NTNU
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Department of Marine Technology

M.Sc.THESIS

Title: **Operational criteria for transporting wind turbine with WindFlip**	**Delivered:** 9 June 2010 **Availability:** Confidential
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Abstract

This master thesis explores the transportation part of the installation concept WindFlip, where fully assembled floating wind turbines are transported lying with a 5° slope on the barge WindFlip. The transportation phase is assumed to last for 24 hours while the total installation time is uncertain. The main object is to find the limiting sea state for the transportation. Several issues need to be taken into account, both physical strains and regulations. The assumed relevant physical strains are situations related to the wind turbine. This includes water impact on the turbine blades or the nacelle or large accelerations (0.3 G vertical acceleration on the nacelle is the maximum tolerable value). The limitations from regulations concern the duration of the operation and weather forecasts.

For finding the limiting sea state for the transportation the MARINTEK software ShipX Vessel Responses was used. When using a 30 m long and 0.5 m broad bilge keel and long-crested waves the limiting Hs for transit in 6 knots was calculated as 2.99 m. This was with a probability of failure on one of thousand wind turbines. For zero velocity and wave heading from behind the limiting Hs was calculated to be 4.26 m. This is suggested as a safe condition if there is a sudden change in weather during transportation. For further analyses the values were round off to respectively 2.5 m and 4 m. This made the results easier to work with and it could be considered as a safety margin which the regulations recommended to apply.

The next step was looking at measured wave data from the Gulf of Maine on the north-east coast of the USA. The seasonal variation was investigated and the five months from May to September came out as the calmest period of the year. Both the monthly mean values of Hs and operability due to the limiting sea states related to scatter diagrams showed this. In these five months more than 97 % of the wave data were within the operational limit and more than 99 % were within the safe condition. Also weather windows were investigated. The summer period is still the best time of the year and it generally looks like the installation operation has good possibilities to be carried through in this area especially during the five summer months. Nevertheless there should be possible to operate the rest of the year as well, but perhaps with a little more patience.

Keywords:
WindFlip
Transport operation criteria
Seasonal variation
Weather windows

Advisors:
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Master Thesis in Marine Technology

SPRING 2010

FOR

STUD. TECHN. IDUNN OLIMB

OPERATIONAL CRITERIA FOR TRANSPORTING WIND TURBINE WITH WINDFLIP

WindFlip is a new transportation solution for transportation of the floating offshore wind turbine HyWind. With the WindFlip solution HyWind is transported horizontally on the deck. The topic of this project is to discover and discuss the possible limiting factors for the transportation. Both environmental loads and regulations will be considered. Water on deck is one of the most probable stop criteria.

On this background, the student shall do the following in the thesis:

1. Concept description. Background for the project and description of issues during the transportation.
2. Regulations. What kind of regulations exists? Marine operations regulations from DnV? In what way could this limit the operation?
3. Use ShipX-Veres to determine the limiting sea state for operation..
4. Use measured wave data from Maine to determine the season and weather windows which are appropriate for transportation.

In the thesis the candidate shall present her 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 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.

Advisor: Professor Bernt Leira
Professor Dag Myrhaug

Deadline: 14.06.2010

Dag Myrhaug

Preface

The last semester of the Master's Degree Program Marine Technology at NTNU the students complete their five years of studies by writing a master thesis. The thesis gives 30 credits and is the only course the students have this semester. The master thesis unifies courses taken at NTNU and is the last contribution to the specialization in the chosen field of study. This report is the result of my master thesis. It has been done individually.

The previous semester the students of the Master's Degree Program Marine Technology wrote a 7.5 credits project thesis. This can be used as a pre-project to the master thesis. In my master thesis I chose to continue on the same subject and looking into the same problem area as in the project thesis, but I looked at the problems from new angles. I used other calculation tools and took the problems further.

This master thesis is written for WindFlip AS. The theme of it was established by WindFlip AS and me, and it was approved by the supervisors.

