| K | Wave number, $k = \frac{2\pi}{\lambda}$ |
| S | Span |
| T | Time |
| (u_w, v_w, w_w) | Wave orbital velocity |
| (u_v, v_v, w_v) | Vessel velocities |
| (x, y, z) | Cartesian coordinates fixed to the ship |
| $(x_{R.C.}, y_{R.C.}, z_{R.C.})$ | Location of the centre of rotation relative to the ship centre of gravity |
| A_{WL} | Water line area |
| B | Ship breadth |
| C_D | Drag coefficient |
| C_L | Lift coefficient |
| D | Drag force |
| D | Ship depth |
| F | Total force |
| F_V | Vertical component of the total force on the foil propeller |
| L | Lift force |

| | |
|--------------------|--|
| L_{OA} | Length over all |
| L_{PP} | Length between perpendiculars |
| P_{REC} | Required propeller power |
| P_{FP} | Power from foil propeller |
| R_{PP} | Relative propulsive power coefficient |
| R_T | Total ship resistance |
| S | Projected area of foil, planform area, foil area |
| T_{FP} | Thrust force from the foil propeller |
| T_{NET} | Net gained thrust force |
| T_0 | Wave period |
| T | Thrust force |
| T | Ship draught |
| U_{REL}, V_{REL} | Relative velocities |
| U | Fluid in-flow velocity |
| U | Ship velocity |
| V | Incident flow |
| V_A | Velocity of advance |

13 Bibliography

- Aerospaceweb.org** <http://www.aerospaceweb.org/question/airfoils/q0041.shtml> [Online] // www.aerospaceweb.org. - 2010.
- Angvik Ingrid** Application of an active foil propeller on an offshore vessel [Report]. - 2009.
- Berg Aa.** Trials with passive foil propulsion on M/S "Kystfangst" [Report]. - [s.l.] : Fiskeriteknologisk Forskningsinstitutt, 1985.
- Bose N** Marine Powering Prediction and Propulsors [Book]. - 2008.
- Dybdahl K.** Foilpropellen kan revolusjonere skipsfarten [Journal]. - [s.l.] : Teknisk Ukeblad, 1988. - Vol. 135 No. 39.
- Faltinsen O. M.** Hydrodynamics of High-Speed Marine Vehicles [Book]. - [s.l.] : Cambridge University Press, 2005.
- Faltinsen O. M.** Sea Loads on Ships and Offshore Structures [Book]. - [s.l.] : Cambridge University Press, 1990.
- Fathi D.** ShipX Vessel Responses (VERES) - Ship motions and Global Loads - Users' Manual [Report]. - [s.l.] : MARINTEK report, 2005.
- Gerritsma J. and Beukelman W.** Analysis of the Resistance Increase in Waves of a Fast Cargo Ship [Report]. - 1971.
- Gustafson C.-G.** Compendium - TMM4100 Materialteknikk [Book]. - 2007. - Vol. I.
- Holtrop J. and Mennen G.G.J.** An approximate power prediction method International [Book]. - 1982.
- Isshiki H. and Murakami M.** A Theory of Wave Devouring Propulsion (4th report) - A Comparison between Theory and Experiment in Case of a Passive-Type Hydrofoil Propulsor [Journal]. - [s.l.] : Journal of the Society of Naval Architects of Japan, 1984.
- Isshiki H. and Murakami M.** Wave Power into Ship Propulsion [Journal]. - Lisbon : 5th Symposium and Exhibit on Offshore Mechanics and Arctic Engineering (OMAE), 1986a.
- Isshiki H.** Wave Energy Utilization into Ship Propulsion by Fins Attached to a Ship [Journal]. - Osaka, Japan : Proceedings of the 4th International Offshore and Polar Engineering Conference, 1994.
- Jakobsen E.** The Foilpropeller, Wave Power for Propulsion [Journal] // Second International Symposium on Wave & Tidal Energy. - 1981.
- Korbijn F.** Analysis of a foil propeller system on a vessel of 300m length sailing between Chile and Japan [Report]. - [s.l.] : Det Norske Veritas Report 89-0034, 1989.
- Minsaas K. J.** Naval Hydrodynamics - Foil Theory [Book]. - Trondheim : NTNU, 2006.
- MotorShip** Wave power for ship propulsion [Journal]. - [s.l.] : The Motor Ship, 1983.

Naito S. and Isshiki H. Effect of Bow Wings on Ship Propulsion and Motions [Journal]. - [s.l.] : Applied Mechanics Review, 2005. - Vol. 58.

NewYorkTimes A Self-Propelling Boat [Journal]. - [s.l.] : The New York Times, 1898.

Rolls-RoyceMarine Rolls-Royce Marine [Online]. - 14 September 2007. - 06 May 2009. - http://www.rolls-royce.com/Images/03.BrBr_2p_14.09.07_tcm92-8902.pdf.

Steen Knut Minsaas and Sverre Kompendium - TMR4220 Naval Hydrodynamics, Foil Theory [Book]. - 2008.

van Oossanen P. and van Oosterveld M.W.C. Hydrodynamic resistance characteristics of humans, dolphins and ships forms [Book]. - 1989. - Vol. 36.

Williams T. M. Nature [Book]. - et al. 1992.

Yamaguchi H. and Bose N. Oscillating Foils for Marine Propulsion [Journal]. - [s.l.] : Proceedings of the 4th International Offshore and Polar Engineering Conference in Japan, 1994.

Yamaguchi H. Hydrodynamic design of an oscillations foil propulsor [Book]. - 1992.

Appendices

Appendix A: Scatter diagram for North Sea and northern Atlantic

| WAVE CONDITIONS | | | | | | | | | | | |
|----------------------------|--------------|---------------------------------|-------------|-------------|-------------|-------------|-------------|--------------|--------------|--|--|
| Area 11 and 4 | | | | | | | | | | | |
| Annual | | | | | | | | | | | |
| | | CONSIDERED WAVE PERIODS | | | | | | | | | |
| 10,5 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | | |
| 9,5 | 0 | 0 | 0 | 1 | 2 | 1 | 1 | 1 | 0 | | |
| 8,5 | 0 | 0 | 0 | 2 | 3 | 4 | 2 | 1 | 1 | | |
| 7,5 | 0 | 0 | 1 | 4 | 7 | 7 | 6 | 2 | 1 | | |
| 6,5 | 0 | 0 | 3 | 9 | 16 | 15 | 10 | 4 | 1 | | |
| 5,5 | 0 | 1 | 5 | 14 | 19 | 17 | 10 | 4 | 1 | | |
| 4,5 | 0 | 2 | 13 | 33 | 42 | 32 | 17 | 7 | 2 | | |
| 3,5 | 0 | 6 | 35 | 75 | 84 | 55 | 24 | 8 | 2 | | |
| 2,5 | 1 | 19 | 87 | 150 | 132 | 68 | 23 | 6 | 1 | | |
| 1,5 | 3 | 55 | 173 | 201 | 118 | 41 | 10 | 2 | 0 | | |
| 0,5 | 20 | 100 | 129 | 71 | 21 | 5 | 0 | 0 | 0 | | |
| Hs/Tz | 3,5 | 4,5 | 5,5 | 6,5 | 7,5 | 8,5 | 9,5 | 10,5 | 11,5 | | |
| Average wave height | | 1,18 | 1,74 | 2,35 | 2,94 | 3,53 | 4,18 | 35 | 9 | | |
| average amplitude | | 0,59 | 0,87 | 1,17 | 1,47 | 1,76 | 2,09 | | | | |
| % of the time | 0,012 | 0,09 | 0,22 | 0,27 | 0,22 | 0,12 | 0,05 | 0,017 | 0,004 | | |
| | | sum | | | | | | | | | |
| | | 96,68 | | | | | | | | | |
| | | % of the time is covered | | | | | | | | | |

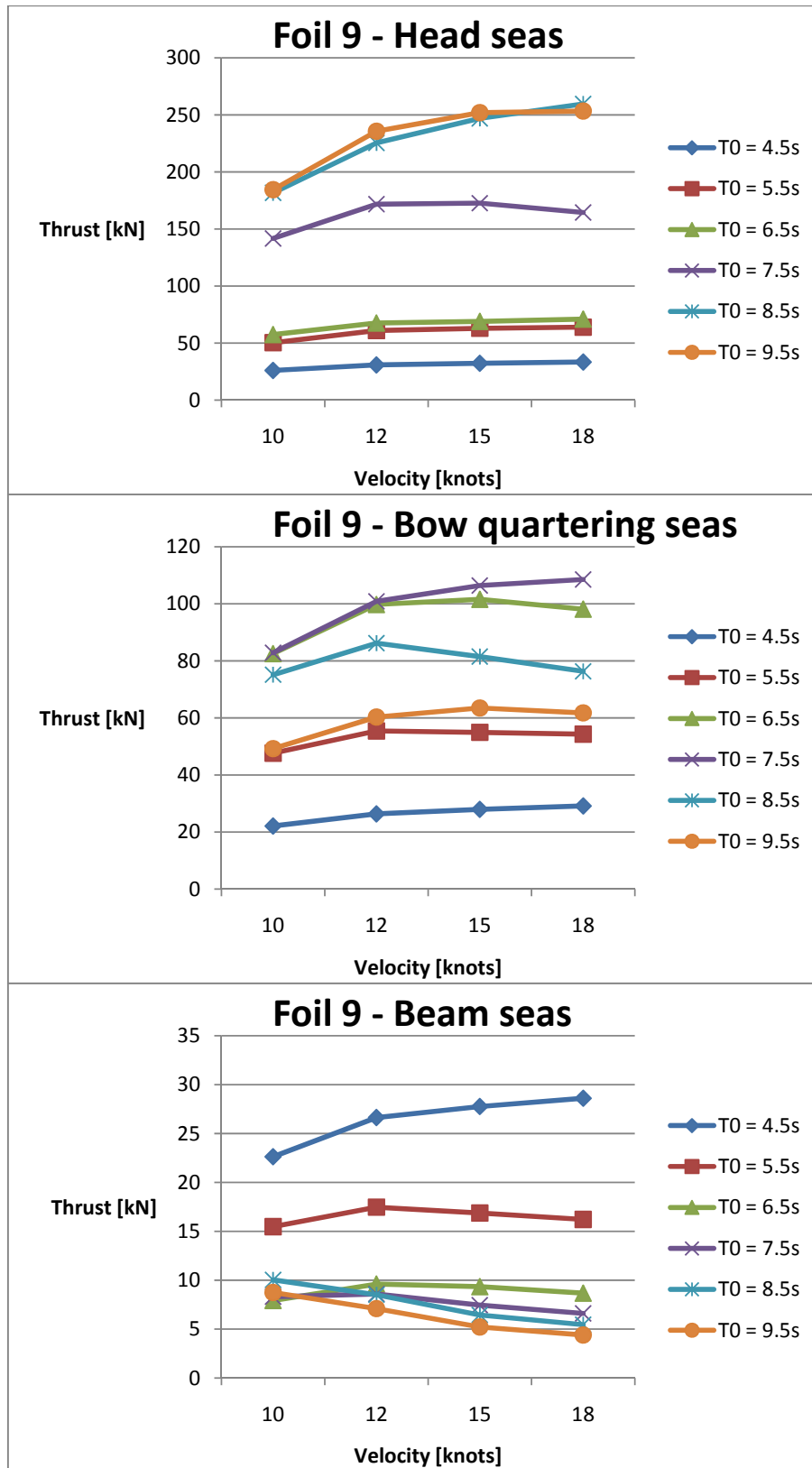
Most probable significant wave height:

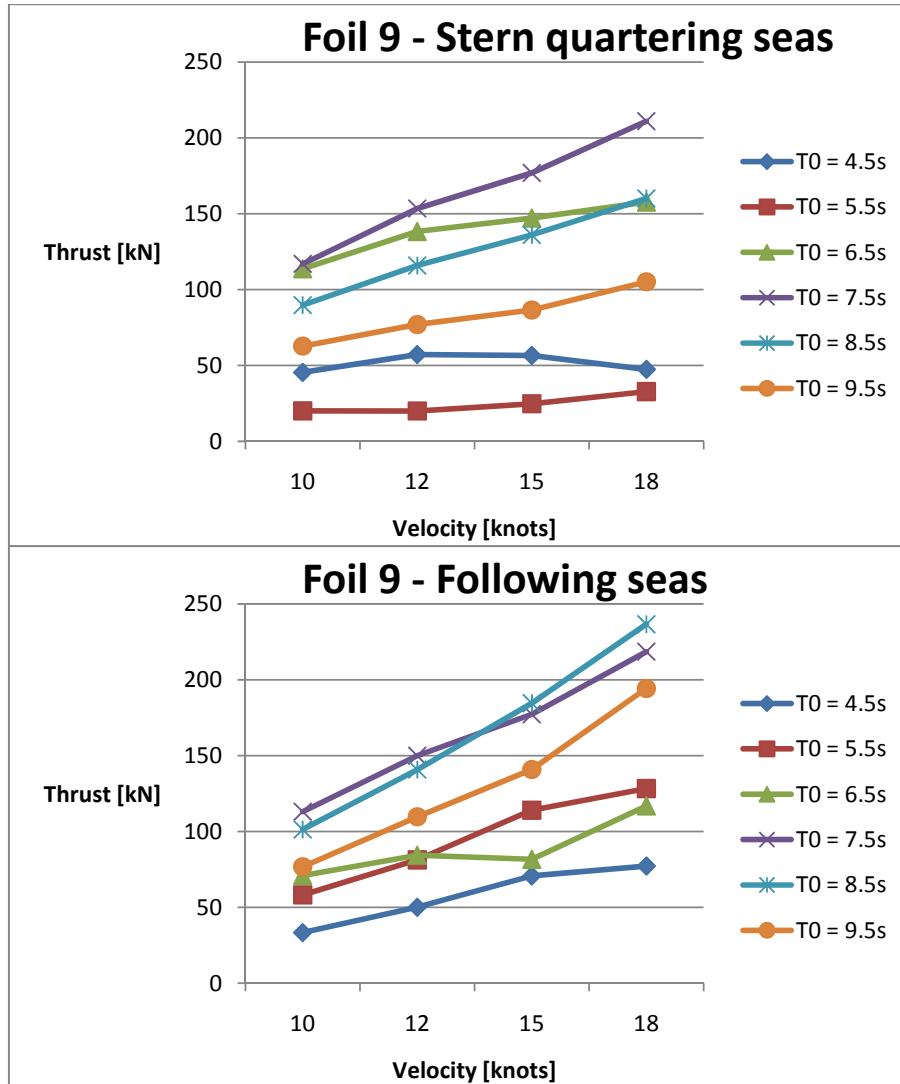
2,51 m

Most probable zero-crossing period:

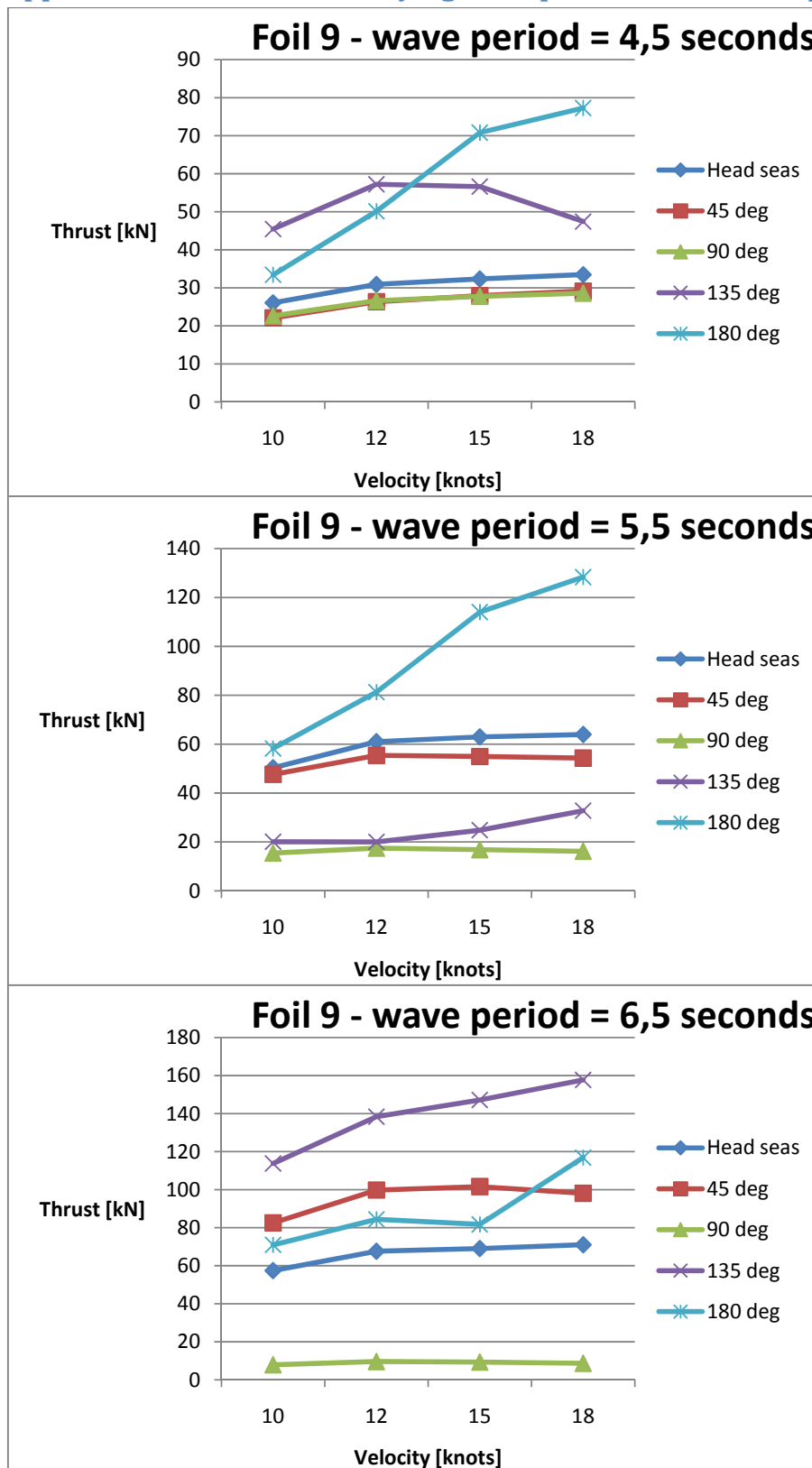
6,77 s

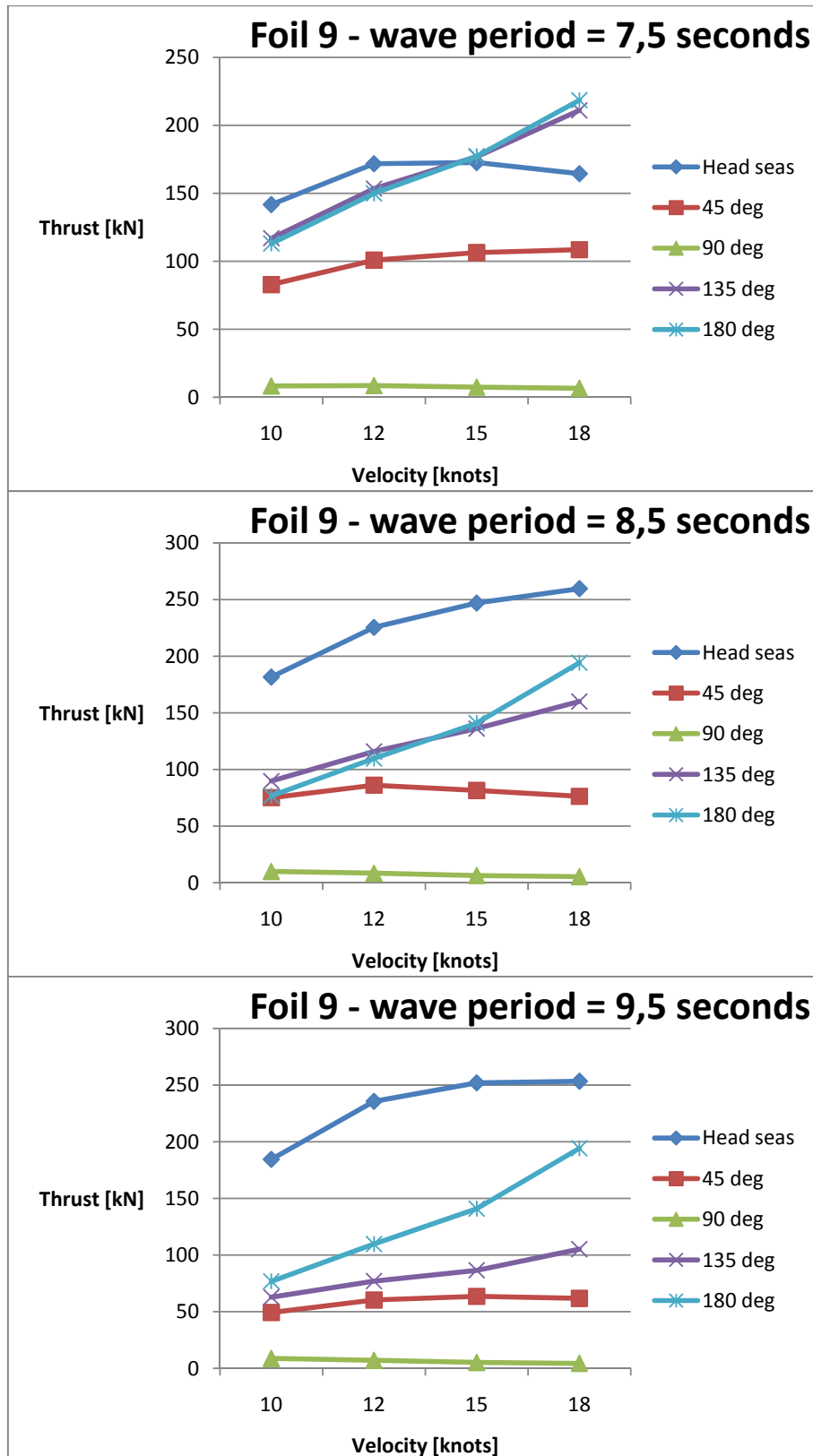
Appendix B: Thrust force, varying wave headings, offshore supply vessel