Important appliances have been MatLab, Excel and the MARINTEK software ShipX Vessel Responses (Veres). Important literature has been the curriculum of the courses TMR4215 Sea loads, TMR4235 Stochastic theory of sea loads and TMR4195 Design of offshore structures. The Users' manual for ShipX Veres has been a great support and I must thank Edvard Ringen and Dariusz Fathi for completive help with the program. I also want to thank Asle Natskår for help with the regulations for marine operations.

I will thank Torbjørn Mannsåker, Anders Hynne and the rest of the WindFlip team for help and support with different problems. I also will thank my two supervisors Dag Myrhaug and Bernt Leira for guidance through the semester.

Trondheim, 9 June 2010

Idunn Olimb

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List of symbols and abbreviations

Symbol	Explanation
(x,y,z)	Coordinates in the ShipX coordinate system
2D	Two-dimensional
3D	Three-dimensional
A_{jk}	Added mass coefficient in relevant equation of motion
B	Beam, vessel
B_{jk}	Damping coefficient in relevant equation of motion
Cd	Design criterion
C_{jk}	Restoring coefficient in relevant equation of motion
Co	Operation criterion
COG	Centre of gravity
DNV	Det Norske Veritas
F	Vertical distance from point to still water
F_{Hs}	Cumulative distribution of three-parameter Weibull
F_j	Force attached in relevant equation of motion
FP	Forward perpendicular
G	Acceleration of gravity, 9.81 m/s2
g	Acceleration of gravity, 9.81 m/s2
GM	Parameter related to stability, distance between centre of gravity and metacentre
g_x	Response per meter wave height
h	wave height
H(ω)	Transfer function
Hs	Significant wave height, the mean of the 1/3 largest waves in sea state.
i.e.	id est (latin), that is/means
ISO	International Organization for Standardization
k	Wave number, 2π/wave length
L	Length, vessel
LCG	Longtudinal centre of gravity
M_{jk}	Mass coefficient in relevant equation of motion
n	Permitted occurences of green water per hour
P	Probability of occurence
PM	Pierson Moskowitz
r_{44}	Radius of gyration roll
r_{55}	Radius of gyration pitch
r_{66}	Radius of gyration yaw
RAO	Response Amplitude Operator, here transfer function
RMS	Root mean square
s	Power of cosine related to wave spreading
S(ω)	Wave spectrum
$S_r(\omega)$	Response spectrum
t	Time in equation of motion
T	Draught, vessel

Tp	Peak period
Tr	Operational period
T_{zR}	The zero-crossing period of the relative motion
U	Velocity of vessel in ShipX - Veres
α	Safety value, relation between Co and Cd
α	Parameter in three-parameter Weibull distribution
β	Wave heading relative to the ship, meeting waves gives $\beta=0$
β	Parameter in three-parameter Weibull distribution
ζ	Wave elevation
ζ_a	Amplitude of ζ
η_1	Surge
η_2	Sway
η_3	Heave
η_4	Roll
η_5	Pitch
η_6	Yaw
η_k	Degree of freedom in equation of motion
$\tilde{\eta}_k$	Substitute for ηk
η_{ka}	Amplitude of ηk
η_{kr}	Relative motion
θ	Phase angle
θ	Wave spreading angle
θ_k	Phase angle
λ	Parameter in three-parameter Weibull distribution
σ_R	Standard deviation of the response
σ_x	Limiting motion criteria defined by user in ShipX - Veres
ω	Frequency of encounter
ω_0	Wave frequency

1 Introduction

The interest in renewable energy has increased rapidly the last years due to climate changes and a growing need for energy. Especially since the oil production is decreasing (at least in the North Sea, see Figure 1-1).