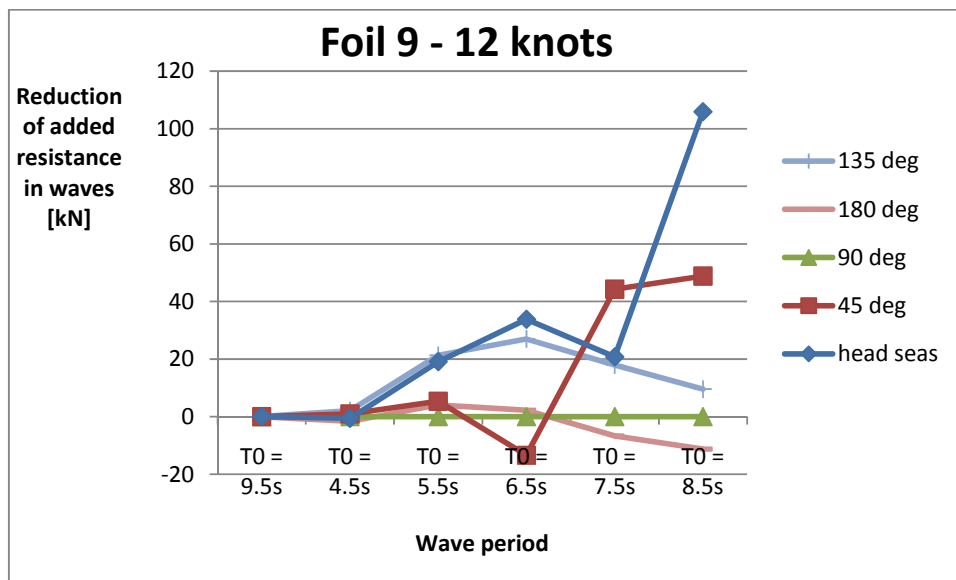
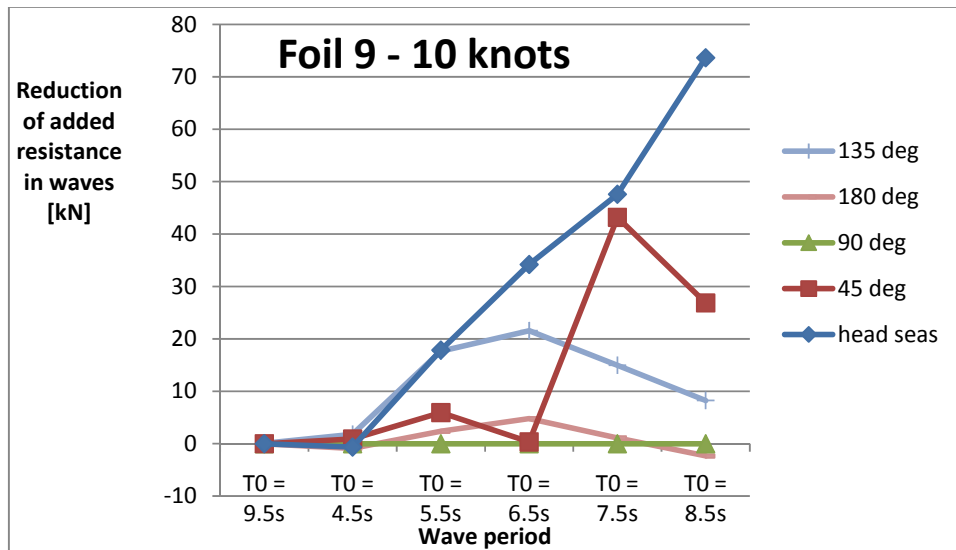


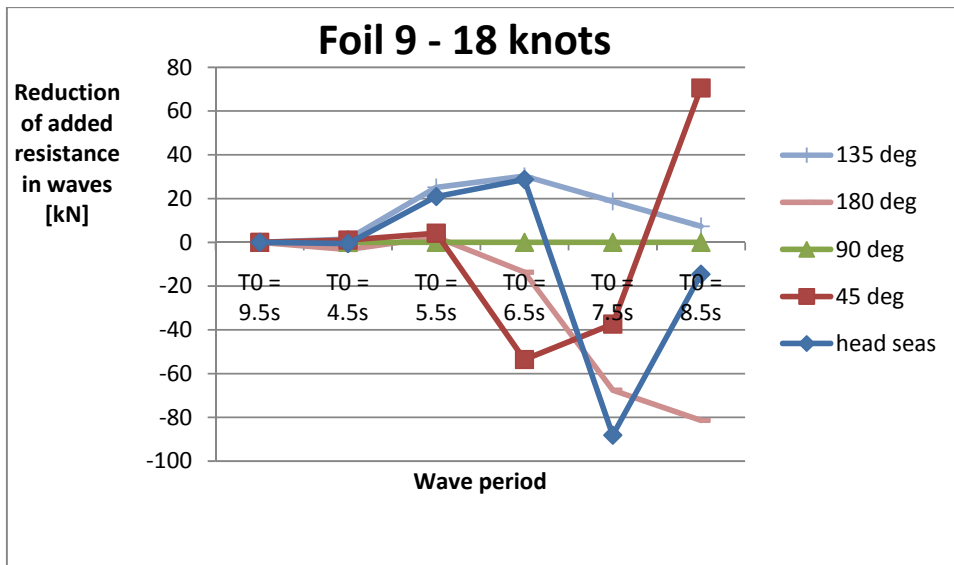
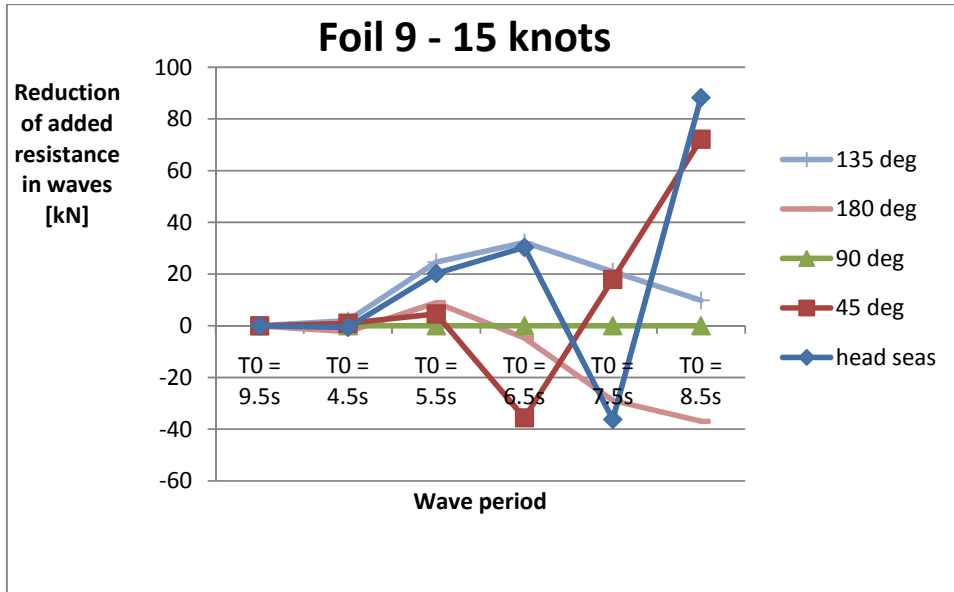
Appendix C: Thrust force, varying wave periods, offshore supply vessel





Appendix D: Reduction in added resistance, offshore supply vessel





Appendix E: Percentage of required thrust covered, offshore supply vessel, irregular waves

| | | Red | < | 15 % | < | Yellow | < | 30 % | < | Green | |
|------------------|---------------------------|------|------|------|------|--------|------|------|------|-------|--|
| 10kt | Percentage covered | | | | | | | | | | |
| | in N | | | | | | | | | | |
| Head seas | T0 = 4.5s | 6 % | 7 % | 9 % | 8 % | 10 % | 11 % | 10 % | 12 % | 15 % | |
| | T0 = 5.5s | 11 % | 14 % | 17 % | 15 % | 19 % | 22 % | 19 % | 23 % | 28 % | |
| | T0 = 6.5s | 19 % | 23 % | 26 % | 23 % | 29 % | 33 % | 28 % | 34 % | 40 % | |
| | T0 = 7.5s | 35 % | 42 % | 48 % | 41 % | 49 % | 56 % | 46 % | 56 % | 64 % | |
| | T0 = 8.5s | 57 % | 65 % | 69 % | 66 % | 75 % | 81 % | 74 % | 84 % | 92 % | |
| | T0 = 9.5s | 61 % | 71 % | 78 % | 70 % | 81 % | 90 % | 77 % | 89 % | 99 % | |
| 45 deg | T0 = 4.5s | 5 % | 6 % | 7 % | 6 % | 8 % | 9 % | 8 % | 10 % | 12 % | |
| | T0 = 5.5s | 10 % | 12 % | 14 % | 13 % | 16 % | 19 % | 16 % | 20 % | 23 % | |
| | T0 = 6.5s | 17 % | 21 % | 24 % | 20 % | 25 % | 29 % | 23 % | 28 % | 33 % | |
| | T0 = 7.5s | 16 % | 18 % | 19 % | 18 % | 20 % | 22 % | 21 % | 23 % | 25 % | |
| | T0 = 8.5s | 19 % | 21 % | 22 % | 22 % | 23 % | 25 % | 23 % | 25 % | 27 % | |
| | T0 = 9.5s | 13 % | 14 % | 15 % | 14 % | 15 % | 16 % | 14 % | 16 % | 18 % | |
| 90 deg | T0 = 4.5s | 5 % | 6 % | 7 % | 6 % | 8 % | 9 % | 8 % | 10 % | 12 % | |
| | T0 = 5.5s | 4 % | 5 % | 6 % | 5 % | 6 % | 7 % | 6 % | 7 % | 8 % | |
| | T0 = 6.5s | 1 % | 2 % | 3 % | 2 % | 3 % | 4 % | 3 % | 4 % | 4 % | |
| | T0 = 7.5s | 4 % | 4 % | 4 % | 6 % | 6 % | 4 % | 8 % | 6 % | 4 % | |
| | T0 = 8.5s | 15 % | 11 % | 8 % | 15 % | 10 % | 6 % | 15 % | 9 % | 5 % | |
| | T0 = 9.5s | 12 % | 10 % | 8 % | 12 % | 9 % | 6 % | 11 % | 7 % | 4 % | |
| 135 deg | T0 = 4.5s | 11 % | 14 % | 17 % | 14 % | 18 % | 22 % | 17 % | 22 % | 27 % | |
| | T0 = 5.5s | 7 % | 8 % | 9 % | 8 % | 9 % | 10 % | 9 % | 11 % | 12 % | |
| | T0 = 6.5s | 28 % | 34 % | 39 % | 31 % | 37 % | 42 % | 34 % | 40 % | 45 % | |
| | T0 = 7.5s | 24 % | 30 % | 34 % | 27 % | 32 % | 37 % | 30 % | 35 % | 39 % | |
| | T0 = 8.5s | 19 % | 23 % | 27 % | 21 % | 26 % | 30 % | 24 % | 29 % | 32 % | |
| | T0 = 9.5s | 13 % | 17 % | 20 % | 16 % | 20 % | 23 % | 18 % | 22 % | 25 % | |
| 180 deg | T0 = 4.5s | 8 % | 10 % | 13 % | 10 % | 13 % | 17 % | 12 % | 16 % | 21 % | |
| | T0 = 5.5s | 13 % | 18 % | 23 % | 17 % | 22 % | 28 % | 20 % | 27 % | 34 % | |
| | T0 = 6.5s | 15 % | 19 % | 24 % | 19 % | 24 % | 30 % | 23 % | 29 % | 35 % | |
| | T0 = 7.5s | 15 % | 20 % | 25 % | 18 % | 23 % | 29 % | 21 % | 27 % | 33 % | |
| | T0 = 8.5s | 11 % | 14 % | 18 % | 13 % | 17 % | 21 % | 15 % | 19 % | 24 % | |
| | T0 = 9.5s | 8 % | 10 % | 13 % | 9 % | 13 % | 16 % | 11 % | 15 % | 18 % | |

12kt

| | | <i>in N</i> | | | | | | | | |
|----------------|-----------|-------------|------|------|------|------|------|------|------|-------|
| <u>Head</u> | | | | | | | | | | |
| <u>seas</u> | T0 = 4.5s | 5 % | 6 % | 7 % | 6 % | 8 % | 9 % | 8 % | 10 % | 12 % |
| | T0 = 5.5s | 9 % | 12 % | 14 % | 12 % | 15 % | 18 % | 16 % | 20 % | 23 % |
| | T0 = 6.5s | 15 % | 19 % | 21 % | 19 % | 24 % | 28 % | 24 % | 29 % | 34 % |
| | T0 = 7.5s | 34 % | 41 % | 47 % | 40 % | 48 % | 56 % | 46 % | 56 % | 64 % |
| | T0 = 8.5s | 57 % | 64 % | 70 % | 66 % | 75 % | 82 % | 73 % | 84 % | 92 % |
| | T0 = 9.5s | 66 % | 75 % | 82 % | 74 % | 84 % | 92 % | 81 % | 92 % | 100 % |
| 45 deg | T0 = 4.5s | 4 % | 5 % | 6 % | 5 % | 7 % | 8 % | 7 % | 8 % | 10 % |
| | T0 = 5.5s | 8 % | 10 % | 12 % | 10 % | 13 % | 15 % | 13 % | 17 % | 20 % |
| | T0 = 6.5s | 16 % | 19 % | 22 % | 19 % | 23 % | 27 % | 22 % | 27 % | 31 % |
| | T0 = 7.5s | 15 % | 16 % | 17 % | 17 % | 19 % | 20 % | 19 % | 22 % | 23 % |
| | T0 = 8.5s | 20 % | 21 % | 22 % | 22 % | 24 % | 25 % | 24 % | 26 % | 27 % |
| | T0 = 9.5s | 15 % | 16 % | 17 % | 16 % | 18 % | 19 % | 18 % | 19 % | 21 % |
| 90 deg | T0 = 4.5s | 4 % | 5 % | 6 % | 5 % | 6 % | 8 % | 6 % | 8 % | 10 % |
| | T0 = 5.5s | 4 % | 5 % | 5 % | 5 % | 5 % | 6 % | 6 % | 6 % | 6 % |
| | T0 = 6.5s | 2 % | 3 % | 3 % | 3 % | 4 % | 4 % | 4 % | 4 % | 3 % |
| | T0 = 7.5s | 4 % | 4 % | 4 % | 5 % | 5 % | 4 % | 6 % | 5 % | 3 % |
| | T0 = 8.5s | 10 % | 7 % | 5 % | 10 % | 6 % | 4 % | 9 % | 5 % | 3 % |
| | T0 = 9.5s | 7 % | 6 % | 5 % | 7 % | 5 % | 3 % | 6 % | 4 % | 3 % |
| 135 deg | T0 = 4.5s | 11 % | 14 % | 16 % | 13 % | 17 % | 20 % | 16 % | 20 % | 24 % |
| | T0 = 5.5s | 5 % | 6 % | 6 % | 6 % | 7 % | 7 % | 7 % | 7 % | 8 % |
| | T0 = 6.5s | 25 % | 30 % | 34 % | 28 % | 33 % | 38 % | 31 % | 37 % | 41 % |
| | T0 = 7.5s | 23 % | 28 % | 33 % | 27 % | 32 % | 36 % | 30 % | 35 % | 39 % |
| | T0 = 8.5s | 18 % | 22 % | 25 % | 21 % | 25 % | 28 % | 23 % | 28 % | 31 % |
| | T0 = 9.5s | 12 % | 15 % | 18 % | 14 % | 18 % | 20 % | 17 % | 20 % | 23 % |
| 180 deg | T0 = 4.5s | 8 % | 10 % | 13 % | 10 % | 13 % | 17 % | 12 % | 17 % | 21 % |
| | T0 = 5.5s | 12 % | 16 % | 20 % | 15 % | 21 % | 26 % | 19 % | 26 % | 32 % |
| | T0 = 6.5s | 13 % | 16 % | 20 % | 16 % | 21 % | 25 % | 20 % | 25 % | 31 % |
| | T0 = 7.5s | 14 % | 19 % | 23 % | 18 % | 23 % | 28 % | 21 % | 27 % | 33 % |
| | T0 = 8.5s | 10 % | 14 % | 17 % | 12 % | 17 % | 21 % | 15 % | 20 % | 25 % |
| | T0 = 9.5s | 7 % | 10 % | 12 % | 9 % | 12 % | 16 % | 11 % | 15 % | 19 % |

15kt

| | | <i>in N</i> | | | | | | | | |
|----------------|------------------|-------------|------|------|------|------|------|------|------|------|
| <u>Head</u> | <u>seas</u> | | | | | | | | | |
| 45 deg | T0 = 4.5s | 3 % | 3 % | 4 % | 4 % | 5 % | 5 % | 5 % | 6 % | 7 % |
| | T0 = 5.5s | 5 % | 7 % | 8 % | 7 % | 9 % | 10 % | 9 % | 11 % | 14 % |
| | T0 = 6.5s | 9 % | 11 % | 13 % | 11 % | 14 % | 16 % | 14 % | 17 % | 20 % |
| | T0 = 7.5s | 21 % | 25 % | 29 % | 25 % | 31 % | 36 % | 30 % | 37 % | 42 % |
| | T0 = 8.5s | 34 % | 39 % | 42 % | 40 % | 47 % | 51 % | 46 % | 54 % | 59 % |
| | T0 = 9.5s | 51 % | 57 % | 60 % | 58 % | 64 % | 68 % | 63 % | 70 % | 74 % |
| 90 deg | T0 = 4.5s | 2 % | 3 % | 4 % | 3 % | 4 % | 5 % | 4 % | 5 % | 6 % |
| | T0 = 5.5s | 4 % | 6 % | 7 % | 6 % | 8 % | 9 % | 8 % | 10 % | 11 % |
| | T0 = 6.5s | 9 % | 12 % | 14 % | 12 % | 15 % | 17 % | 14 % | 18 % | 20 % |
| | T0 = 7.5s | 8 % | 9 % | 9 % | 10 % | 11 % | 11 % | 12 % | 13 % | 14 % |
| | T0 = 8.5s | 13 % | 13 % | 13 % | 15 % | 15 % | 15 % | 16 % | 16 % | 16 % |
| | T0 = 9.5s | 15 % | 15 % | 16 % | 16 % | 17 % | 17 % | 17 % | 18 % | 19 % |
| 135 deg | T0 = 4.5s | 2 % | 3 % | 3 % | 3 % | 4 % | 4 % | 4 % | 5 % | 6 % |
| | T0 = 5.5s | 2 % | 3 % | 3 % | 3 % | 3 % | 3 % | 3 % | 4 % | 3 % |
| | T0 = 6.5s | 1 % | 2 % | 2 % | 2 % | 2 % | 2 % | 3 % | 3 % | 2 % |
| | T0 = 7.5s | 2 % | 2 % | 2 % | 3 % | 3 % | 2 % | 3 % | 2 % | 2 % |
| | T0 = 8.5s | 4 % | 3 % | 2 % | 4 % | 3 % | 2 % | 3 % | 2 % | 1 % |
| | T0 = 9.5s | 3 % | 2 % | 2 % | 3 % | 2 % | 1 % | 3 % | 2 % | 1 % |
| 180 deg | T0 = 4.5s | 6 % | 7 % | 8 % | 7 % | 9 % | 11 % | 9 % | 11 % | 13 % |
| | T0 = 5.5s | 4 % | 4 % | 4 % | 4 % | 5 % | 5 % | 5 % | 5 % | 6 % |
| | T0 = 6.5s | 16 % | 19 % | 22 % | 19 % | 22 % | 25 % | 22 % | 25 % | 28 % |
| | T0 = 7.5s | 17 % | 20 % | 23 % | 20 % | 23 % | 26 % | 22 % | 26 % | 29 % |
| | T0 = 8.5s | 13 % | 16 % | 18 % | 15 % | 18 % | 21 % | 18 % | 21 % | 23 % |
| | T0 = 9.5s | 8 % | 10 % | 12 % | 10 % | 12 % | 14 % | 12 % | 14 % | 16 % |

18kt

| | | <i>in N</i> | | | | | | | | |
|----------------|------------------|-------------|------|------|------|------|------|------|------|------|
| <u>Head</u> | <u>seas</u> | | | | | | | | | |
| | T0 = 4.5s | 1 % | 2 % | 2 % | 2 % | 2 % | 3 % | 2 % | 3 % | 4 % |
| | T0 = 5.5s | 3 % | 3 % | 4 % | 3 % | 4 % | 5 % | 4 % | 5 % | 7 % |
| | T0 = 6.5s | 4 % | 5 % | 6 % | 5 % | 7 % | 8 % | 7 % | 8 % | 10 % |
| | T0 = 7.5s | 9 % | 11 % | 13 % | 12 % | 14 % | 17 % | 14 % | 17 % | 20 % |
| | T0 = 8.5s | 12 % | 13 % | 14 % | 15 % | 17 % | 18 % | 18 % | 20 % | 23 % |
| | T0 = 9.5s | 21 % | 23 % | 24 % | 24 % | 26 % | 27 % | 27 % | 30 % | 31 % |
| 45 deg | T0 = 4.5s | 1 % | 2 % | 2 % | 2 % | 2 % | 2 % | 2 % | 3 % | 3 % |
| | T0 = 5.5s | 2 % | 3 % | 3 % | 3 % | 4 % | 4 % | 4 % | 5 % | 6 % |
| | T0 = 6.5s | 5 % | 6 % | 7 % | 6 % | 7 % | 8 % | 7 % | 9 % | 10 % |
| | T0 = 7.5s | 3 % | 3 % | 3 % | 4 % | 4 % | 4 % | 5 % | 5 % | 6 % |
| | T0 = 8.5s | 4 % | 3 % | 3 % | 4 % | 4 % | 3 % | 5 % | 4 % | 4 % |
| | T0 = 9.5s | 9 % | 10 % | 10 % | 10 % | 10 % | 10 % | 10 % | 11 % | 11 % |
| 90 deg | T0 = 4.5s | 1 % | 1 % | 2 % | 1 % | 2 % | 2 % | 2 % | 2 % | 3 % |
| | T0 = 5.5s | 1 % | 1 % | 2 % | 2 % | 2 % | 2 % | 2 % | 2 % | 2 % |
| | T0 = 6.5s | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % |
| | T0 = 7.5s | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % |
| | T0 = 8.5s | 2 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % |
| | T0 = 9.5s | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 0 % |
| 135 deg | T0 = 4.5s | 2 % | 3 % | 3 % | 3 % | 3 % | 4 % | 3 % | 4 % | 5 % |
| | T0 = 5.5s | 2 % | 2 % | 3 % | 2 % | 3 % | 3 % | 3 % | 3 % | 4 % |
| | T0 = 6.5s | 9 % | 10 % | 12 % | 11 % | 12 % | 14 % | 12 % | 14 % | 16 % |
| | T0 = 7.5s | 10 % | 12 % | 14 % | 12 % | 15 % | 16 % | 14 % | 17 % | 19 % |
| | T0 = 8.5s | 7 % | 9 % | 11 % | 9 % | 11 % | 13 % | 11 % | 13 % | 14 % |
| | T0 = 9.5s | 5 % | 6 % | 7 % | 6 % | 7 % | 8 % | 7 % | 9 % | 10 % |
| 180 deg | T0 = 4.5s | 3 % | 4 % | 5 % | 4 % | 5 % | 7 % | 5 % | 7 % | 8 % |
| | T0 = 5.5s | 4 % | 6 % | 7 % | 6 % | 8 % | 10 % | 7 % | 10 % | 13 % |
| | T0 = 6.5s | 4 % | 6 % | 7 % | 6 % | 8 % | 10 % | 7 % | 10 % | 12 % |
| | T0 = 7.5s | 5 % | 7 % | 9 % | 7 % | 10 % | 13 % | 9 % | 13 % | 16 % |
| | T0 = 8.5s | 2 % | 4 % | 6 % | 4 % | 6 % | 9 % | 5 % | 9 % | 12 % |
| | T0 = 9.5s | 0 % | 1 % | 3 % | 1 % | 3 % | 6 % | 3 % | 6 % | 8 % |

Appendix F: Fuel savings, regular waves, offshore supply vessel

| | | Red | < | 15 % | < | Yellow | < | 30 % | < | Green |
|------------------|-----------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 10kt | Percentage covered <i>in N</i> | Foil 1 | Foil 2 | Foil 3 | Foil 4 | Foil 5 | Foil 6 | Foil 7 | Foil 8 | Foil 9 |
| Head seas | T0 = 4.5s | 20 % | 21 % | 22 % | 21 % | 23 % | 24 % | 23 % | 25 % | 27 % |
| | T0 = 5.5s | 24 % | 27 % | 29 % | 27 % | 31 % | 33 % | 31 % | 35 % | 38 % |
| | T0 = 6.5s | 31 % | 34 % | 37 % | 35 % | 39 % | 43 % | 39 % | 44 % | 49 % |
| | T0 = 7.5s | 45 % | 51 % | 55 % | 50 % | 57 % | 63 % | 54 % | 63 % | 70 % |
| | T0 = 8.5s | 63 % | 70 % | 74 % | 71 % | 79 % | 84 % | 78 % | 87 % | 93 % |
| | T0 = 9.5s | 67 % | 75 % | 81 % | 74 % | 84 % | 91 % | 80 % | 91 % | 99 % |
| 45 deg | T0 = 4.5s | 17 % | 18 % | 19 % | 18 % | 19 % | 21 % | 19 % | 21 % | 23 % |
| | T0 = 5.5s | 21 % | 23 % | 25 % | 24 % | 26 % | 29 % | 26 % | 30 % | 33 % |
| | T0 = 6.5s | 28 % | 31 % | 34 % | 30 % | 34 % | 38 % | 33 % | 37 % | 41 % |
| | T0 = 7.5s | 26 % | 28 % | 29 % | 29 % | 30 % | 32 % | 31 % | 33 % | 34 % |
| | T0 = 8.5s | 29 % | 31 % | 32 % | 31 % | 33 % | 34 % | 33 % | 35 % | 36 % |
| | T0 = 9.5s | 24 % | 25 % | 26 % | 24 % | 25 % | 27 % | 25 % | 26 % | 28 % |
| 90 deg | T0 = 4.5s | 12 % | 13 % | 14 % | 13 % | 14 % | 16 % | 14 % | 16 % | 19 % |
| | T0 = 5.5s | 11 % | 12 % | 13 % | 12 % | 13 % | 14 % | 13 % | 14 % | 14 % |
| | T0 = 6.5s | 9 % | 9 % | 10 % | 9 % | 10 % | 11 % | 10 % | 11 % | 11 % |
| | T0 = 7.5s | 11 % | 11 % | 11 % | 13 % | 13 % | 11 % | 15 % | 13 % | 11 % |
| | T0 = 8.5s | 22 % | 18 % | 14 % | 21 % | 17 % | 13 % | 21 % | 15 % | 12 % |
| | T0 = 9.5s | 19 % | 17 % | 15 % | 18 % | 15 % | 13 % | 17 % | 14 % | 11 % |
| 135 deg | T0 = 4.5s | 14 % | 17 % | 20 % | 17 % | 21 % | 24 % | 20 % | 25 % | 30 % |
| | T0 = 5.5s | 10 % | 11 % | 12 % | 11 % | 12 % | 13 % | 13 % | 14 % | 15 % |
| | T0 = 6.5s | 31 % | 36 % | 41 % | 34 % | 39 % | 44 % | 36 % | 42 % | 47 % |
| | T0 = 7.5s | 27 % | 32 % | 36 % | 30 % | 35 % | 39 % | 32 % | 37 % | 41 % |
| | T0 = 8.5s | 21 % | 26 % | 30 % | 24 % | 29 % | 32 % | 27 % | 31 % | 34 % |
| | T0 = 9.5s | 16 % | 20 % | 23 % | 19 % | 22 % | 25 % | 21 % | 25 % | 28 % |
| 180 deg | T0 = 4.5s | 14 % | 17 % | 20 % | 17 % | 20 % | 23 % | 19 % | 23 % | 27 % |
| | T0 = 5.5s | 19 % | 24 % | 28 % | 23 % | 28 % | 34 % | 26 % | 32 % | 39 % |
| | T0 = 6.5s | 21 % | 25 % | 29 % | 25 % | 30 % | 35 % | 28 % | 34 % | 40 % |
| | T0 = 7.5s | 22 % | 26 % | 30 % | 24 % | 29 % | 34 % | 27 % | 32 % | 38 % |
| | T0 = 8.5s | 17 % | 21 % | 24 % | 19 % | 23 % | 27 % | 21 % | 25 % | 29 % |
| | T0 = 9.5s | 14 % | 17 % | 20 % | 16 % | 19 % | 22 % | 18 % | 21 % | 24 % |

12kt

| | | <i>in N</i> | | | | | | | | |
|------------------|------------------|-------------|------|------|------|------|------|------|------|-------|
| Head seas | T0 = 4.5s | 19 % | 20 % | 21 % | 20 % | 21 % | 23 % | 22 % | 23 % | 25 % |
| | T0 = 5.5s | 23 % | 25 % | 26 % | 25 % | 28 % | 30 % | 28 % | 32 % | 35 % |
| | T0 = 6.5s | 28 % | 31 % | 33 % | 31 % | 35 % | 38 % | 35 % | 40 % | 44 % |
| | T0 = 7.5s | 43 % | 50 % | 54 % | 49 % | 56 % | 62 % | 54 % | 62 % | 69 % |
| | T0 = 8.5s | 63 % | 70 % | 74 % | 71 % | 79 % | 84 % | 77 % | 87 % | 93 % |
| | T0 = 9.5s | 71 % | 79 % | 84 % | 78 % | 87 % | 93 % | 84 % | 93 % | 100 % |
| 45 deg | T0 = 4.5s | 16 % | 17 % | 18 % | 17 % | 18 % | 19 % | 18 % | 20 % | 21 % |
| | T0 = 5.5s | 19 % | 21 % | 23 % | 22 % | 24 % | 26 % | 24 % | 27 % | 30 % |
| | T0 = 6.5s | 26 % | 29 % | 32 % | 29 % | 33 % | 36 % | 32 % | 36 % | 40 % |
| | T0 = 7.5s | 25 % | 27 % | 27 % | 28 % | 29 % | 30 % | 30 % | 31 % | 33 % |
| | T0 = 8.5s | 30 % | 31 % | 32 % | 32 % | 33 % | 34 % | 34 % | 35 % | 36 % |
| | T0 = 9.5s | 26 % | 27 % | 27 % | 27 % | 28 % | 29 % | 28 % | 29 % | 31 % |
| 90 deg | T0 = 4.5s | 11 % | 12 % | 13 % | 12 % | 13 % | 14 % | 13 % | 15 % | 17 % |
| | T0 = 5.5s | 11 % | 12 % | 12 % | 12 % | 12 % | 13 % | 12 % | 13 % | 13 % |
| | T0 = 6.5s | 9 % | 10 % | 10 % | 10 % | 11 % | 11 % | 11 % | 11 % | 10 % |
| | T0 = 7.5s | 11 % | 11 % | 11 % | 12 % | 12 % | 11 % | 13 % | 12 % | 10 % |
| | T0 = 8.5s | 17 % | 14 % | 12 % | 16 % | 13 % | 11 % | 15 % | 12 % | 10 % |
| | T0 = 9.5s | 14 % | 13 % | 12 % | 14 % | 12 % | 10 % | 13 % | 11 % | 10 % |
| 135 deg | T0 = 4.5s | 14 % | 17 % | 19 % | 16 % | 20 % | 22 % | 19 % | 23 % | 26 % |
| | T0 = 5.5s | 8 % | 9 % | 9 % | 9 % | 10 % | 10 % | 10 % | 11 % | 12 % |
| | T0 = 6.5s | 27 % | 32 % | 36 % | 31 % | 36 % | 40 % | 34 % | 39 % | 43 % |
| | T0 = 7.5s | 26 % | 31 % | 35 % | 29 % | 34 % | 38 % | 32 % | 37 % | 41 % |
| | T0 = 8.5s | 20 % | 24 % | 28 % | 23 % | 28 % | 31 % | 26 % | 30 % | 33 % |
| | T0 = 9.5s | 15 % | 18 % | 20 % | 17 % | 21 % | 23 % | 20 % | 23 % | 25 % |
| 180 deg | T0 = 4.5s | 15 % | 17 % | 20 % | 17 % | 20 % | 23 % | 19 % | 23 % | 27 % |
| | T0 = 5.5s | 18 % | 22 % | 26 % | 22 % | 27 % | 32 % | 25 % | 31 % | 37 % |
| | T0 = 6.5s | 19 % | 22 % | 26 % | 22 % | 27 % | 31 % | 26 % | 31 % | 36 % |
| | T0 = 7.5s | 21 % | 25 % | 29 % | 24 % | 29 % | 34 % | 27 % | 33 % | 38 % |
| | T0 = 8.5s | 17 % | 20 % | 23 % | 19 % | 23 % | 27 % | 21 % | 26 % | 30 % |
| | T0 = 9.5s | 14 % | 16 % | 19 % | 16 % | 19 % | 22 % | 18 % | 21 % | 25 % |

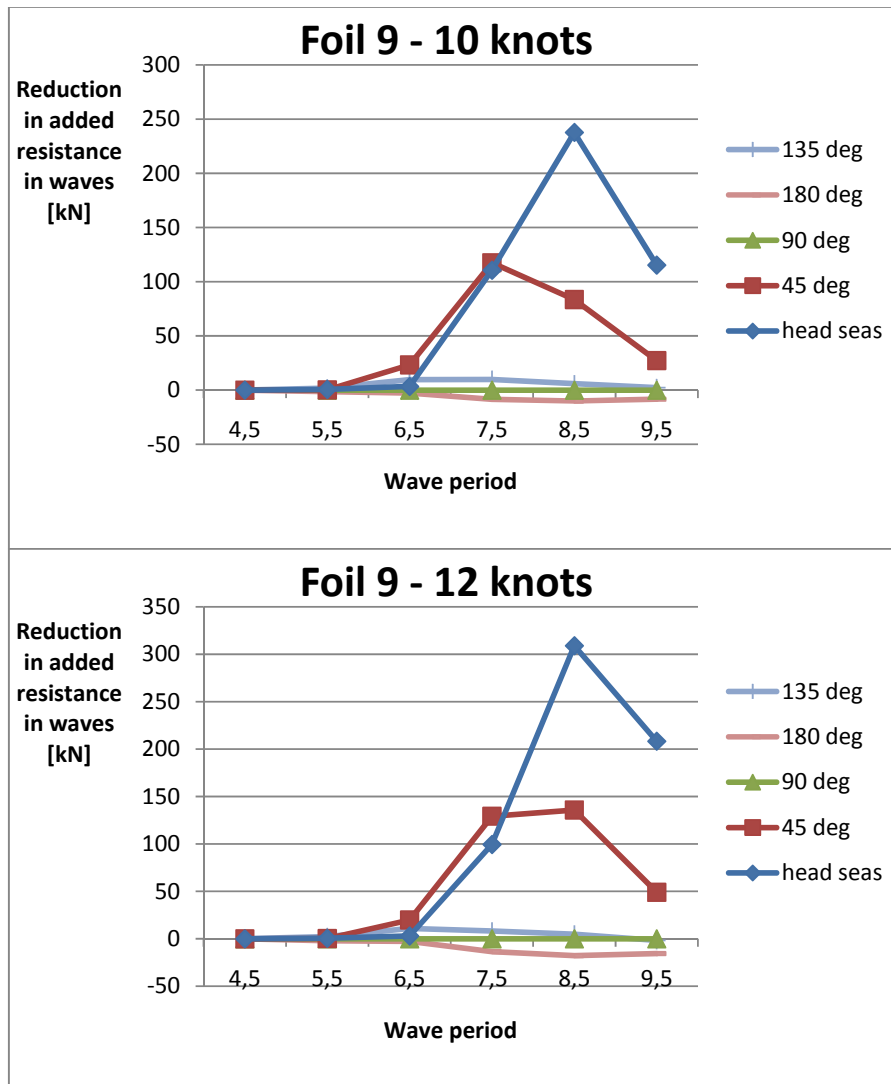
15kt

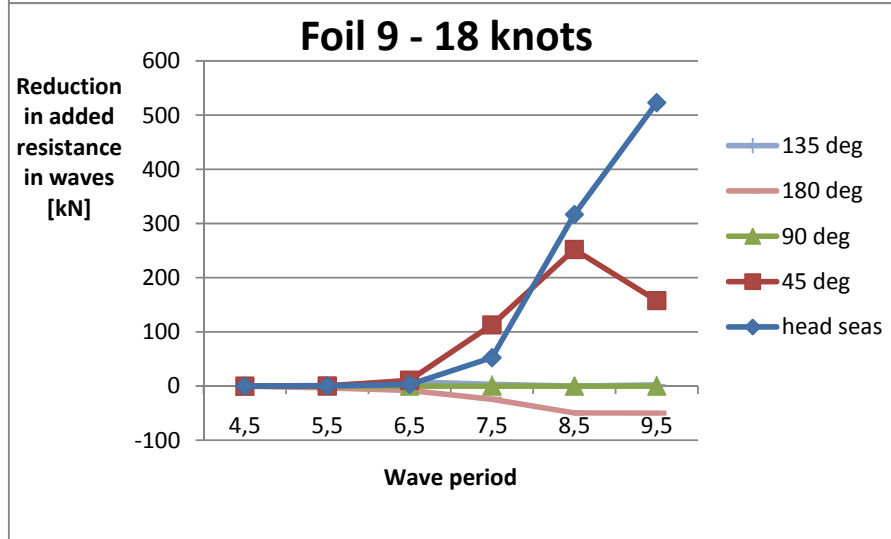
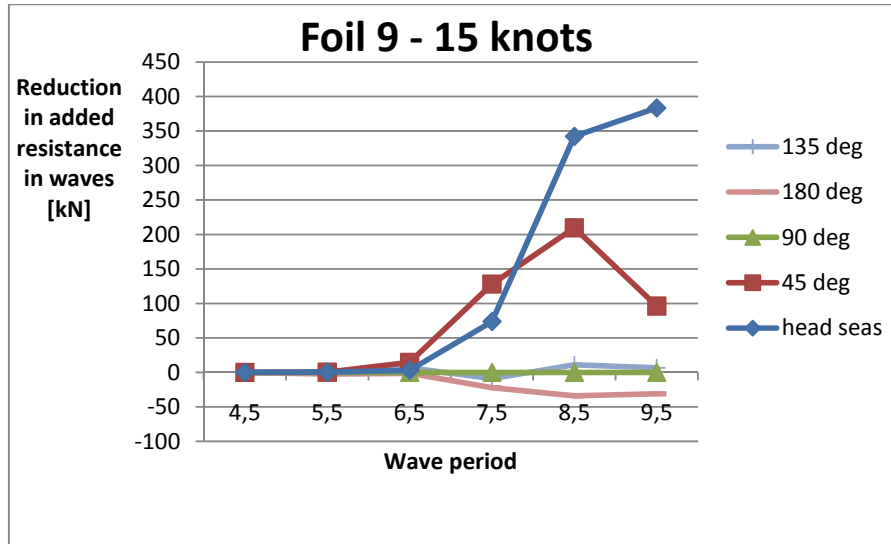
| | | <i>in N</i> | | | | | | | | |
|------------------|------------------|-------------|------|------|------|------|------|------|------|------|
| Head seas | T0 = 4.5s | 17 % | 18 % | 18 % | 18 % | 19 % | 19 % | 19 % | 20 % | 21 % |
| | T0 = 5.5s | 19 % | 20 % | 21 % | 21 % | 22 % | 24 % | 22 % | 24 % | 26 % |
| | T0 = 6.5s | 22 % | 24 % | 25 % | 24 % | 27 % | 28 % | 26 % | 29 % | 32 % |
| | T0 = 7.5s | 32 % | 36 % | 39 % | 36 % | 41 % | 45 % | 40 % | 46 % | 51 % |
| | T0 = 8.5s | 44 % | 48 % | 51 % | 49 % | 54 % | 58 % | 54 % | 60 % | 65 % |
| | T0 = 9.5s | 58 % | 63 % | 66 % | 64 % | 69 % | 73 % | 68 % | 74 % | 78 % |
| 45 deg | T0 = 4.5s | 15 % | 15 % | 16 % | 15 % | 16 % | 17 % | 16 % | 17 % | 18 % |
| | T0 = 5.5s | 16 % | 18 % | 18 % | 18 % | 19 % | 20 % | 19 % | 21 % | 23 % |
| | T0 = 6.5s | 21 % | 23 % | 24 % | 23 % | 25 % | 27 % | 25 % | 28 % | 30 % |
| | T0 = 7.5s | 20 % | 20 % | 20 % | 21 % | 22 % | 23 % | 23 % | 24 % | 25 % |
| | T0 = 8.5s | 24 % | 24 % | 24 % | 25 % | 26 % | 26 % | 27 % | 27 % | 27 % |
| | T0 = 9.5s | 25 % | 26 % | 26 % | 26 % | 27 % | 28 % | 27 % | 28 % | 29 % |
| 90 deg | T0 = 4.5s | 9 % | 10 % | 10 % | 10 % | 11 % | 11 % | 11 % | 12 % | 13 % |
| | T0 = 5.5s | 9 % | 10 % | 10 % | 10 % | 10 % | 10 % | 10 % | 11 % | 10 % |
| | T0 = 6.5s | 9 % | 9 % | 9 % | 9 % | 10 % | 9 % | 10 % | 10 % | 9 % |
| | T0 = 7.5s | 10 % | 10 % | 9 % | 10 % | 10 % | 9 % | 10 % | 9 % | 9 % |
| | T0 = 8.5s | 11 % | 10 % | 9 % | 11 % | 10 % | 9 % | 11 % | 9 % | 9 % |
| | T0 = 9.5s | 10 % | 10 % | 9 % | 10 % | 9 % | 9 % | 10 % | 9 % | 8 % |
| 135 deg | T0 = 4.5s | 9 % | 10 % | 12 % | 10 % | 12 % | 14 % | 12 % | 14 % | 16 % |
| | T0 = 5.5s | 7 % | 7 % | 8 % | 7 % | 8 % | 8 % | 8 % | 9 % | 9 % |
| | T0 = 6.5s | 19 % | 22 % | 24 % | 22 % | 25 % | 27 % | 24 % | 28 % | 30 % |
| | T0 = 7.5s | 20 % | 23 % | 26 % | 22 % | 26 % | 29 % | 25 % | 29 % | 32 % |
| | T0 = 8.5s | 16 % | 18 % | 21 % | 18 % | 21 % | 23 % | 20 % | 24 % | 26 % |
| | T0 = 9.5s | 11 % | 13 % | 15 % | 13 % | 15 % | 17 % | 15 % | 17 % | 19 % |
| 180 deg | T0 = 4.5s | 13 % | 15 % | 16 % | 14 % | 17 % | 19 % | 16 % | 19 % | 23 % |
| | T0 = 5.5s | 15 % | 18 % | 21 % | 18 % | 22 % | 26 % | 21 % | 26 % | 31 % |
| | T0 = 6.5s | 15 % | 16 % | 18 % | 16 % | 19 % | 21 % | 18 % | 21 % | 24 % |
| | T0 = 7.5s | 16 % | 19 % | 22 % | 19 % | 23 % | 26 % | 21 % | 26 % | 30 % |
| | T0 = 8.5s | 13 % | 16 % | 18 % | 15 % | 19 % | 22 % | 17 % | 21 % | 25 % |
| | T0 = 9.5s | 10 % | 12 % | 14 % | 12 % | 14 % | 17 % | 13 % | 17 % | 20 % |