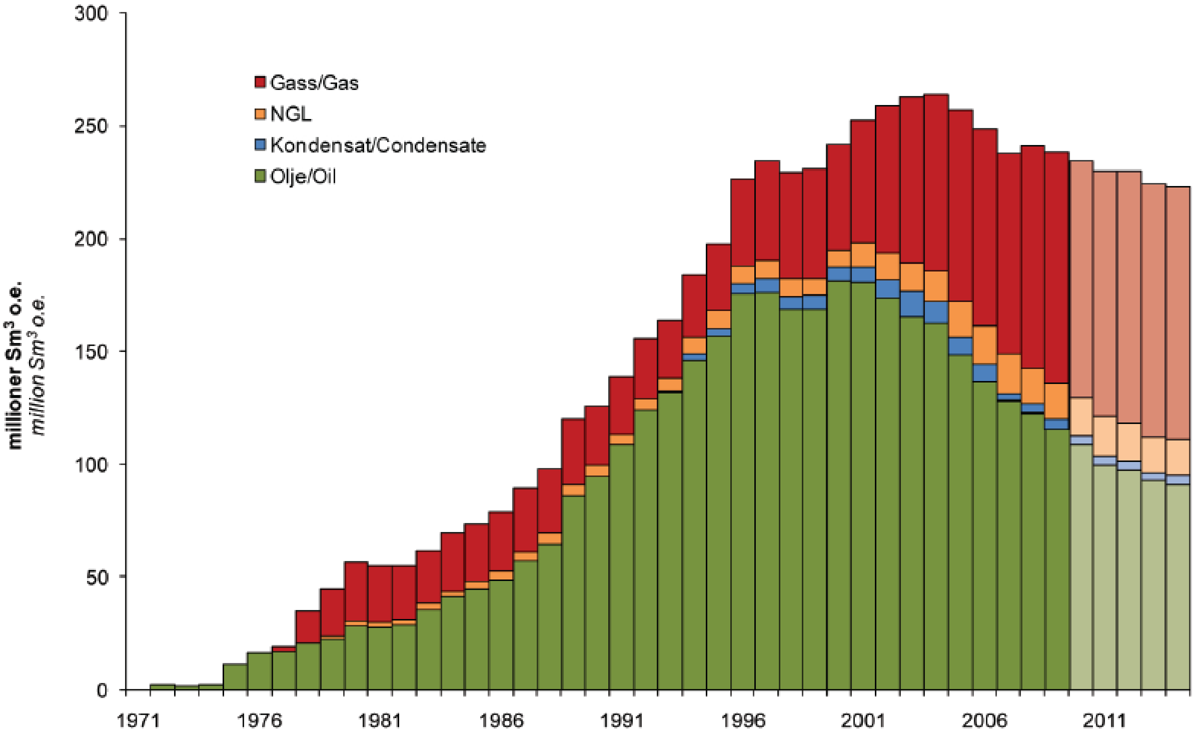


Figure 1-1 Actual and forecasted sales of petroleum 1971 – 2014 (Oljedirektoratet, 2010)

Modern wind turbines on land have been used for several years, and the technology is known and tried. The last years the idea of placing wind turbines offshore has been developed. There already exist parks with bottom fixed wind turbines located around the world, but they are dependent of shallow sea (<70m (Oljedirektoratet, 2009)). To employ deeper waters the concept of floating wind turbines has been developed. When an object is floating, new and different problems emerge. Issues related to motions and loads created by waves and other environmental factors must be looked into and solved. Also the installation of floating wind turbines can be very difficult.

When installing bottom fixed wind turbines the basis is placed steadily on the sea bottom. This means that the top of the turbine can be installed on a steady ground with a jacked-down crane vessel. The installation of a floating wind turbine is much more complicated. The turbine and the installing vessel will never be fixed because they are floating in waves and current.

WindFlip is a concept for transporting and installing floating wind turbines. The idea of WindFlip is to assemble the wind turbines ashore and transport them lying horizontal on the deck of a specialized barge. When arriving at the operation site the barge can by trimming the ballast flip slowly until it is standing vertically in the ocean. Then the wind turbine can be released from the barge and towed to the right spot. This will be more detailed described in chapter 2.