18kt

| | | <i>in N</i> | | | | | | | | |
|-------------------------|------------------|-------------|------|------|------|------|------|------|------|------|
| <u>Head seas</u> | T0 = 4.5s | 16 % | 16 % | 16 % | 16 % | 17 % | 17 % | 17 % | 17 % | 18 % |
| | T0 = 5.5s | 17 % | 17 % | 18 % | 18 % | 18 % | 19 % | 18 % | 19 % | 20 % |
| | T0 = 6.5s | 18 % | 19 % | 20 % | 19 % | 20 % | 21 % | 20 % | 22 % | 23 % |
| | T0 = 7.5s | 23 % | 24 % | 26 % | 25 % | 27 % | 29 % | 27 % | 30 % | 32 % |
| | T0 = 8.5s | 25 % | 26 % | 27 % | 27 % | 29 % | 30 % | 30 % | 32 % | 34 % |
| | T0 = 9.5s | 33 % | 34 % | 35 % | 36 % | 37 % | 38 % | 38 % | 40 % | 41 % |
| <u>45 deg</u> | T0 = 4.5s | 14 % | 14 % | 14 % | 14 % | 14 % | 15 % | 14 % | 15 % | 15 % |
| | T0 = 5.5s | 14 % | 15 % | 15 % | 15 % | 16 % | 16 % | 16 % | 17 % | 17 % |
| | T0 = 6.5s | 17 % | 18 % | 18 % | 18 % | 19 % | 20 % | 19 % | 20 % | 21 % |
| | T0 = 7.5s | 15 % | 15 % | 15 % | 16 % | 16 % | 16 % | 17 % | 17 % | 18 % |
| | T0 = 8.5s | 16 % | 15 % | 15 % | 16 % | 16 % | 15 % | 17 % | 16 % | 16 % |
| | T0 = 9.5s | 21 % | 21 % | 21 % | 21 % | 21 % | 22 % | 22 % | 22 % | 22 % |
| <u>90 deg</u> | T0 = 4.5s | 8 % | 9 % | 9 % | 9 % | 9 % | 9 % | 9 % | 9 % | 10 % |
| | T0 = 5.5s | 8 % | 9 % | 9 % | 9 % | 9 % | 9 % | 9 % | 9 % | 9 % |
| | T0 = 6.5s | 8 % | 8 % | 8 % | 8 % | 8 % | 8 % | 9 % | 8 % | 8 % |
| | T0 = 7.5s | 8 % | 8 % | 8 % | 9 % | 8 % | 8 % | 9 % | 8 % | 8 % |
| | T0 = 8.5s | 9 % | 8 % | 8 % | 9 % | 8 % | 8 % | 8 % | 8 % | 8 % |
| | T0 = 9.5s | 8 % | 8 % | 8 % | 8 % | 8 % | 8 % | 8 % | 8 % | 8 % |
| <u>135 deg</u> | T0 = 4.5s | 5 % | 6 % | 6 % | 6 % | 7 % | 7 % | 7 % | 7 % | 8 % |
| | T0 = 5.5s | 5 % | 6 % | 6 % | 6 % | 6 % | 6 % | 6 % | 6 % | 7 % |
| | T0 = 6.5s | 12 % | 14 % | 15 % | 14 % | 15 % | 17 % | 15 % | 17 % | 19 % |
| | T0 = 7.5s | 13 % | 15 % | 17 % | 15 % | 18 % | 19 % | 17 % | 19 % | 21 % |
| | T0 = 8.5s | 11 % | 12 % | 14 % | 12 % | 14 % | 16 % | 14 % | 16 % | 17 % |
| | T0 = 9.5s | 8 % | 9 % | 10 % | 9 % | 11 % | 12 % | 10 % | 12 % | 13 % |
| <u>180 deg</u> | T0 = 4.5s | 10 % | 11 % | 12 % | 11 % | 12 % | 14 % | 12 % | 14 % | 15 % |
| | T0 = 5.5s | 11 % | 13 % | 14 % | 13 % | 15 % | 17 % | 14 % | 17 % | 20 % |
| | T0 = 6.5s | 11 % | 13 % | 14 % | 13 % | 14 % | 16 % | 14 % | 16 % | 19 % |
| | T0 = 7.5s | 12 % | 14 % | 16 % | 14 % | 17 % | 19 % | 16 % | 19 % | 22 % |
| | T0 = 8.5s | 9 % | 11 % | 13 % | 11 % | 13 % | 16 % | 12 % | 16 % | 19 % |
| | T0 = 9.5s | 7 % | 9 % | 10 % | 9 % | 11 % | 13 % | 10 % | 13 % | 15 % |

Appendix G: Reduction in added resistance, coastal tanker





Appendix H: Fuel Savings, Coastal tanker

| | | Red | < | 15 % | < | Yellow | < | 30 % | < | Green |
|----------------|-------------|--------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| | | Percentage covered | | | | | | | | |
| | | Foil 1 | Foil 2 | Foil 3 | Foil 4 | Foil 5 | Foil 6 | Foil 7 | Foil 8 | Foil 9 |
| 10kt | Head | | | | | | | | | |
| | seas | | | | | | | | | |
| | T0 = 4.5s | 25 % | 27 % | 29 % | 28 % | 30 % | 32 % | 30 % | 33 % | 36 % |
| | T0 = 5.5s | 31 % | 34 % | 36 % | 34 % | 38 % | 41 % | 37 % | 42 % | 47 % |
| | T0 = 6.5s | 32 % | 35 % | 37 % | 35 % | 39 % | 42 % | 39 % | 44 % | 47 % |
| | T0 = 7.5s | 52 % | 59 % | 64 % | 56 % | 63 % | 69 % | 59 % | 67 % | 73 % |
| 45 deg | T0 = 8.5s | 56 % | 62 % | 67 % | 60 % | 67 % | 72 % | 63 % | 70 % | 75 % |
| | T0 = 9.5s | 48 % | 55 % | 60 % | 53 % | 59 % | 65 % | 56 % | 63 % | 69 % |
| | T0 = 4.5s | 23 % | 25 % | 26 % | 25 % | 27 % | 28 % | 27 % | 29 % | 31 % |
| | T0 = 5.5s | 26 % | 28 % | 30 % | 29 % | 32 % | 34 % | 31 % | 35 % | 38 % |
| | T0 = 6.5s | 34 % | 37 % | 40 % | 35 % | 39 % | 42 % | 37 % | 42 % | 45 % |
| | T0 = 7.5s | 38 % | 41 % | 43 % | 40 % | 43 % | 45 % | 41 % | 44 % | 47 % |
| 90 deg | T0 = 8.5s | 33 % | 35 % | 37 % | 34 % | 37 % | 39 % | 36 % | 38 % | 40 % |
| | T0 = 9.5s | 25 % | 27 % | 28 % | 27 % | 28 % | 29 % | 28 % | 29 % | 30 % |
| | T0 = 4.5s | 17 % | 19 % | 20 % | 19 % | 21 % | 24 % | 21 % | 24 % | 28 % |
| | T0 = 5.5s | 14 % | 15 % | 15 % | 14 % | 15 % | 16 % | 15 % | 17 % | 18 % |
| | T0 = 6.5s | 13 % | 13 % | 13 % | 14 % | 14 % | 14 % | 15 % | 16 % | 16 % |
| | T0 = 7.5s | 15 % | 16 % | 16 % | 17 % | 17 % | 17 % | 18 % | 19 % | 18 % |
| 135 deg | T0 = 8.5s | 16 % | 17 % | 17 % | 18 % | 19 % | 18 % | 20 % | 20 % | 19 % |
| | T0 = 9.5s | 17 % | 18 % | 18 % | 19 % | 19 % | 18 % | 21 % | 20 % | 18 % |
| | T0 = 4.5s | 19 % | 21 % | 23 % | 22 % | 24 % | 26 % | 24 % | 26 % | 30 % |
| | T0 = 5.5s | 30 % | 36 % | 39 % | 36 % | 42 % | 43 % | 41 % | 46 % | 46 % |
| | T0 = 6.5s | 31 % | 37 % | 42 % | 35 % | 42 % | 47 % | 39 % | 46 % | 50 % |
| | T0 = 7.5s | 23 % | 26 % | 29 % | 25 % | 29 % | 32 % | 28 % | 31 % | 35 % |
| 180 deg | T0 = 8.5s | 17 % | 18 % | 20 % | 18 % | 19 % | 21 % | 19 % | 21 % | 24 % |
| | T0 = 9.5s | 12 % | 12 % | 13 % | 12 % | 12 % | 14 % | 12 % | 14 % | 16 % |
| | T0 = 4.5s | 20 % | 23 % | 26 % | 23 % | 27 % | 31 % | 26 % | 32 % | 37 % |
| | T0 = 5.5s | 22 % | 26 % | 31 % | 26 % | 31 % | 37 % | 30 % | 36 % | 43 % |
| | T0 = 6.5s | 24 % | 29 % | 34 % | 28 % | 34 % | 41 % | 32 % | 40 % | 47 % |
| | T0 = 7.5s | 19 % | 23 % | 28 % | 22 % | 27 % | 32 % | 25 % | 30 % | 36 % |
| | T0 = 8.5s | 16 % | 19 % | 22 % | 18 % | 21 % | 25 % | 20 % | 24 % | 28 % |
| | T0 = 9.5s | 14 % | 16 % | 19 % | 16 % | 19 % | 22 % | 18 % | 21 % | 25 % |

12kt

| <u>Head</u> | | | | | | | | | | |
|-----------------------|-----------|------|------|------|------|------|------|------|------|------|
| <u>seas</u> | T0 = 4.5s | 24 % | 26 % | 27 % | 26 % | 28 % | 29 % | 28 % | 30 % | 33 % |
| | T0 = 5.5s | 28 % | 31 % | 33 % | 31 % | 35 % | 38 % | 34 % | 39 % | 43 % |
| | T0 = 6.5s | 30 % | 32 % | 34 % | 33 % | 36 % | 39 % | 36 % | 41 % | 44 % |
| | T0 = 7.5s | 51 % | 58 % | 63 % | 55 % | 63 % | 69 % | 59 % | 67 % | 74 % |
| | T0 = 8.5s | 59 % | 65 % | 70 % | 62 % | 69 % | 74 % | 66 % | 72 % | 78 % |
| | T0 = 9.5s | 54 % | 60 % | 66 % | 58 % | 65 % | 70 % | 62 % | 69 % | 74 % |
| <u>45 deg</u> | T0 = 4.5s | 22 % | 23 % | 24 % | 24 % | 25 % | 26 % | 25 % | 27 % | 29 % |
| | T0 = 5.5s | 25 % | 26 % | 28 % | 27 % | 29 % | 31 % | 29 % | 33 % | 35 % |
| | T0 = 6.5s | 33 % | 36 % | 39 % | 35 % | 39 % | 42 % | 37 % | 42 % | 45 % |
| | T0 = 7.5s | 39 % | 42 % | 45 % | 41 % | 44 % | 47 % | 42 % | 46 % | 49 % |
| | T0 = 8.5s | 37 % | 39 % | 41 % | 39 % | 41 % | 43 % | 40 % | 43 % | 45 % |
| | T0 = 9.5s | 28 % | 29 % | 30 % | 29 % | 31 % | 32 % | 30 % | 32 % | 33 % |
| <u>90 deg</u> | T0 = 4.5s | 17 % | 18 % | 19 % | 18 % | 20 % | 22 % | 20 % | 22 % | 25 % |
| | T0 = 5.5s | 14 % | 15 % | 15 % | 14 % | 16 % | 16 % | 15 % | 17 % | 18 % |
| | T0 = 6.5s | 13 % | 13 % | 14 % | 14 % | 14 % | 15 % | 15 % | 15 % | 15 % |
| | T0 = 7.5s | 14 % | 15 % | 15 % | 15 % | 16 % | 16 % | 17 % | 17 % | 16 % |
| | T0 = 8.5s | 15 % | 16 % | 16 % | 16 % | 17 % | 16 % | 18 % | 17 % | 16 % |
| | T0 = 9.5s | 16 % | 16 % | 16 % | 17 % | 17 % | 16 % | 18 % | 17 % | 16 % |
| <u>135 deg</u> | T0 = 4.5s | 13 % | 14 % | 16 % | 14 % | 16 % | 20 % | 15 % | 19 % | 25 % |
| | T0 = 5.5s | 27 % | 29 % | 28 % | 31 % | 31 % | 29 % | 33 % | 32 % | 29 % |
| | T0 = 6.5s | 29 % | 33 % | 37 % | 33 % | 37 % | 40 % | 36 % | 40 % | 44 % |
| | T0 = 7.5s | 20 % | 22 % | 25 % | 22 % | 25 % | 28 % | 24 % | 28 % | 32 % |
| | T0 = 8.5s | 13 % | 15 % | 17 % | 15 % | 17 % | 20 % | 16 % | 19 % | 23 % |
| | T0 = 9.5s | 8 % | 9 % | 11 % | 8 % | 10 % | 13 % | 9 % | 12 % | 15 % |
| <u>180 deg</u> | T0 = 4.5s | 18 % | 21 % | 24 % | 21 % | 25 % | 29 % | 24 % | 29 % | 33 % |
| | T0 = 5.5s | 21 % | 25 % | 29 % | 24 % | 29 % | 35 % | 28 % | 35 % | 41 % |
| | T0 = 6.5s | 22 % | 26 % | 31 % | 26 % | 32 % | 37 % | 30 % | 37 % | 44 % |
| | T0 = 7.5s | 19 % | 23 % | 27 % | 22 % | 27 % | 32 % | 25 % | 31 % | 37 % |
| | T0 = 8.5s | 15 % | 18 % | 21 % | 17 % | 22 % | 26 % | 20 % | 25 % | 29 % |
| | T0 = 9.5s | 13 % | 16 % | 19 % | 15 % | 19 % | 22 % | 18 % | 22 % | 26 % |

15kt

Head
seas

| | | | | | | | | | | |
|--|------------------|------|------|------|------|------|------|------|------|------|
| <u>Head</u> <u>seas</u> | T0 = 4.5s | 22 % | 23 % | 23 % | 23 % | 24 % | 25 % | 24 % | 25 % | 27 % |
| | T0 = 5.5s | 24 % | 26 % | 27 % | 26 % | 28 % | 29 % | 28 % | 30 % | 32 % |
| | T0 = 6.5s | 25 % | 27 % | 28 % | 27 % | 29 % | 31 % | 29 % | 32 % | 34 % |
| | T0 = 7.5s | 41 % | 46 % | 50 % | 45 % | 50 % | 55 % | 48 % | 55 % | 59 % |
| | T0 = 8.5s | 55 % | 60 % | 65 % | 58 % | 64 % | 69 % | 61 % | 67 % | 72 % |
| | T0 = 9.5s | 56 % | 61 % | 65 % | 59 % | 64 % | 68 % | 62 % | 67 % | 71 % |
| <u>45 deg</u> | T0 = 4.5s | 20 % | 21 % | 22 % | 21 % | 22 % | 23 % | 22 % | 23 % | 24 % |
| | T0 = 5.5s | 22 % | 23 % | 24 % | 23 % | 24 % | 26 % | 24 % | 26 % | 28 % |
| | T0 = 6.5s | 27 % | 29 % | 31 % | 29 % | 32 % | 34 % | 31 % | 35 % | 37 % |
| | T0 = 7.5s | 36 % | 39 % | 41 % | 38 % | 41 % | 43 % | 39 % | 43 % | 45 % |
| | T0 = 8.5s | 38 % | 41 % | 42 % | 40 % | 42 % | 44 % | 42 % | 44 % | 45 % |
| | T0 = 9.5s | 30 % | 31 % | 32 % | 31 % | 32 % | 34 % | 32 % | 33 % | 35 % |
| <u>90 deg</u> | T0 = 4.5s | 15 % | 16 % | 16 % | 16 % | 17 % | 18 % | 17 % | 18 % | 20 % |
| | T0 = 5.5s | 14 % | 14 % | 15 % | 14 % | 15 % | 15 % | 15 % | 16 % | 16 % |
| | T0 = 6.5s | 13 % | 13 % | 14 % | 13 % | 14 % | 14 % | 14 % | 14 % | 14 % |
| | T0 = 7.5s | 14 % | 14 % | 14 % | 14 % | 14 % | 14 % | 15 % | 15 % | 14 % |
| | T0 = 8.5s | 14 % | 14 % | 14 % | 14 % | 14 % | 14 % | 15 % | 15 % | 14 % |
| | T0 = 9.5s | 14 % | 14 % | 14 % | 15 % | 14 % | 14 % | 15 % | 14 % | 14 % |
| <u>135 deg</u> | T0 = 4.5s | 13 % | 14 % | 16 % | 15 % | 16 % | 18 % | 16 % | 18 % | 20 % |
| | T0 = 5.5s | 11 % | 12 % | 12 % | 12 % | 12 % | 13 % | 13 % | 13 % | 14 % |
| | T0 = 6.5s | 19 % | 21 % | 22 % | 21 % | 23 % | 25 % | 23 % | 26 % | 28 % |
| | T0 = 7.5s | 12 % | 14 % | 16 % | 14 % | 16 % | 19 % | 16 % | 19 % | 22 % |
| | T0 = 8.5s | 13 % | 15 % | 16 % | 14 % | 16 % | 18 % | 16 % | 18 % | 21 % |
| | T0 = 9.5s | 11 % | 12 % | 13 % | 12 % | 13 % | 15 % | 13 % | 14 % | 16 % |
| <u>180 deg</u> | T0 = 4.5s | 15 % | 17 % | 19 % | 17 % | 19 % | 22 % | 19 % | 22 % | 25 % |
| | T0 = 5.5s | 18 % | 21 % | 24 % | 21 % | 25 % | 29 % | 24 % | 29 % | 34 % |
| | T0 = 6.5s | 17 % | 20 % | 23 % | 20 % | 23 % | 27 % | 23 % | 27 % | 31 % |
| | T0 = 7.5s | 15 % | 18 % | 21 % | 18 % | 22 % | 26 % | 21 % | 25 % | 30 % |
| | T0 = 8.5s | 12 % | 15 % | 18 % | 14 % | 18 % | 22 % | 17 % | 21 % | 25 % |
| | T0 = 9.5s | 10 % | 13 % | 15 % | 12 % | 15 % | 18 % | 14 % | 18 % | 21 % |

18kt

| Head seas | | | | | | | | | | |
|------------------|------------------|------|------|------|------|------|------|------|------|------|
| Head seas | T0 = 4.5s | 20 % | 21 % | 21 % | 21 % | 21 % | 22 % | 21 % | 22 % | 23 % |
| | T0 = 5.5s | 21 % | 22 % | 23 % | 22 % | 23 % | 24 % | 23 % | 25 % | 26 % |
| | T0 = 6.5s | 22 % | 23 % | 24 % | 23 % | 24 % | 25 % | 24 % | 26 % | 27 % |
| | T0 = 7.5s | 30 % | 33 % | 35 % | 33 % | 36 % | 38 % | 35 % | 38 % | 41 % |
| | T0 = 8.5s | 46 % | 50 % | 53 % | 48 % | 53 % | 57 % | 51 % | 56 % | 59 % |
| | T0 = 9.5s | 51 % | 55 % | 57 % | 54 % | 57 % | 60 % | 56 % | 60 % | 62 % |
| 45 deg | T0 = 4.5s | 19 % | 19 % | 20 % | 19 % | 20 % | 20 % | 20 % | 21 % | 21 % |
| | T0 = 5.5s | 20 % | 20 % | 21 % | 20 % | 21 % | 22 % | 21 % | 22 % | 23 % |
| | T0 = 6.5s | 23 % | 24 % | 25 % | 24 % | 25 % | 27 % | 25 % | 27 % | 29 % |
| | T0 = 7.5s | 30 % | 32 % | 34 % | 32 % | 34 % | 35 % | 33 % | 35 % | 37 % |
| | T0 = 8.5s | 35 % | 37 % | 38 % | 36 % | 38 % | 39 % | 37 % | 39 % | 41 % |
| | T0 = 9.5s | 30 % | 31 % | 32 % | 31 % | 32 % | 33 % | 32 % | 33 % | 34 % |
| 90 deg | T0 = 4.5s | 14 % | 14 % | 15 % | 14 % | 15 % | 15 % | 15 % | 16 % | 16 % |
| | T0 = 5.5s | 13 % | 14 % | 14 % | 14 % | 14 % | 14 % | 14 % | 14 % | 15 % |
| | T0 = 6.5s | 13 % | 13 % | 13 % | 13 % | 13 % | 14 % | 13 % | 14 % | 14 % |
| | T0 = 7.5s | 13 % | 13 % | 13 % | 13 % | 13 % | 13 % | 14 % | 14 % | 13 % |
| | T0 = 8.5s | 13 % | 13 % | 13 % | 13 % | 13 % | 13 % | 14 % | 13 % | 13 % |
| | T0 = 9.5s | 13 % | 13 % | 13 % | 13 % | 13 % | 13 % | 13 % | 13 % | 13 % |
| 135 deg | T0 = 4.5s | 10 % | 11 % | 12 % | 11 % | 12 % | 13 % | 12 % | 13 % | 15 % |
| | T0 = 5.5s | 9 % | 10 % | 10 % | 10 % | 10 % | 10 % | 10 % | 10 % | 11 % |
| | T0 = 6.5s | 14 % | 15 % | 16 % | 15 % | 16 % | 18 % | 16 % | 18 % | 19 % |
| | T0 = 7.5s | 13 % | 14 % | 15 % | 14 % | 16 % | 17 % | 15 % | 17 % | 19 % |
| | T0 = 8.5s | 11 % | 12 % | 13 % | 12 % | 13 % | 14 % | 12 % | 14 % | 15 % |
| | T0 = 9.5s | 10 % | 11 % | 11 % | 10 % | 11 % | 12 % | 11 % | 12 % | 13 % |
| 180 deg | T0 = 4.5s | 13 % | 14 % | 14 % | 13 % | 15 % | 16 % | 14 % | 16 % | 17 % |
| | T0 = 5.5s | 14 % | 16 % | 18 % | 16 % | 18 % | 20 % | 17 % | 20 % | 23 % |
| | T0 = 6.5s | 14 % | 16 % | 18 % | 16 % | 19 % | 22 % | 18 % | 21 % | 25 % |
| | T0 = 7.5s | 14 % | 16 % | 18 % | 16 % | 19 % | 22 % | 18 % | 21 % | 25 % |
| | T0 = 8.5s | 11 % | 13 % | 15 % | 12 % | 15 % | 18 % | 14 % | 18 % | 21 % |
| | T0 = 9.5s | 9 % | 11 % | 13 % | 11 % | 13 % | 15 % | 13 % | 15 % | 18 % |

12kt

| | | <i>in N</i> | | | | | | | | |
|------------------|------------------|-------------|------|------|------|------|------|------|------|------|
| <u>Head seas</u> | | | | | | | | | | |
| | T0 = 4.5s | 7 % | 8 % | 10 % | 9 % | 11 % | 13 % | 11 % | 14 % | 17 % |
| | T0 = 5.5s | 12 % | 15 % | 18 % | 15 % | 19 % | 23 % | 19 % | 25 % | 29 % |
| | T0 = 6.5s | 13 % | 16 % | 19 % | 18 % | 22 % | 25 % | 22 % | 27 % | 31 % |
| | T0 = 7.5s | 40 % | 48 % | 54 % | 45 % | 54 % | 61 % | 50 % | 60 % | 68 % |
| | T0 = 8.5s | 49 % | 57 % | 63 % | 54 % | 62 % | 68 % | 58 % | 66 % | 73 % |
| | T0 = 9.5s | 44 % | 51 % | 58 % | 49 % | 57 % | 63 % | 53 % | 61 % | 68 % |
| 45 deg | T0 = 4.5s | 5 % | 7 % | 8 % | 7 % | 9 % | 11 % | 9 % | 11 % | 14 % |
| | T0 = 5.5s | 8 % | 11 % | 13 % | 11 % | 14 % | 17 % | 14 % | 18 % | 21 % |
| | T0 = 6.5s | 18 % | 22 % | 25 % | 21 % | 25 % | 29 % | 24 % | 29 % | 33 % |
| | T0 = 7.5s | 26 % | 30 % | 33 % | 28 % | 32 % | 35 % | 30 % | 34 % | 38 % |
| | T0 = 8.5s | 23 % | 26 % | 28 % | 26 % | 29 % | 31 % | 27 % | 30 % | 33 % |
| | T0 = 9.5s | 12 % | 14 % | 15 % | 14 % | 16 % | 17 % | 15 % | 17 % | 18 % |
| 90 deg | T0 = 4.5s | 5 % | 6 % | 7 % | 6 % | 8 % | 10 % | 8 % | 11 % | 15 % |
| | T0 = 5.5s | 2 % | 2 % | 3 % | 2 % | 3 % | 5 % | 3 % | 5 % | 6 % |
| | T0 = 6.5s | 1 % | 1 % | 1 % | 1 % | 2 % | 2 % | 2 % | 3 % | 3 % |
| | T0 = 7.5s | 2 % | 3 % | 2 % | 3 % | 4 % | 3 % | 5 % | 5 % | 4 % |
| | T0 = 8.5s | 3 % | 4 % | 3 % | 4 % | 5 % | 4 % | 6 % | 5 % | 4 % |
| | T0 = 9.5s | 4 % | 4 % | 4 % | 5 % | 5 % | 4 % | 6 % | 5 % | 4 % |
| 135 deg | T0 = 4.5s | 6 % | 7 % | 9 % | 7 % | 9 % | 13 % | 9 % | 13 % | 19 % |
| | T0 = 5.5s | 21 % | 23 % | 22 % | 26 % | 25 % | 23 % | 28 % | 26 % | 23 % |
| | T0 = 6.5s | 23 % | 28 % | 32 % | 28 % | 32 % | 36 % | 31 % | 36 % | 39 % |
| | T0 = 7.5s | 13 % | 16 % | 19 % | 16 % | 19 % | 23 % | 18 % | 22 % | 26 % |
| | T0 = 8.5s | 6 % | 8 % | 11 % | 8 % | 10 % | 13 % | 9 % | 13 % | 16 % |
| | T0 = 9.5s | 0 % | 2 % | 3 % | 1 % | 3 % | 5 % | 2 % | 5 % | 8 % |
| 180 deg | T0 = 4.5s | 9 % | 12 % | 16 % | 12 % | 16 % | 21 % | 15 % | 21 % | 26 % |
| | T0 = 5.5s | 12 % | 16 % | 21 % | 16 % | 21 % | 27 % | 20 % | 27 % | 34 % |
| | T0 = 6.5s | 13 % | 18 % | 23 % | 18 % | 24 % | 30 % | 22 % | 30 % | 37 % |
| | T0 = 7.5s | 9 % | 14 % | 19 % | 13 % | 19 % | 24 % | 16 % | 23 % | 30 % |
| | T0 = 8.5s | 5 % | 9 % | 13 % | 8 % | 13 % | 17 % | 11 % | 16 % | 21 % |
| | T0 = 9.5s | 3 % | 6 % | 9 % | 6 % | 10 % | 13 % | 8 % | 13 % | 17 % |

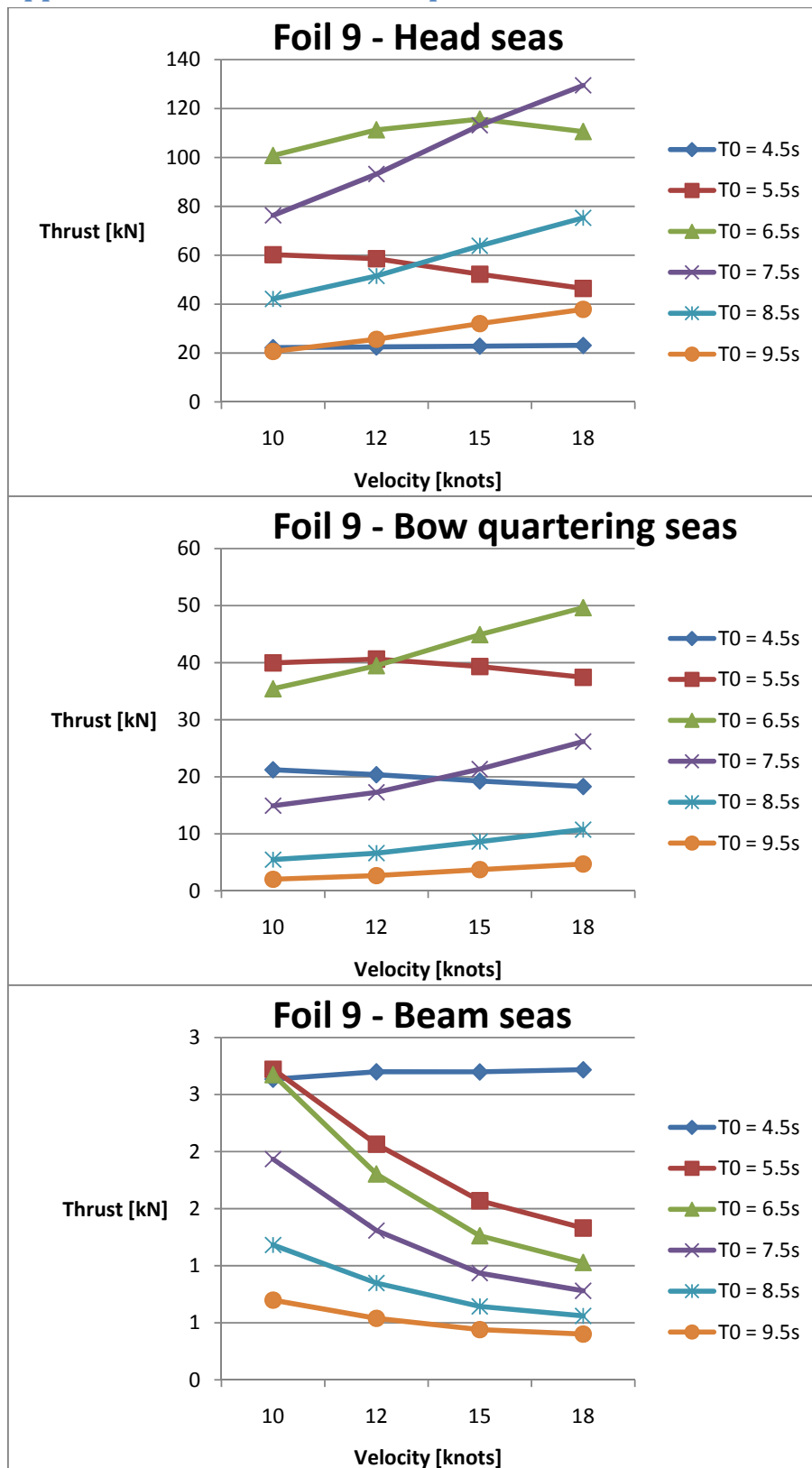
15kt

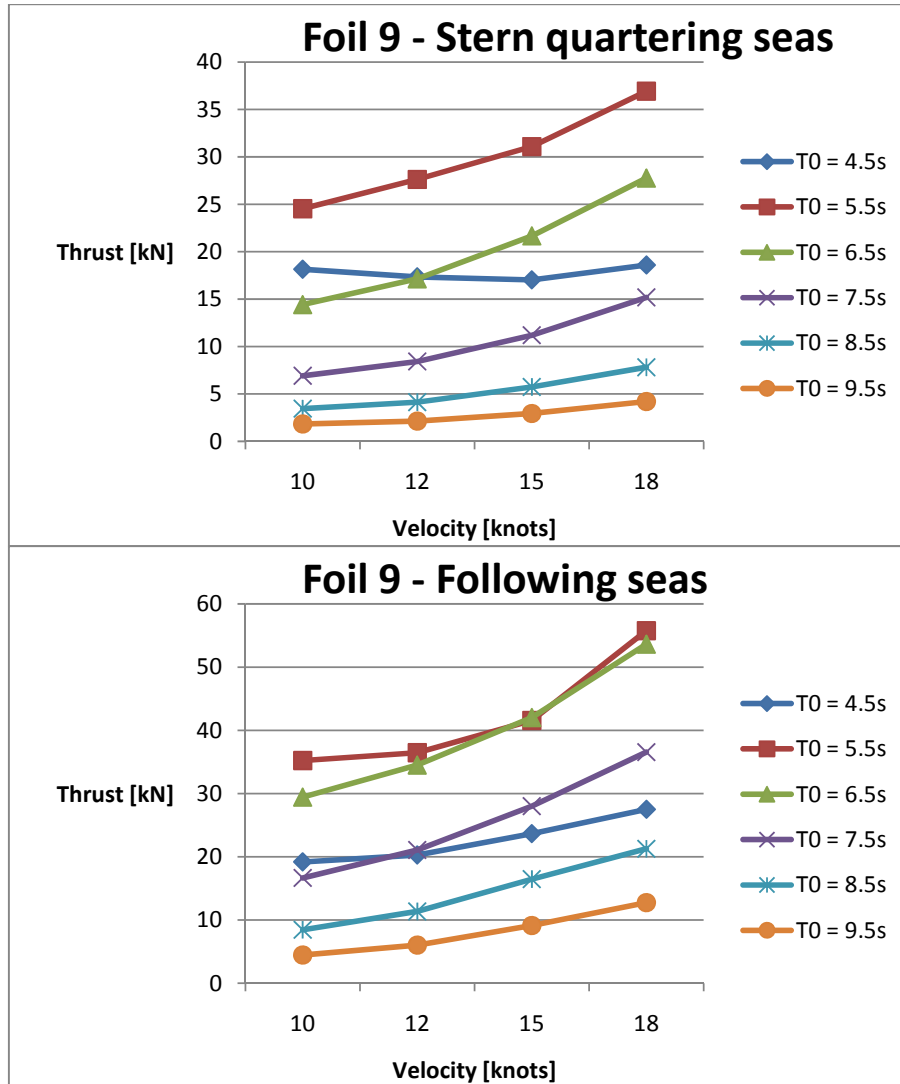
| | | <i>in N</i> | | | | | | | | |
|----------------|------------------|-------------|------|------|------|------|------|------|------|------|
| <u>Head</u> | <u>seas</u> | | | | | | | | | |
| 45 deg | T0 = 4.5s | 4 % | 5 % | 6 % | 5 % | 6 % | 7 % | 6 % | 8 % | 10 % |
| | T0 = 5.5s | 7 % | 8 % | 10 % | 9 % | 11 % | 13 % | 11 % | 14 % | 17 % |
| | T0 = 6.5s | 8 % | 10 % | 11 % | 10 % | 13 % | 15 % | 13 % | 16 % | 19 % |
| | T0 = 7.5s | 28 % | 33 % | 38 % | 32 % | 39 % | 44 % | 36 % | 44 % | 50 % |
| | T0 = 8.5s | 44 % | 51 % | 57 % | 49 % | 56 % | 61 % | 52 % | 60 % | 65 % |
| | T0 = 9.5s | 45 % | 52 % | 56 % | 50 % | 56 % | 61 % | 53 % | 60 % | 64 % |
| 90 deg | T0 = 4.5s | 3 % | 4 % | 5 % | 4 % | 5 % | 6 % | 5 % | 7 % | 8 % |
| | T0 = 5.5s | 5 % | 6 % | 7 % | 6 % | 8 % | 10 % | 8 % | 10 % | 12 % |
| | T0 = 6.5s | 12 % | 14 % | 17 % | 14 % | 17 % | 20 % | 17 % | 21 % | 24 % |
| | T0 = 7.5s | 22 % | 26 % | 28 % | 24 % | 28 % | 31 % | 26 % | 30 % | 33 % |
| | T0 = 8.5s | 25 % | 28 % | 30 % | 27 % | 30 % | 32 % | 29 % | 32 % | 34 % |
| | T0 = 9.5s | 15 % | 16 % | 18 % | 16 % | 18 % | 19 % | 18 % | 19 % | 21 % |
| 135 deg | T0 = 4.5s | 3 % | 4 % | 4 % | 4 % | 5 % | 6 % | 5 % | 7 % | 9 % |
| | T0 = 5.5s | 1 % | 2 % | 2 % | 2 % | 3 % | 3 % | 2 % | 3 % | 4 % |
| | T0 = 6.5s | 1 % | 1 % | 1 % | 1 % | 2 % | 2 % | 2 % | 2 % | 2 % |
| | T0 = 7.5s | 1 % | 1 % | 1 % | 2 % | 2 % | 2 % | 2 % | 2 % | 2 % |
| | T0 = 8.5s | 2 % | 2 % | 2 % | 2 % | 2 % | 2 % | 3 % | 2 % | 2 % |
| | T0 = 9.5s | 2 % | 2 % | 2 % | 2 % | 2 % | 2 % | 3 % | 2 % | 1 % |
| 180 deg | T0 = 4.5s | 6 % | 8 % | 9 % | 8 % | 9 % | 11 % | 9 % | 11 % | 14 % |
| | T0 = 5.5s | 4 % | 5 % | 5 % | 5 % | 5 % | 6 % | 6 % | 6 % | 7 % |
| | T0 = 6.5s | 12 % | 14 % | 16 % | 14 % | 17 % | 19 % | 17 % | 20 % | 23 % |
| | T0 = 7.5s | 5 % | 7 % | 9 % | 7 % | 10 % | 12 % | 9 % | 12 % | 16 % |
| | T0 = 8.5s | 6 % | 8 % | 10 % | 7 % | 10 % | 12 % | 9 % | 12 % | 14 % |
| | T0 = 9.5s | 4 % | 5 % | 6 % | 5 % | 6 % | 8 % | 6 % | 8 % | 9 % |

18kt

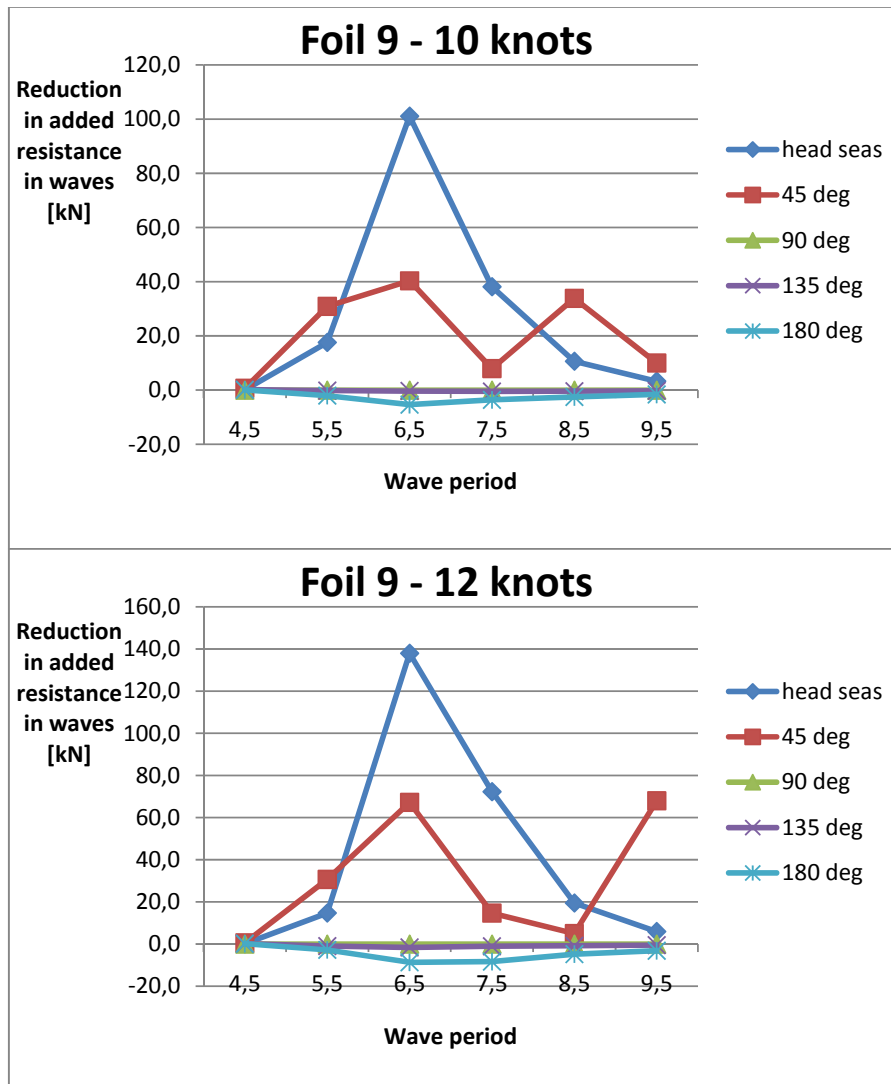
| | | <i>in N</i> | | | | | | | | |
|-----------------------|------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| <u>Head</u> | | | | | | | | | | |
| <u>seas</u> | T0 = 4.5s | 2 % | 2 % | 3 % | 2 % | 3 % | 4 % | 3 % | 4 % | 5 % |
| | T0 = 5.5s | 3 % | 4 % | 5 % | 4 % | 5 % | 7 % | 5 % | 7 % | 8 % |
| | T0 = 6.5s | 4 % | 5 % | 6 % | 5 % | 7 % | 8 % | 7 % | 8 % | 10 % |
| | T0 = 7.5s | 14 % | 17 % | 19 % | 17 % | 21 % | 23 % | 20 % | 24 % | 27 % |
| | T0 = 8.5s | 33 % | 38 % | 43 % | 37 % | 42 % | 47 % | 40 % | 46 % | 50 % |
| | T0 = 9.5s | 39 % | 44 % | 48 % | 43 % | 48 % | 51 % | 45 % | 50 % | 54 % |
| <u>45 deg</u> | T0 = 4.5s | 2 % | 2 % | 2 % | 2 % | 3 % | 3 % | 3 % | 3 % | 4 % |
| | T0 = 5.5s | 2 % | 3 % | 4 % | 3 % | 4 % | 5 % | 4 % | 5 % | 6 % |
| | T0 = 6.5s | 6 % | 8 % | 9 % | 8 % | 9 % | 11 % | 9 % | 11 % | 13 % |
| | T0 = 7.5s | 15 % | 17 % | 19 % | 17 % | 19 % | 21 % | 18 % | 21 % | 23 % |
| | T0 = 8.5s | 21 % | 23 % | 25 % | 23 % | 25 % | 26 % | 24 % | 26 % | 28 % |
| | T0 = 9.5s | 15 % | 16 % | 17 % | 16 % | 17 % | 18 % | 17 % | 18 % | 19 % |
| <u>90 deg</u> | T0 = 4.5s | 1 % | 2 % | 2 % | 2 % | 3 % | 3 % | 3 % | 3 % | 4 % |
| | T0 = 5.5s | 1 % | 1 % | 1 % | 1 % | 2 % | 2 % | 2 % | 2 % | 2 % |
| | T0 = 6.5s | 0 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % |
| | T0 = 7.5s | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % |
| | T0 = 8.5s | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % |
| | T0 = 9.5s | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % |
| <u>135 deg</u> | T0 = 4.5s | 3 % | 4 % | 5 % | 4 % | 5 % | 6 % | 5 % | 6 % | 8 % |
| | T0 = 5.5s | 2 % | 2 % | 3 % | 3 % | 3 % | 3 % | 3 % | 3 % | 4 % |
| | T0 = 6.5s | 7 % | 8 % | 9 % | 8 % | 10 % | 11 % | 10 % | 11 % | 13 % |
| | T0 = 7.5s | 6 % | 7 % | 9 % | 7 % | 9 % | 11 % | 9 % | 11 % | 13 % |
| | T0 = 8.5s | 4 % | 5 % | 6 % | 4 % | 6 % | 7 % | 5 % | 7 % | 8 % |
| | T0 = 9.5s | 3 % | 3 % | 4 % | 3 % | 4 % | 5 % | 4 % | 5 % | 6 % |
| <u>180 deg</u> | T0 = 4.5s | 3 % | 4 % | 5 % | 4 % | 5 % | 6 % | 5 % | 6 % | 8 % |
| | T0 = 5.5s | 5 % | 6 % | 8 % | 6 % | 9 % | 11 % | 8 % | 11 % | 15 % |
| | T0 = 6.5s | 5 % | 7 % | 9 % | 7 % | 10 % | 13 % | 9 % | 12 % | 17 % |
| | T0 = 7.5s | 4 % | 6 % | 9 % | 6 % | 9 % | 13 % | 8 % | 12 % | 17 % |
| | T0 = 8.5s | 0 % | 3 % | 5 % | 3 % | 6 % | 9 % | 5 % | 8 % | 12 % |
| | T0 = 9.5s | -1 % | 1 % | 3 % | 1 % | 3 % | 6 % | 3 % | 6 % | 9 % |