This report is written for WindFlip AS and it focuses on the transporting phase when the wind turbine lies horizontally on the barge. The rest of the installation is not considered. The objective is to find the limiting sea state for the transport. The regulations related to this should be found and looked into Further this project aim at looking into seasonal variation in sea states and clarify the probable operability of the transportation. This will be done be using measured metocean data from Maine on the north-east coast of the United States of America.

In the fall of 2009 a project thesis was written on this subject (Olimb, 2009). The main focus was the issue of water impact on the wind turbine which is assumed to mean failure (WindFlip AS, 2010d), and the relative motion of specific points on the turbine compared to the sea surface was explored. A simplified model was used to find operability limiting boundaries. The barge and the wind turbine on top were assumed to be one rigid body. Through calculations in MatLab it was possible to find the most probable largest relative wave and the expected largest relative wave for different sea states lasting a given period of time. Even though finding the probability of exceeding of a critical level for different sea state may have given a clearer result, this project gives a general idea of the critical level of significant wave height, Hs. It seems like it may be around 3 meter.

This master thesis will use numerical tools as ShipX Vessel Responses (VERES) to find the limiting sea state. In addition to green water on the turbine, strain like large accelerations will be taken into account. For the exploring of seasonal variation and weather windows MatLab and Excel will be helpful tools.

2 Concept description of WindFlip

WindFlip AS is a company established of a group of students from Marin Technology at NTNU. They have worked with this concept since 2008. They have in the spring of 2010 eight students writing their master thesis for them. In February 2010 there were done tests of a model (in size 1:45) of the concept in the model testing tanks at Marin Teknisk Senter at NTNU.

The idea behind the company was to find a solution for transporting floating offshore wind turbines. The concept is to transport complete assembled wind turbines lying horizontally (with an angle of five degrees, see Figure 2-3) on a special made barge. The barge is towed out from shore. When arriving at the decided operation spot, the barge will trim from its horizontal position to an angle of 85 degrees. In this angle the turbine stands vertically in the water, like it is supposed to in its operational life. The turbine can be released from the barge and towed away to the exact place of operation. There it will be anchored up and connected to the relevant power grid. After the turbine is unattached the barge can trim back to its horizontal position. Figure 2-1 shows the concept.