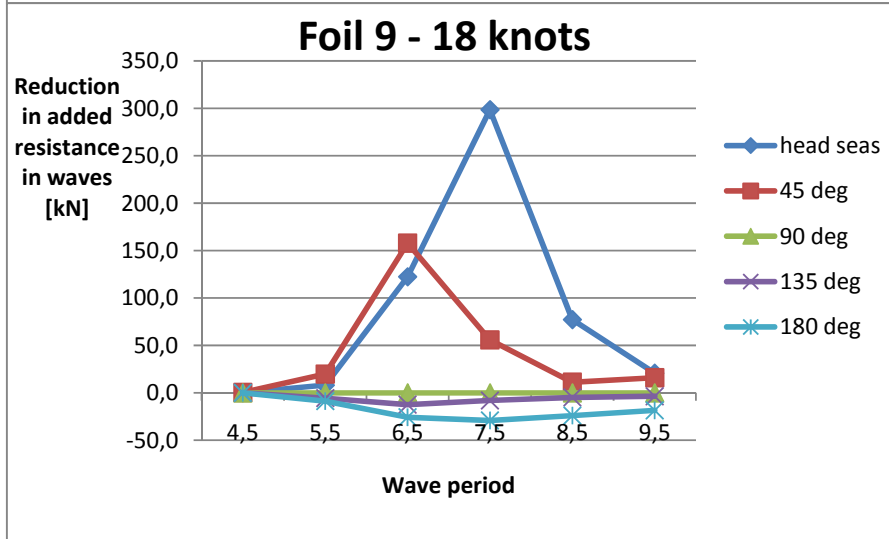
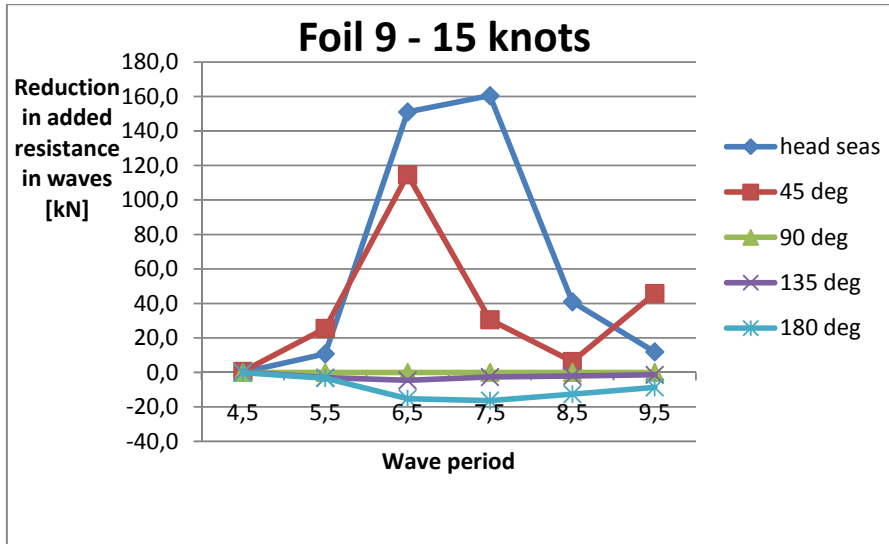
Appendix I: Thrust force, foil 9, purse seiner





Appendix J: Reduction in added resistance in waves, purse seiner





Appendix K: Reduction in required thrust force, purse seiner

| | | Red | < | 15 % | < | Yellow | < | 30 % | < | Green | |
|------------------|---------------------------|------|------|------|------|--------|------|------|------|-------|--|
| 10kt | Percentage covered | | | | | | | | | | |
| | in N | | | | | | | | | | |
| Head seas | T0 = 4.5s | 9 % | 11 % | 13 % | 11 % | 14 % | 17 % | 15 % | 18 % | 22 % | |
| | T0 = 5.5s | 31 % | 37 % | 41 % | 36 % | 43 % | 48 % | 41 % | 49 % | 55 % | |
| | T0 = 6.5s | 47 % | 54 % | 60 % | 51 % | 59 % | 65 % | 55 % | 63 % | 69 % | |
| | T0 = 7.5s | 33 % | 40 % | 46 % | 38 % | 45 % | 52 % | 42 % | 50 % | 56 % | |
| | T0 = 8.5s | 20 % | 25 % | 30 % | 24 % | 30 % | 35 % | 28 % | 34 % | 40 % | |
| | T0 = 9.5s | 11 % | 14 % | 17 % | 13 % | 17 % | 20 % | 16 % | 20 % | 24 % | |
| 45 deg | T0 = 4.5s | 10 % | 12 % | 13 % | 12 % | 14 % | 16 % | 14 % | 17 % | 20 % | |
| | T0 = 5.5s | 26 % | 30 % | 33 % | 28 % | 32 % | 35 % | 30 % | 35 % | 38 % | |
| | T0 = 6.5s | 22 % | 25 % | 27 % | 25 % | 28 % | 30 % | 27 % | 29 % | 32 % | |
| | T0 = 7.5s | 9 % | 10 % | 10 % | 10 % | 10 % | 11 % | 11 % | 11 % | 12 % | |
| | T0 = 8.5s | 23 % | 23 % | 23 % | 23 % | 23 % | 23 % | 23 % | 23 % | 23 % | |
| | T0 = 9.5s | 7 % | 8 % | 8 % | 8 % | 8 % | 9 % | 8 % | 9 % | 9 % | |
| 90 deg | T0 = 4.5s | 1 % | 1 % | 2 % | 2 % | 2 % | 2 % | 3 % | 3 % | 3 % | |
| | T0 = 5.5s | 5 % | 4 % | 4 % | 6 % | 5 % | 4 % | 7 % | 5 % | 3 % | |
| | T0 = 6.5s | 12 % | 9 % | 6 % | 12 % | 8 % | 4 % | 12 % | 6 % | 3 % | |
| | T0 = 7.5s | 12 % | 8 % | 5 % | 10 % | 6 % | 3 % | 9 % | 4 % | 2 % | |
| | T0 = 8.5s | 3 % | 3 % | 3 % | 4 % | 3 % | 2 % | 4 % | 2 % | 2 % | |
| | T0 = 9.5s | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | |
| 135 deg | T0 = 4.5s | 14 % | 16 % | 17 % | 16 % | 18 % | 20 % | 19 % | 21 % | 24 % | |
| | T0 = 5.5s | 17 % | 19 % | 21 % | 19 % | 22 % | 24 % | 22 % | 24 % | 28 % | |
| | T0 = 6.5s | 10 % | 13 % | 14 % | 12 % | 14 % | 15 % | 14 % | 15 % | 17 % | |
| | T0 = 7.5s | 5 % | 6 % | 7 % | 6 % | 7 % | 8 % | 7 % | 8 % | 8 % | |
| | T0 = 8.5s | 2 % | 3 % | 4 % | 3 % | 4 % | 4 % | 4 % | 4 % | 4 % | |
| | T0 = 9.5s | 1 % | 1 % | 2 % | 1 % | 2 % | 2 % | 2 % | 2 % | 2 % | |
| 180 deg | T0 = 4.5s | 11 % | 14 % | 18 % | 14 % | 19 % | 24 % | 18 % | 24 % | 30 % | |
| | T0 = 5.5s | 14 % | 19 % | 25 % | 19 % | 26 % | 33 % | 24 % | 32 % | 41 % | |
| | T0 = 6.5s | 5 % | 9 % | 13 % | 8 % | 13 % | 18 % | 12 % | 18 % | 24 % | |
| | T0 = 7.5s | 2 % | 4 % | 7 % | 4 % | 7 % | 10 % | 6 % | 10 % | 14 % | |
| | T0 = 8.5s | 0 % | 1 % | 3 % | 1 % | 3 % | 5 % | 2 % | 4 % | 6 % | |
| | T0 = 9.5s | 0 % | 0 % | 1 % | 0 % | 1 % | 2 % | 1 % | 2 % | 3 % | |

12kt

| | | <i>in N</i> | | | | | | | | |
|----------------|------------------|-------------|------|------|------|------|------|------|------|------|
| <u>Head</u> | <u>seas</u> | | | | | | | | | |
| | T0 = 4.5s | 7 % | 8 % | 10 % | 9 % | 11 % | 13 % | 11 % | 14 % | 17 % |
| | T0 = 5.5s | 24 % | 29 % | 32 % | 29 % | 35 % | 39 % | 34 % | 40 % | 46 % |
| | T0 = 6.5s | 49 % | 56 % | 61 % | 54 % | 61 % | 66 % | 57 % | 65 % | 71 % |
| | T0 = 7.5s | 38 % | 45 % | 50 % | 43 % | 50 % | 56 % | 47 % | 54 % | 60 % |
| | T0 = 8.5s | 22 % | 27 % | 31 % | 26 % | 32 % | 36 % | 30 % | 36 % | 40 % |
| | T0 = 9.5s | 12 % | 15 % | 17 % | 14 % | 17 % | 20 % | 16 % | 20 % | 23 % |
| 45 deg | T0 = 4.5s | 7 % | 9 % | 10 % | 9 % | 11 % | 12 % | 11 % | 13 % | 15 % |
| | T0 = 5.5s | 23 % | 26 % | 29 % | 25 % | 29 % | 32 % | 28 % | 32 % | 34 % |
| | T0 = 6.5s | 27 % | 30 % | 32 % | 30 % | 32 % | 35 % | 31 % | 34 % | 37 % |
| | T0 = 7.5s | 11 % | 11 % | 12 % | 11 % | 12 % | 13 % | 12 % | 13 % | 14 % |
| | T0 = 8.5s | 5 % | 5 % | 5 % | 5 % | 5 % | 5 % | 5 % | 5 % | 6 % |
| | T0 = 9.5s | 31 % | 31 % | 32 % | 31 % | 32 % | 32 % | 31 % | 32 % | 32 % |
| 90 deg | T0 = 4.5s | 1 % | 1 % | 2 % | 2 % | 2 % | 2 % | 2 % | 2 % | 2 % |
| | T0 = 5.5s | 3 % | 3 % | 3 % | 4 % | 3 % | 2 % | 5 % | 3 % | 2 % |
| | T0 = 6.5s | 7 % | 5 % | 3 % | 7 % | 4 % | 2 % | 6 % | 3 % | 2 % |
| | T0 = 7.5s | 6 % | 4 % | 3 % | 5 % | 3 % | 2 % | 4 % | 2 % | 1 % |
| | T0 = 8.5s | 2 % | 2 % | 1 % | 2 % | 2 % | 1 % | 2 % | 1 % | 1 % |
| | T0 = 9.5s | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % |
| 135 deg | T0 = 4.5s | 10 % | 12 % | 13 % | 12 % | 14 % | 15 % | 14 % | 16 % | 17 % |
| | T0 = 5.5s | 13 % | 16 % | 18 % | 16 % | 19 % | 21 % | 19 % | 22 % | 24 % |
| | T0 = 6.5s | 8 % | 10 % | 11 % | 10 % | 12 % | 13 % | 12 % | 13 % | 15 % |
| | T0 = 7.5s | 4 % | 5 % | 6 % | 5 % | 6 % | 7 % | 6 % | 7 % | 8 % |
| | T0 = 8.5s | 2 % | 2 % | 3 % | 2 % | 3 % | 3 % | 3 % | 3 % | 4 % |
| | T0 = 9.5s | 1 % | 1 % | 1 % | 1 % | 1 % | 2 % | 1 % | 2 % | 2 % |
| 180 deg | T0 = 4.5s | 9 % | 12 % | 15 % | 12 % | 15 % | 19 % | 15 % | 19 % | 24 % |
| | T0 = 5.5s | 11 % | 15 % | 20 % | 15 % | 21 % | 27 % | 19 % | 27 % | 34 % |
| | T0 = 6.5s | 3 % | 7 % | 11 % | 6 % | 11 % | 16 % | 10 % | 16 % | 22 % |
| | T0 = 7.5s | -1 % | 1 % | 4 % | 1 % | 4 % | 8 % | 3 % | 8 % | 12 % |
| | T0 = 8.5s | -1 % | 1 % | 2 % | 0 % | 2 % | 4 % | 2 % | 4 % | 6 % |
| | T0 = 9.5s | -1 % | 0 % | 1 % | 0 % | 1 % | 2 % | 0 % | 2 % | 3 % |

15kt

| | | <i>in N</i> | | | | | | | | |
|----------------|------------------|-------------|------|------|------|------|------|------|------|------|
| <u>Head</u> | <u>seas</u> | | | | | | | | | |
| | T0 = 4.5s | 3 % | 4 % | 5 % | 4 % | 6 % | 7 % | 6 % | 7 % | 8 % |
| | T0 = 5.5s | 11 % | 14 % | 16 % | 14 % | 17 % | 19 % | 17 % | 20 % | 23 % |
| | T0 = 6.5s | 40 % | 46 % | 50 % | 44 % | 50 % | 54 % | 47 % | 53 % | 57 % |
| | T0 = 7.5s | 39 % | 45 % | 48 % | 43 % | 48 % | 52 % | 46 % | 52 % | 55 % |
| | T0 = 8.5s | 20 % | 24 % | 26 % | 23 % | 27 % | 30 % | 26 % | 30 % | 33 % |
| 45 deg | T0 = 9.5s | 9 % | 12 % | 13 % | 11 % | 13 % | 15 % | 13 % | 15 % | 17 % |
| | T0 = 4.5s | 3 % | 4 % | 5 % | 4 % | 5 % | 6 % | 5 % | 6 % | 7 % |
| | T0 = 5.5s | 13 % | 16 % | 17 % | 15 % | 18 % | 19 % | 17 % | 19 % | 21 % |
| | T0 = 6.5s | 28 % | 31 % | 32 % | 30 % | 33 % | 34 % | 32 % | 34 % | 36 % |
| | T0 = 7.5s | 11 % | 12 % | 13 % | 12 % | 13 % | 14 % | 12 % | 14 % | 15 % |
| 90 deg | T0 = 8.5s | 4 % | 3 % | 4 % | 4 % | 4 % | 4 % | 4 % | 4 % | 5 % |
| | T0 = 9.5s | 15 % | 16 % | 16 % | 16 % | 16 % | 16 % | 16 % | 16 % | 16 % |
| | T0 = 4.5s | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % |
| | T0 = 5.5s | 2 % | 2 % | 1 % | 2 % | 1 % | 1 % | 2 % | 1 % | 1 % |
| | T0 = 6.5s | 3 % | 2 % | 1 % | 2 % | 1 % | 1 % | 2 % | 1 % | 1 % |
| 135 deg | T0 = 7.5s | 2 % | 1 % | 1 % | 2 % | 1 % | 1 % | 1 % | 1 % | 0 % |
| | T0 = 8.5s | 1 % | 1 % | 0 % | 1 % | 1 % | 0 % | 1 % | 0 % | 0 % |
| | T0 = 9.5s | 0 % | 0 % | 0 % | 0 % | 0 % | 0 % | 0 % | 0 % | 0 % |
| | T0 = 4.5s | 5 % | 6 % | 7 % | 6 % | 7 % | 8 % | 7 % | 8 % | 9 % |
| | T0 = 5.5s | 6 % | 8 % | 10 % | 8 % | 10 % | 11 % | 10 % | 12 % | 13 % |
| 180 deg | T0 = 6.5s | 3 % | 5 % | 6 % | 5 % | 6 % | 7 % | 6 % | 7 % | 8 % |
| | T0 = 7.5s | 2 % | 2 % | 3 % | 2 % | 3 % | 4 % | 3 % | 4 % | 4 % |
| | T0 = 8.5s | 0 % | 1 % | 1 % | 1 % | 1 % | 2 % | 1 % | 2 % | 2 % |
| | T0 = 9.5s | 0 % | 0 % | 0 % | 0 % | 0 % | 1 % | 0 % | 1 % | 1 % |
| | T0 = 4.5s | 4 % | 6 % | 8 % | 6 % | 8 % | 10 % | 7 % | 10 % | 13 % |
| | T0 = 5.5s | 6 % | 9 % | 12 % | 9 % | 13 % | 17 % | 12 % | 16 % | 21 % |
| | T0 = 6.5s | 0 % | 2 % | 5 % | 2 % | 6 % | 9 % | 5 % | 9 % | 13 % |
| | T0 = 7.5s | -4 % | -2 % | 0 % | -2 % | 0 % | 3 % | 0 % | 3 % | 5 % |
| | T0 = 8.5s | -4 % | -3 % | -2 % | -3 % | -2 % | 0 % | -2 % | 0 % | 2 % |
| | T0 = 9.5s | -4 % | -3 % | -2 % | -3 % | -2 % | -1 % | -2 % | -1 % | 0 % |

18kt

| | | <i>in N</i> | | | | | | | | |
|-----------------------|------------------|-------------|------|------|------|------|------|------|------|------|
| <u>Head</u> | | | | | | | | | | |
| <u>seas</u> | | | | | | | | | | |
| | T0 = 4.5s | 2 % | 2 % | 3 % | 2 % | 3 % | 4 % | 3 % | 4 % | 5 % |
| | T0 = 5.5s | 5 % | 7 % | 8 % | 7 % | 8 % | 9 % | 8 % | 10 % | 11 % |
| | T0 = 6.5s | 25 % | 29 % | 32 % | 28 % | 33 % | 35 % | 31 % | 35 % | 38 % |
| | T0 = 7.5s | 39 % | 43 % | 46 % | 42 % | 46 % | 49 % | 45 % | 49 % | 51 % |
| | T0 = 8.5s | 18 % | 21 % | 23 % | 21 % | 23 % | 25 % | 23 % | 25 % | 27 % |
| | T0 = 9.5s | 8 % | 9 % | 10 % | 9 % | 10 % | 11 % | 10 % | 12 % | 13 % |
| <u>45 deg</u> | T0 = 4.5s | 2 % | 2 % | 2 % | 2 % | 3 % | 3 % | 3 % | 3 % | 4 % |
| | T0 = 5.5s | 7 % | 8 % | 9 % | 8 % | 9 % | 10 % | 9 % | 10 % | 12 % |
| | T0 = 6.5s | 25 % | 27 % | 29 % | 26 % | 28 % | 30 % | 28 % | 30 % | 31 % |
| | T0 = 7.5s | 11 % | 12 % | 13 % | 12 % | 13 % | 14 % | 13 % | 14 % | 15 % |
| | T0 = 8.5s | 3 % | 3 % | 4 % | 3 % | 4 % | 4 % | 3 % | 4 % | 4 % |
| | T0 = 9.5s | 4 % | 4 % | 4 % | 4 % | 4 % | 4 % | 4 % | 4 % | 4 % |
| <u>90 deg</u> | T0 = 4.5s | 0 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % | 1 % |
| | T0 = 5.5s | 1 % | 1 % | 1 % | 1 % | 1 % | 0 % | 1 % | 1 % | 0 % |
| | T0 = 6.5s | 1 % | 1 % | 0 % | 1 % | 1 % | 0 % | 1 % | 0 % | 0 % |
| | T0 = 7.5s | 1 % | 0 % | 0 % | 1 % | 0 % | 0 % | 0 % | 0 % | 0 % |
| | T0 = 8.5s | 0 % | 0 % | 0 % | 0 % | 0 % | 0 % | 0 % | 0 % | 0 % |
| | T0 = 9.5s | 0 % | 0 % | 0 % | 0 % | 0 % | 0 % | 0 % | 0 % | 0 % |
| <u>135 deg</u> | T0 = 4.5s | 3 % | 3 % | 4 % | 3 % | 4 % | 5 % | 4 % | 5 % | 5 % |
| | T0 = 5.5s | 3 % | 5 % | 6 % | 5 % | 6 % | 7 % | 6 % | 7 % | 8 % |
| | T0 = 6.5s | 0 % | 1 % | 2 % | 1 % | 2 % | 3 % | 2 % | 3 % | 4 % |
| | T0 = 7.5s | 0 % | 0 % | 1 % | 0 % | 1 % | 1 % | 1 % | 1 % | 2 % |
| | T0 = 8.5s | 0 % | 0 % | 0 % | 0 % | 0 % | 0 % | 0 % | 1 % | 1 % |
| | T0 = 9.5s | 0 % | 0 % | 0 % | 0 % | 0 % | 0 % | 0 % | 0 % | 0 % |
| <u>180 deg</u> | T0 = 4.5s | 2 % | 3 % | 4 % | 3 % | 4 % | 6 % | 4 % | 6 % | 7 % |
| | T0 = 5.5s | 3 % | 5 % | 7 % | 4 % | 7 % | 10 % | 6 % | 10 % | 14 % |
| | T0 = 6.5s | -2 % | 0 % | 2 % | 0 % | 3 % | 5 % | 2 % | 5 % | 8 % |
| | T0 = 7.5s | -5 % | -3 % | -2 % | -3 % | -2 % | 0 % | -2 % | 0 % | 2 % |
| | T0 = 8.5s | -5 % | -4 % | -3 % | -4 % | -3 % | -2 % | -4 % | -2 % | -1 % |
| | T0 = 9.5s | -5 % | -4 % | -4 % | -4 % | -4 % | -3 % | -4 % | -3 % | -2 % |

Appendix L: Fuel Savings, purse seiner

| | | Red | < | 15 % | < | Yellow | < | 30 % | < | Green |
|------------------|------------------|--------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| 10kt | | Percentage covered | | | | | | | | |
| | | Foil 1 | Foil 2 | Foil 3 | Foil 4 | Foil 5 | Foil 6 | Foil 7 | Foil 8 | Foil 9 |
| Head seas | T0 = 4.5s | 22 % | 24 % | 25 % | 24 % | 27 % | 29 % | 27 % | 30 % | 33 % |
| | T0 = 5.5s | 41 % | 46 % | 50 % | 45 % | 51 % | 56 % | 49 % | 56 % | 61 % |
| | T0 = 6.5s | 54 % | 61 % | 65 % | 58 % | 65 % | 70 % | 62 % | 69 % | 74 % |
| | T0 = 7.5s | 43 % | 49 % | 54 % | 47 % | 53 % | 59 % | 50 % | 57 % | 63 % |
| | T0 = 8.5s | 32 % | 36 % | 40 % | 35 % | 40 % | 44 % | 38 % | 43 % | 48 % |
| 45 deg | T0 = 9.5s | 24 % | 26 % | 29 % | 26 % | 29 % | 32 % | 28 % | 31 % | 35 % |
| | T0 = 4.5s | 22 % | 24 % | 26 % | 24 % | 26 % | 28 % | 27 % | 29 % | 31 % |
| | T0 = 5.5s | 36 % | 40 % | 42 % | 38 % | 42 % | 45 % | 40 % | 44 % | 47 % |
| | T0 = 6.5s | 33 % | 36 % | 38 % | 35 % | 38 % | 40 % | 37 % | 39 % | 41 % |
| | T0 = 7.5s | 22 % | 22 % | 23 % | 23 % | 23 % | 23 % | 23 % | 23 % | 24 % |
| 90 deg | T0 = 8.5s | 34 % | 34 % | 34 % | 34 % | 34 % | 34 % | 34 % | 34 % | 34 % |
| | T0 = 9.5s | 20 % | 21 % | 21 % | 21 % | 21 % | 22 % | 21 % | 22 % | 22 % |
| | T0 = 4.5s | 12 % | 13 % | 13 % | 13 % | 13 % | 13 % | 14 % | 14 % | 14 % |
| | T0 = 5.5s | 15 % | 15 % | 15 % | 17 % | 16 % | 15 % | 18 % | 16 % | 14 % |
| | T0 = 6.5s | 22 % | 19 % | 17 % | 22 % | 18 % | 15 % | 22 % | 17 % | 14 % |
| 135 deg | T0 = 7.5s | 22 % | 18 % | 16 % | 20 % | 16 % | 14 % | 19 % | 15 % | 13 % |
| | T0 = 8.5s | 14 % | 14 % | 14 % | 15 % | 14 % | 13 % | 15 % | 14 % | 13 % |
| | T0 = 9.5s | 12 % | 12 % | 12 % | 13 % | 13 % | 12 % | 13 % | 12 % | 12 % |
| | T0 = 4.5s | 22 % | 23 % | 25 % | 24 % | 26 % | 27 % | 26 % | 28 % | 31 % |
| | T0 = 5.5s | 24 % | 27 % | 28 % | 27 % | 29 % | 31 % | 29 % | 31 % | 34 % |
| 180 deg | T0 = 6.5s | 18 % | 20 % | 22 % | 20 % | 22 % | 23 % | 22 % | 23 % | 24 % |
| | T0 = 7.5s | 13 % | 15 % | 15 % | 14 % | 15 % | 16 % | 15 % | 16 % | 17 % |
| | T0 = 8.5s | 11 % | 12 % | 12 % | 12 % | 12 % | 13 % | 12 % | 13 % | 13 % |
| | T0 = 9.5s | 10 % | 10 % | 11 % | 10 % | 11 % | 11 % | 11 % | 11 % | 11 % |
| | T0 = 4.5s | 17 % | 20 % | 24 % | 20 % | 25 % | 29 % | 24 % | 29 % | 34 % |
| | T0 = 5.5s | 19 % | 25 % | 30 % | 24 % | 31 % | 37 % | 29 % | 37 % | 45 % |
| | T0 = 6.5s | 11 % | 15 % | 19 % | 14 % | 19 % | 24 % | 18 % | 23 % | 29 % |
| | T0 = 7.5s | 9 % | 11 % | 13 % | 11 % | 13 % | 16 % | 13 % | 16 % | 20 % |
| | T0 = 8.5s | 7 % | 8 % | 9 % | 8 % | 9 % | 11 % | 9 % | 11 % | 13 % |
| | T0 = 9.5s | 7 % | 7 % | 8 % | 7 % | 8 % | 9 % | 8 % | 9 % | 10 % |

12kt

| | | | | | | | | | | |
|-------------------------|------------------|------|------|------|------|------|------|------|------|------|
| <u>Head seas</u> | T0 = 4.5s | 20 % | 22 % | 23 % | 22 % | 24 % | 25 % | 24 % | 26 % | 29 % |
| | T0 = 5.5s | 35 % | 39 % | 42 % | 39 % | 44 % | 48 % | 43 % | 49 % | 54 % |
| | T0 = 6.5s | 56 % | 62 % | 67 % | 60 % | 67 % | 71 % | 64 % | 70 % | 75 % |
| | T0 = 7.5s | 47 % | 53 % | 58 % | 51 % | 57 % | 62 % | 55 % | 61 % | 66 % |
| | T0 = 8.5s | 33 % | 38 % | 41 % | 37 % | 41 % | 45 % | 40 % | 45 % | 49 % |
| | T0 = 9.5s | 24 % | 27 % | 29 % | 26 % | 29 % | 32 % | 28 % | 32 % | 34 % |
| <u>45 deg</u> | T0 = 4.5s | 20 % | 22 % | 23 % | 22 % | 23 % | 25 % | 23 % | 25 % | 27 % |
| | T0 = 5.5s | 34 % | 37 % | 39 % | 36 % | 39 % | 41 % | 38 % | 41 % | 44 % |
| | T0 = 6.5s | 37 % | 40 % | 42 % | 39 % | 42 % | 44 % | 41 % | 44 % | 46 % |
| | T0 = 7.5s | 23 % | 24 % | 24 % | 24 % | 24 % | 25 % | 24 % | 25 % | 26 % |
| | T0 = 8.5s | 19 % | 18 % | 18 % | 18 % | 18 % | 19 % | 18 % | 19 % | 19 % |
| | T0 = 9.5s | 41 % | 41 % | 41 % | 41 % | 41 % | 41 % | 41 % | 41 % | 42 % |
| <u>90 deg</u> | T0 = 4.5s | 12 % | 13 % | 13 % | 13 % | 13 % | 13 % | 13 % | 14 % | 13 % |
| | T0 = 5.5s | 14 % | 14 % | 14 % | 15 % | 14 % | 13 % | 16 % | 14 % | 13 % |
| | T0 = 6.5s | 18 % | 16 % | 14 % | 17 % | 15 % | 13 % | 17 % | 14 % | 13 % |
| | T0 = 7.5s | 17 % | 15 % | 14 % | 16 % | 14 % | 13 % | 15 % | 13 % | 12 % |
| | T0 = 8.5s | 13 % | 13 % | 13 % | 13 % | 13 % | 12 % | 13 % | 13 % | 12 % |
| | T0 = 9.5s | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % |
| <u>135 deg</u> | T0 = 4.5s | 18 % | 20 % | 21 % | 20 % | 22 % | 23 % | 22 % | 23 % | 25 % |
| | T0 = 5.5s | 21 % | 24 % | 26 % | 24 % | 26 % | 28 % | 26 % | 29 % | 31 % |
| | T0 = 6.5s | 16 % | 18 % | 19 % | 18 % | 20 % | 21 % | 20 % | 21 % | 23 % |
| | T0 = 7.5s | 13 % | 14 % | 14 % | 14 % | 14 % | 15 % | 15 % | 15 % | 16 % |
| | T0 = 8.5s | 10 % | 11 % | 11 % | 11 % | 12 % | 12 % | 12 % | 12 % | 12 % |
| | T0 = 9.5s | 10 % | 10 % | 10 % | 10 % | 10 % | 10 % | 10 % | 10 % | 11 % |
| <u>180 deg</u> | T0 = 4.5s | 15 % | 18 % | 21 % | 18 % | 21 % | 25 % | 20 % | 25 % | 30 % |
| | T0 = 5.5s | 17 % | 21 % | 25 % | 21 % | 26 % | 32 % | 25 % | 32 % | 38 % |
| | T0 = 6.5s | 10 % | 13 % | 17 % | 13 % | 18 % | 22 % | 16 % | 22 % | 28 % |
| | T0 = 7.5s | 6 % | 8 % | 11 % | 8 % | 11 % | 14 % | 10 % | 14 % | 18 % |
| | T0 = 8.5s | 6 % | 7 % | 9 % | 7 % | 9 % | 11 % | 8 % | 11 % | 13 % |
| | T0 = 9.5s | 6 % | 7 % | 7 % | 6 % | 8 % | 9 % | 7 % | 8 % | 10 % |

15kt

| | | | | | | | | | | |
|-------------------------|------------------|------|------|------|------|------|------|------|------|------|
| <u>Head seas</u> | T0 = 4.5s | 17 % | 18 % | 19 % | 18 % | 19 % | 20 % | 19 % | 20 % | 22 % |
| | T0 = 5.5s | 24 % | 26 % | 28 % | 26 % | 29 % | 31 % | 29 % | 32 % | 34 % |
| | T0 = 6.5s | 49 % | 53 % | 57 % | 52 % | 57 % | 60 % | 55 % | 60 % | 64 % |
| | T0 = 7.5s | 48 % | 52 % | 56 % | 51 % | 56 % | 59 % | 54 % | 59 % | 62 % |
| | T0 = 8.5s | 32 % | 35 % | 37 % | 34 % | 37 % | 40 % | 37 % | 40 % | 42 % |
| | T0 = 9.5s | 23 % | 24 % | 26 % | 24 % | 26 % | 27 % | 26 % | 28 % | 29 % |
| <u>45 deg</u> | T0 = 4.5s | 17 % | 18 % | 18 % | 18 % | 19 % | 19 % | 19 % | 20 % | 20 % |
| | T0 = 5.5s | 26 % | 28 % | 29 % | 27 % | 29 % | 31 % | 29 % | 31 % | 32 % |
| | T0 = 6.5s | 38 % | 40 % | 42 % | 40 % | 42 % | 44 % | 41 % | 44 % | 45 % |
| | T0 = 7.5s | 23 % | 24 % | 25 % | 24 % | 25 % | 26 % | 25 % | 26 % | 27 % |
| | T0 = 8.5s | 17 % | 17 % | 17 % | 17 % | 17 % | 18 % | 17 % | 18 % | 18 % |
| | T0 = 9.5s | 27 % | 27 % | 28 % | 27 % | 28 % | 28 % | 28 % | 28 % | 28 % |
| <u>90 deg</u> | T0 = 4.5s | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 13 % | 12 % | 12 % |
| | T0 = 5.5s | 13 % | 13 % | 12 % | 13 % | 13 % | 12 % | 13 % | 12 % | 12 % |
| | T0 = 6.5s | 14 % | 13 % | 12 % | 13 % | 13 % | 12 % | 13 % | 12 % | 12 % |
| | T0 = 7.5s | 13 % | 12 % | 12 % | 13 % | 12 % | 12 % | 13 % | 12 % | 12 % |
| | T0 = 8.5s | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % |
| | T0 = 9.5s | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % |
| <u>135 deg</u> | T0 = 4.5s | 14 % | 15 % | 15 % | 15 % | 16 % | 16 % | 16 % | 16 % | 17 % |
| | T0 = 5.5s | 15 % | 17 % | 18 % | 17 % | 18 % | 19 % | 18 % | 20 % | 21 % |
| | T0 = 6.5s | 12 % | 13 % | 14 % | 13 % | 14 % | 15 % | 15 % | 16 % | 17 % |
| | T0 = 7.5s | 11 % | 11 % | 12 % | 11 % | 12 % | 12 % | 12 % | 13 % | 13 % |
| | T0 = 8.5s | 9 % | 10 % | 10 % | 10 % | 10 % | 10 % | 10 % | 10 % | 11 % |
| | T0 = 9.5s | 9 % | 9 % | 9 % | 9 % | 9 % | 10 % | 9 % | 10 % | 10 % |
| <u>180 deg</u> | T0 = 4.5s | 11 % | 12 % | 14 % | 12 % | 14 % | 17 % | 14 % | 16 % | 19 % |
| | T0 = 5.5s | 13 % | 15 % | 18 % | 15 % | 19 % | 22 % | 18 % | 22 % | 27 % |
| | T0 = 6.5s | 7 % | 9 % | 12 % | 9 % | 12 % | 15 % | 11 % | 15 % | 19 % |
| | T0 = 7.5s | 3 % | 5 % | 7 % | 5 % | 7 % | 9 % | 7 % | 9 % | 12 % |
| | T0 = 8.5s | 3 % | 4 % | 5 % | 4 % | 5 % | 7 % | 5 % | 7 % | 8 % |
| | T0 = 9.5s | 4 % | 4 % | 5 % | 4 % | 5 % | 6 % | 5 % | 6 % | 7 % |

18kt

| | | | | | | | | | | |
|-------------------------|------------------|------|------|------|------|------|------|------|------|------|
| <u>Head seas</u> | T0 = 4.5s | 16 % | 16 % | 17 % | 16 % | 17 % | 17 % | 17 % | 18 % | 18 % |
| | T0 = 5.5s | 19 % | 20 % | 21 % | 20 % | 21 % | 22 % | 21 % | 23 % | 24 % |
| | T0 = 6.5s | 36 % | 39 % | 42 % | 39 % | 42 % | 45 % | 41 % | 45 % | 47 % |
| | T0 = 7.5s | 48 % | 51 % | 54 % | 51 % | 54 % | 56 % | 53 % | 56 % | 58 % |
| | T0 = 8.5s | 30 % | 32 % | 34 % | 32 % | 34 % | 36 % | 34 % | 36 % | 38 % |
| <u>45 deg</u> | T0 = 9.5s | 21 % | 22 % | 23 % | 22 % | 23 % | 24 % | 23 % | 24 % | 25 % |
| | T0 = 4.5s | 16 % | 16 % | 16 % | 16 % | 16 % | 17 % | 16 % | 17 % | 17 % |
| | T0 = 5.5s | 20 % | 21 % | 22 % | 21 % | 22 % | 23 % | 22 % | 23 % | 24 % |
| | T0 = 6.5s | 35 % | 37 % | 39 % | 37 % | 39 % | 40 % | 38 % | 40 % | 41 % |
| | T0 = 7.5s | 24 % | 24 % | 25 % | 24 % | 25 % | 26 % | 25 % | 26 % | 27 % |
| <u>90 deg</u> | T0 = 8.5s | 17 % | 17 % | 17 % | 17 % | 17 % | 17 % | 17 % | 17 % | 18 % |
| | T0 = 9.5s | 17 % | 17 % | 18 % | 17 % | 18 % | 18 % | 18 % | 18 % | 18 % |
| | T0 = 4.5s | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % |
| | T0 = 5.5s | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % |
| | T0 = 6.5s | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % |
| <u>135 deg</u> | T0 = 7.5s | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % |
| | T0 = 8.5s | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % | 12 % |
| | T0 = 9.5s | 12 % | 12 % | 11 % | 12 % | 11 % | 11 % | 12 % | 11 % | 11 % |
| | T0 = 4.5s | 11 % | 12 % | 13 % | 12 % | 13 % | 13 % | 13 % | 13 % | 14 % |
| | T0 = 5.5s | 12 % | 13 % | 14 % | 13 % | 15 % | 15 % | 15 % | 16 % | 17 % |
| <u>180 deg</u> | T0 = 6.5s | 9 % | 10 % | 11 % | 10 % | 11 % | 12 % | 11 % | 12 % | 13 % |
| | T0 = 7.5s | 9 % | 9 % | 10 % | 9 % | 10 % | 10 % | 10 % | 10 % | 11 % |
| | T0 = 8.5s | 9 % | 9 % | 9 % | 9 % | 9 % | 9 % | 9 % | 10 % | 10 % |
| | T0 = 9.5s | 9 % | 9 % | 9 % | 9 % | 9 % | 9 % | 9 % | 9 % | 9 % |
| | T0 = 4.5s | 9 % | 10 % | 11 % | 10 % | 11 % | 12 % | 11 % | 12 % | 14 % |
| T0 = 5.5s | 9 % | 11 % | 13 % | 11 % | 14 % | 17 % | 13 % | 16 % | 20 % | |
| T0 = 6.5s | 5 % | 7 % | 9 % | 7 % | 9 % | 12 % | 9 % | 12 % | 15 % | |
| T0 = 7.5s | 2 % | 4 % | 5 % | 4 % | 5 % | 7 % | 5 % | 7 % | 9 % | |
| T0 = 8.5s | 2 % | 3 % | 4 % | 3 % | 4 % | 5 % | 4 % | 5 % | 6 % | |
| T0 = 9.5s | 3 % | 3 % | 4 % | 3 % | 4 % | 4 % | 3 % | 4 % | 5 % | |

Appendix M: Combined coefficient for unsteady flow and flexible foil

Combined unsteady lift effect coefficient and flexible foil coefficient

We = frequency of encounter

| 10 knots <u>Head</u> <u>seas</u> | | We | foil 1 | foil 2 | foil 3 | foil 4 | foil 5 | foil 6 | foil 7 | foil 8 | foil 9 |
|---|-----------|-------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| | T0 = 4.5s | 3,24 | 0,64 | 0,62 | 0,60 | 0,63 | 0,61 | 0,59 | 0,66 | 0,63 | 0,61 |
| | T0 = 5.5s | 2,37 | 0,69 | 0,67 | 0,65 | 0,69 | 0,66 | 0,64 | 0,70 | 0,68 | 0,66 |
| | T0 = 6.5s | 1,85 | 0,73 | 0,71 | 0,69 | 0,72 | 0,70 | 0,68 | 0,74 | 0,72 | 0,70 |
| | T0 = 7.5s | 1,50 | 0,76 | 0,74 | 0,72 | 0,75 | 0,73 | 0,72 | 0,77 | 0,75 | 0,73 |
| | T0 = 8.5s | 1,25 | 0,78 | 0,76 | 0,75 | 0,77 | 0,76 | 0,74 | 0,79 | 0,77 | 0,76 |
| 45 deg | T0 = 9.5s | 1,07 | 0,80 | 0,78 | 0,77 | 0,79 | 0,78 | 0,76 | 0,81 | 0,79 | 0,78 |
| | T0 = 4.5s | 2,70 | 0,67 | 0,65 | 0,63 | 0,67 | 0,64 | 0,62 | 0,68 | 0,66 | 0,64 |
| | T0 = 5.5s | 2,01 | 0,72 | 0,70 | 0,68 | 0,71 | 0,69 | 0,67 | 0,73 | 0,71 | 0,69 |
| | T0 = 6.5s | 1,59 | 0,75 | 0,73 | 0,71 | 0,74 | 0,72 | 0,71 | 0,76 | 0,74 | 0,72 |
| | T0 = 7.5s | 1,31 | 0,78 | 0,76 | 0,74 | 0,77 | 0,75 | 0,74 | 0,78 | 0,77 | 0,75 |
| 90 deg | T0 = 8.5s | 1,10 | 0,80 | 0,78 | 0,76 | 0,79 | 0,77 | 0,76 | 0,80 | 0,79 | 0,77 |
| | T0 = 9.5s | 0,95 | 0,81 | 0,80 | 0,78 | 0,81 | 0,79 | 0,78 | 0,82 | 0,80 | 0,79 |
| | T0 = 4.5s | 1,40 | 0,77 | 0,75 | 0,73 | 0,76 | 0,74 | 0,73 | 0,78 | 0,76 | 0,74 |
| | T0 = 5.5s | 1,14 | 0,79 | 0,77 | 0,76 | 0,79 | 0,77 | 0,75 | 0,80 | 0,78 | 0,77 |
| | T0 = 6.5s | 0,97 | 0,81 | 0,79 | 0,78 | 0,81 | 0,79 | 0,77 | 0,82 | 0,80 | 0,79 |
| 135 deg | T0 = 7.5s | 0,84 | 0,83 | 0,81 | 0,80 | 0,82 | 0,81 | 0,79 | 0,83 | 0,82 | 0,81 |
| | T0 = 8.5s | 0,74 | 0,84 | 0,82 | 0,81 | 0,83 | 0,82 | 0,81 | 0,85 | 0,83 | 0,82 |
| | T0 = 9.5s | 0,66 | 0,85 | 0,84 | 0,82 | 0,85 | 0,83 | 0,82 | 0,86 | 0,84 | 0,83 |
| | T0 = 4.5s | 0,10 | 0,99 | 0,98 | 0,97 | 0,99 | 0,98 | 0,97 | 0,99 | 0,98 | 0,98 |
| | T0 = 5.5s | 0,27 | 0,92 | 0,91 | 0,91 | 0,92 | 0,91 | 0,90 | 0,93 | 0,92 | 0,91 |
| 180 deg | T0 = 6.5s | 0,34 | 0,91 | 0,90 | 0,89 | 0,90 | 0,89 | 0,88 | 0,91 | 0,90 | 0,89 |
| | T0 = 7.5s | 0,37 | 0,90 | 0,89 | 0,88 | 0,90 | 0,89 | 0,88 | 0,91 | 0,90 | 0,89 |
| | T0 = 8.5s | 0,37 | 0,90 | 0,89 | 0,88 | 0,90 | 0,88 | 0,87 | 0,91 | 0,89 | 0,89 |
| | T0 = 9.5s | 0,37 | 0,90 | 0,89 | 0,88 | 0,90 | 0,89 | 0,88 | 0,91 | 0,90 | 0,89 |
| | T0 = 4.5s | 0,44 | 0,89 | 0,87 | 0,86 | 0,88 | 0,87 | 0,86 | 0,89 | 0,88 | 0,87 |
| | T0 = 5.5s | 0,09 | 0,99 | 0,98 | 0,98 | 0,99 | 0,98 | 0,97 | 0,99 | 0,99 | 0,98 |
| | T0 = 6.5s | 0,08 | 0,99 | 0,99 | 0,98 | 0,99 | 0,98 | 0,98 | 1,00 | 0,99 | 0,98 |
| | T0 = 7.5s | 0,18 | 0,95 | 0,94 | 0,94 | 0,95 | 0,94 | 0,93 | 0,96 | 0,95 | 0,94 |
| | T0 = 8.5s | 0,22 | 0,94 | 0,93 | 0,92 | 0,93 | 0,92 | 0,92 | 0,94 | 0,93 | 0,93 |
| | T0 = 9.5s | 0,25 | 0,93 | 0,92 | 0,91 | 0,93 | 0,92 | 0,91 | 0,94 | 0,93 | 0,92 |

| 15 | | We | foil 1 | foil 2 | foil 3 | foil 4 | foil 5 | foil 6 | foil 7 | foil 8 | foil 9 | |
|----------------|------------------|------------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|------|
| knots | Head | | | | | | | | | | | |
| | seas | T0 = 4.5s | 2,93 | 0,63 | 0,60 | 0,58 | 0,62 | 0,59 | 0,57 | 0,64 | 0,62 | 0,60 |
| | | T0 = 5.5s | 2,17 | 0,68 | 0,66 | 0,64 | 0,67 | 0,65 | 0,63 | 0,69 | 0,67 | 0,65 |
| | | T0 = 6.5s | 1,70 | 0,72 | 0,69 | 0,68 | 0,71 | 0,69 | 0,67 | 0,73 | 0,71 | 0,69 |
| | | T0 = 7.5s | 1,39 | 0,74 | 0,72 | 0,71 | 0,74 | 0,72 | 0,70 | 0,75 | 0,73 | 0,72 |
| | | T0 = 8.5s | 1,17 | 0,77 | 0,75 | 0,73 | 0,76 | 0,74 | 0,73 | 0,78 | 0,76 | 0,74 |
| 45 deg | | T0 = 9.5s | 1,01 | 0,79 | 0,77 | 0,75 | 0,78 | 0,76 | 0,75 | 0,79 | 0,78 | 0,76 |
| | | T0 = 4.5s | 2,48 | 0,66 | 0,63 | 0,61 | 0,65 | 0,62 | 0,60 | 0,67 | 0,65 | 0,63 |
| | | T0 = 5.5s | 1,87 | 0,70 | 0,68 | 0,66 | 0,69 | 0,67 | 0,65 | 0,71 | 0,69 | 0,67 |
| | | T0 = 6.5s | 1,49 | 0,73 | 0,71 | 0,70 | 0,73 | 0,71 | 0,69 | 0,74 | 0,72 | 0,71 |
| | | T0 = 7.5s | 1,23 | 0,76 | 0,74 | 0,73 | 0,75 | 0,73 | 0,72 | 0,77 | 0,75 | 0,74 |
| | | T0 = 8.5s | 1,04 | 0,78 | 0,76 | 0,75 | 0,77 | 0,76 | 0,74 | 0,79 | 0,77 | 0,76 |
| 90 deg | | T0 = 9.5s | 0,90 | 0,80 | 0,78 | 0,77 | 0,79 | 0,77 | 0,76 | 0,81 | 0,79 | 0,78 |
| | | T0 = 4.5s | 1,40 | 0,74 | 0,72 | 0,71 | 0,74 | 0,72 | 0,70 | 0,75 | 0,73 | 0,72 |
| | | T0 = 5.5s | 1,14 | 0,77 | 0,75 | 0,74 | 0,76 | 0,74 | 0,73 | 0,78 | 0,76 | 0,75 |
| | | T0 = 6.5s | 0,97 | 0,79 | 0,77 | 0,76 | 0,78 | 0,77 | 0,75 | 0,80 | 0,78 | 0,77 |
| | | T0 = 7.5s | 0,84 | 0,81 | 0,79 | 0,78 | 0,80 | 0,78 | 0,77 | 0,81 | 0,80 | 0,79 |
| | | T0 = 8.5s | 0,74 | 0,82 | 0,80 | 0,79 | 0,82 | 0,80 | 0,79 | 0,83 | 0,81 | 0,80 |
| 135 deg | | T0 = 9.5s | 0,66 | 0,83 | 0,82 | 0,80 | 0,83 | 0,81 | 0,80 | 0,84 | 0,82 | 0,81 |
| | | T0 = 4.5s | 0,31 | 0,90 | 0,89 | 0,88 | 0,90 | 0,89 | 0,88 | 0,91 | 0,90 | 0,89 |
| | | T0 = 5.5s | 0,42 | 0,88 | 0,86 | 0,85 | 0,87 | 0,86 | 0,85 | 0,88 | 0,87 | 0,86 |
| | | T0 = 6.5s | 0,45 | 0,87 | 0,86 | 0,85 | 0,87 | 0,85 | 0,84 | 0,88 | 0,86 | 0,85 |
| | | T0 = 7.5s | 0,45 | 0,87 | 0,86 | 0,85 | 0,87 | 0,85 | 0,84 | 0,88 | 0,86 | 0,85 |
| | | T0 = 8.5s | 0,44 | 0,87 | 0,86 | 0,85 | 0,87 | 0,85 | 0,84 | 0,88 | 0,87 | 0,86 |
| 180 deg | | T0 = 9.5s | 0,42 | 0,88 | 0,86 | 0,85 | 0,87 | 0,86 | 0,85 | 0,88 | 0,87 | 0,86 |
| | | T0 = 4.5s | 0,14 | 0,96 | 0,95 | 0,94 | 0,96 | 0,95 | 0,94 | 0,96 | 0,95 | 0,95 |
| | | T0 = 5.5s | 0,12 | 0,97 | 0,96 | 0,95 | 0,97 | 0,96 | 0,95 | 0,97 | 0,96 | 0,96 |
| | | T0 = 6.5s | 0,23 | 0,92 | 0,91 | 0,90 | 0,92 | 0,91 | 0,90 | 0,93 | 0,92 | 0,91 |
| | | T0 = 7.5s | 0,29 | 0,91 | 0,90 | 0,89 | 0,90 | 0,89 | 0,88 | 0,91 | 0,90 | 0,89 |
| | | T0 = 8.5s | 0,31 | 0,90 | 0,89 | 0,88 | 0,90 | 0,89 | 0,88 | 0,91 | 0,90 | 0,89 |
| | T0 = 9.5s | 0,32 | 0,90 | 0,89 | 0,88 | 0,90 | 0,88 | 0,87 | 0,91 | 0,89 | 0,88 | |

| 12 | | We | foil 1 | foil 2 | foil 3 | foil 4 | foil 5 | foil 6 | foil 7 | foil 8 | foil 9 | |
|----------------|------------------|------------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|------|
| knots | Head | | | | | | | | | | | |
| | seas | T0 = 4.5s | 2,62 | 0,61 | 0,58 | 0,56 | 0,60 | 0,57 | 0,55 | 0,62 | 0,60 | 0,57 |
| | | T0 = 5.5s | 1,96 | 0,66 | 0,64 | 0,62 | 0,65 | 0,63 | 0,61 | 0,67 | 0,65 | 0,63 |
| | | T0 = 6.5s | 1,55 | 0,70 | 0,67 | 0,66 | 0,69 | 0,67 | 0,65 | 0,71 | 0,69 | 0,67 |
| | | T0 = 7.5s | 1,28 | 0,73 | 0,70 | 0,69 | 0,72 | 0,70 | 0,68 | 0,74 | 0,71 | 0,70 |
| | | T0 = 8.5s | 1,08 | 0,75 | 0,73 | 0,71 | 0,74 | 0,72 | 0,71 | 0,76 | 0,74 | 0,72 |
| 45 deg | | T0 = 9.5s | 0,94 | 0,77 | 0,75 | 0,73 | 0,76 | 0,74 | 0,73 | 0,78 | 0,76 | 0,74 |
| | | T0 = 4.5s | 2,26 | 0,64 | 0,61 | 0,59 | 0,63 | 0,60 | 0,58 | 0,65 | 0,62 | 0,60 |
| | | T0 = 5.5s | 1,72 | 0,68 | 0,66 | 0,64 | 0,67 | 0,65 | 0,63 | 0,69 | 0,67 | 0,65 |
| | | T0 = 6.5s | 1,38 | 0,71 | 0,69 | 0,68 | 0,71 | 0,69 | 0,67 | 0,72 | 0,70 | 0,69 |
| | | T0 = 7.5s | 1,15 | 0,74 | 0,72 | 0,70 | 0,73 | 0,71 | 0,70 | 0,75 | 0,73 | 0,71 |
| | | T0 = 8.5s | 0,98 | 0,76 | 0,74 | 0,73 | 0,75 | 0,74 | 0,72 | 0,77 | 0,75 | 0,74 |
| 90 deg | | T0 = 9.5s | 0,86 | 0,78 | 0,76 | 0,75 | 0,77 | 0,75 | 0,74 | 0,79 | 0,77 | 0,75 |
| | | T0 = 4.5s | 1,40 | 0,71 | 0,69 | 0,67 | 0,71 | 0,68 | 0,67 | 0,72 | 0,70 | 0,68 |
| | | T0 = 5.5s | 1,14 | 0,74 | 0,72 | 0,70 | 0,73 | 0,71 | 0,70 | 0,75 | 0,73 | 0,72 |
| | | T0 = 6.5s | 0,97 | 0,76 | 0,74 | 0,73 | 0,76 | 0,74 | 0,72 | 0,77 | 0,75 | 0,74 |
| | | T0 = 7.5s | 0,84 | 0,78 | 0,76 | 0,75 | 0,78 | 0,76 | 0,74 | 0,79 | 0,77 | 0,76 |
| | | T0 = 8.5s | 0,74 | 0,80 | 0,78 | 0,76 | 0,79 | 0,77 | 0,76 | 0,80 | 0,79 | 0,77 |
| 135 deg | | T0 = 9.5s | 0,66 | 0,81 | 0,79 | 0,78 | 0,80 | 0,79 | 0,77 | 0,82 | 0,80 | 0,79 |
| | | T0 = 4.5s | 0,53 | 0,83 | 0,82 | 0,81 | 0,83 | 0,81 | 0,80 | 0,84 | 0,83 | 0,81 |
| | | T0 = 5.5s | 0,56 | 0,83 | 0,81 | 0,80 | 0,82 | 0,81 | 0,79 | 0,83 | 0,82 | 0,81 |
| | | T0 = 6.5s | 0,55 | 0,83 | 0,81 | 0,80 | 0,82 | 0,81 | 0,79 | 0,84 | 0,82 | 0,81 |
| | | T0 = 7.5s | 0,53 | 0,83 | 0,82 | 0,81 | 0,83 | 0,81 | 0,80 | 0,84 | 0,83 | 0,81 |
| | | T0 = 8.5s | 0,50 | 0,84 | 0,82 | 0,81 | 0,83 | 0,82 | 0,81 | 0,85 | 0,83 | 0,82 |
| 180 deg | | T0 = 9.5s | 0,47 | 0,85 | 0,83 | 0,82 | 0,84 | 0,83 | 0,81 | 0,85 | 0,84 | 0,83 |
| | | T0 = 4.5s | 0,17 | 0,93 | 0,92 | 0,91 | 0,93 | 0,92 | 0,91 | 0,94 | 0,93 | 0,92 |
| | | T0 = 5.5s | 0,32 | 0,88 | 0,87 | 0,86 | 0,88 | 0,86 | 0,85 | 0,89 | 0,87 | 0,86 |
| | | T0 = 6.5s | 0,38 | 0,87 | 0,85 | 0,84 | 0,86 | 0,85 | 0,84 | 0,87 | 0,86 | 0,85 |
| | | T0 = 7.5s | 0,40 | 0,86 | 0,85 | 0,84 | 0,86 | 0,84 | 0,83 | 0,87 | 0,85 | 0,84 |
| | | T0 = 8.5s | 0,40 | 0,86 | 0,85 | 0,84 | 0,86 | 0,84 | 0,83 | 0,87 | 0,85 | 0,84 |
| | T0 = 9.5s | 0,25 | 0,90 | 0,89 | 0,88 | 0,90 | 0,89 | 0,88 | 0,91 | 0,90 | 0,89 | |

| 10 | | We | foil 1 | foil 2 | foil 3 | foil 4 | foil 5 | foil 6 | foil 7 | foil 8 | foil 9 | |
|----------------|------------------|------------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|------|
| knots | Head | | | | | | | | | | | |
| | seas | T0 = 4.5s | 2,42 | 0,52 | 0,50 | 0,48 | 0,51 | 0,49 | 0,47 | 0,53 | 0,51 | 0,49 |
| | | T0 = 5.5s | 1,83 | 0,57 | 0,54 | 0,53 | 0,56 | 0,54 | 0,52 | 0,58 | 0,56 | 0,54 |
| | | T0 = 6.5s | 1,46 | 0,60 | 0,58 | 0,56 | 0,59 | 0,57 | 0,56 | 0,61 | 0,59 | 0,57 |
| | | T0 = 7.5s | 1,21 | 0,63 | 0,61 | 0,59 | 0,62 | 0,60 | 0,58 | 0,64 | 0,62 | 0,60 |
| | | T0 = 8.5s | 1,03 | 0,65 | 0,63 | 0,61 | 0,64 | 0,62 | 0,61 | 0,66 | 0,64 | 0,62 |
| 45 deg | | T0 = 9.5s | 0,89 | 0,66 | 0,65 | 0,63 | 0,66 | 0,64 | 0,63 | 0,67 | 0,65 | 0,64 |
| | | T0 = 4.5s | 2,12 | 0,54 | 0,52 | 0,50 | 0,54 | 0,51 | 0,49 | 0,56 | 0,53 | 0,51 |
| | | T0 = 5.5s | 1,63 | 0,58 | 0,56 | 0,55 | 0,58 | 0,56 | 0,54 | 0,59 | 0,57 | 0,56 |
| | | T0 = 6.5s | 1,31 | 0,61 | 0,59 | 0,58 | 0,61 | 0,59 | 0,57 | 0,62 | 0,60 | 0,59 |
| | | T0 = 7.5s | 1,10 | 0,64 | 0,62 | 0,60 | 0,63 | 0,61 | 0,60 | 0,65 | 0,63 | 0,61 |
| | | T0 = 8.5s | 0,94 | 0,66 | 0,64 | 0,62 | 0,65 | 0,63 | 0,62 | 0,67 | 0,65 | 0,63 |
| 90 deg | | T0 = 9.5s | 0,82 | 0,67 | 0,66 | 0,64 | 0,67 | 0,65 | 0,64 | 0,68 | 0,66 | 0,65 |
| | | T0 = 4.5s | 1,40 | 0,61 | 0,59 | 0,57 | 0,60 | 0,58 | 0,56 | 0,62 | 0,60 | 0,58 |
| | | T0 = 5.5s | 1,14 | 0,63 | 0,61 | 0,60 | 0,63 | 0,61 | 0,59 | 0,64 | 0,62 | 0,61 |
| | | T0 = 6.5s | 0,97 | 0,65 | 0,64 | 0,62 | 0,65 | 0,63 | 0,61 | 0,66 | 0,64 | 0,63 |
| | | T0 = 7.5s | 0,84 | 0,67 | 0,65 | 0,64 | 0,67 | 0,65 | 0,63 | 0,68 | 0,66 | 0,65 |
| | | T0 = 8.5s | 0,74 | 0,68 | 0,67 | 0,66 | 0,68 | 0,66 | 0,65 | 0,69 | 0,68 | 0,66 |
| 135 deg | | T0 = 9.5s | 0,66 | 0,70 | 0,68 | 0,67 | 0,69 | 0,68 | 0,66 | 0,70 | 0,69 | 0,68 |
| | | T0 = 4.5s | 0,67 | 0,69 | 0,68 | 0,67 | 0,69 | 0,67 | 0,66 | 0,70 | 0,69 | 0,67 |
| | | T0 = 5.5s | 0,66 | 0,70 | 0,68 | 0,67 | 0,69 | 0,68 | 0,66 | 0,70 | 0,69 | 0,68 |
| | | T0 = 6.5s | 0,62 | 0,70 | 0,69 | 0,68 | 0,70 | 0,68 | 0,67 | 0,71 | 0,70 | 0,68 |
| | | T0 = 7.5s | 0,58 | 0,71 | 0,70 | 0,68 | 0,71 | 0,69 | 0,68 | 0,72 | 0,70 | 0,69 |
| | | T0 = 8.5s | 0,54 | 0,72 | 0,70 | 0,69 | 0,71 | 0,70 | 0,69 | 0,73 | 0,71 | 0,70 |
| 180 deg | | T0 = 9.5s | 0,50 | 0,73 | 0,71 | 0,70 | 0,72 | 0,71 | 0,69 | 0,73 | 0,72 | 0,71 |
| | | T0 = 4.5s | 0,37 | 0,75 | 0,74 | 0,73 | 0,75 | 0,73 | 0,72 | 0,76 | 0,75 | 0,74 |
| | | T0 = 5.5s | 0,46 | 0,73 | 0,72 | 0,71 | 0,73 | 0,71 | 0,70 | 0,74 | 0,73 | 0,72 |
| | | T0 = 6.5s | 0,48 | 0,73 | 0,72 | 0,70 | 0,73 | 0,71 | 0,70 | 0,74 | 0,72 | 0,71 |
| | | T0 = 7.5s | 0,47 | 0,73 | 0,72 | 0,71 | 0,73 | 0,71 | 0,70 | 0,74 | 0,72 | 0,71 |
| | | T0 = 8.5s | 0,45 | 0,73 | 0,72 | 0,71 | 0,73 | 0,72 | 0,70 | 0,74 | 0,73 | 0,72 |
| | T0 = 9.5s | 0,43 | 0,74 | 0,73 | 0,71 | 0,73 | 0,72 | 0,71 | 0,75 | 0,73 | 0,72 | |