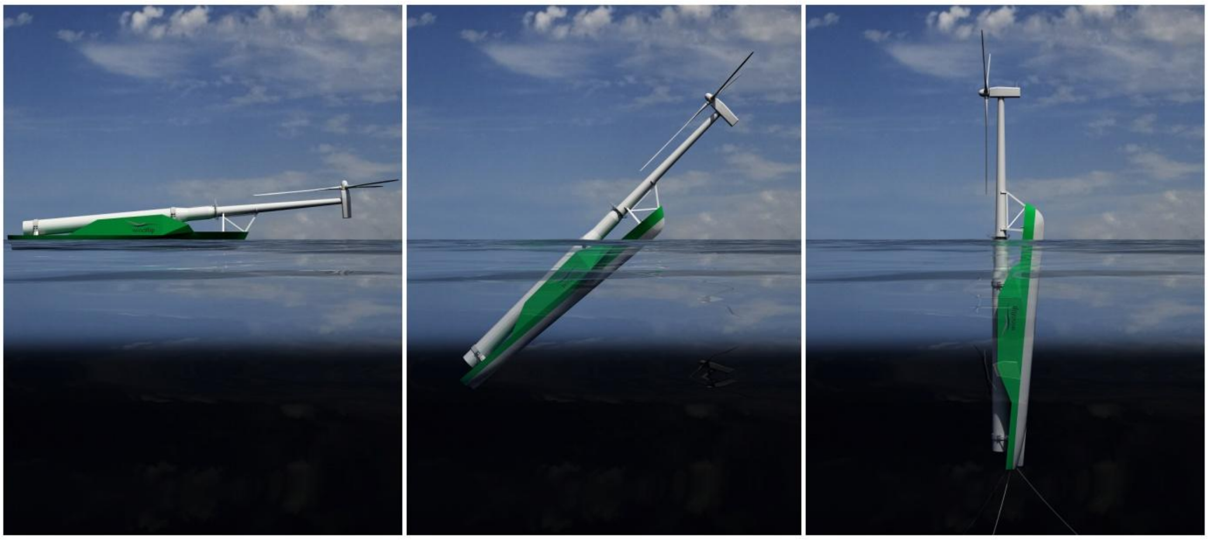


Figure 2-1 The concept of WindFlip

The wind turbine is relatively large with a total height of 190 m (110 m below the water line and 80 m above). The diameter is 6.5 m in the water line and 8.75 m on the substructure. The diameter of the rotor (the turbine blades) is about 120 m (See Appendix A). Table 2-1 assembles this information and Figure 2-2 illustrates the dimensions.

Table 2-1 Dimensions of wind turbine

Part of structure	[m]
Height of turbine, total	190
Diameter of turbine in waterline	6.5
Diameter of turbine substructure	8.75
Length of turbine blade	60

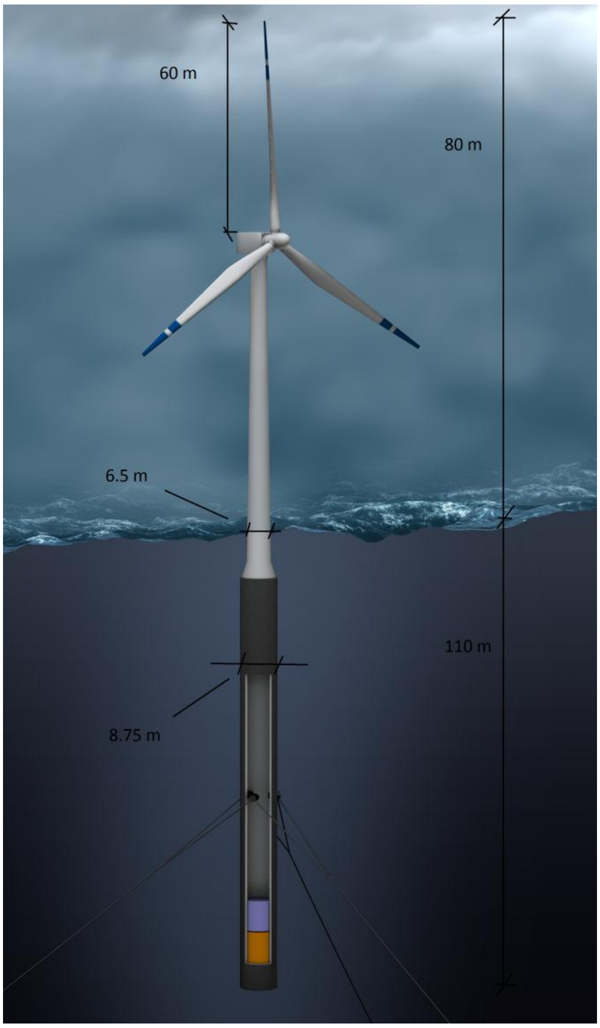


Figure 2-2 Dimensions of the wind turbine (edited image from Statoil (Statoil, 2008) for illustration)

WindFlip needs to be in accordance to the turbine when it comes to size to be able to transport it. The main dimensions (Appendix A) for the barge are represented in Table 2-2 and Table 2-3. Figure 2-3 and Figure 2-4 illustrates by edited images from the web site of WindFlip As (WindFlip AS, 2010a).

Table 2-2 Dimension of WindFlip, transit

WindFlip dimensions in transit (0° trim angle)	[m]
Length	140
Draft	5.7
Beam	27.8

Table 2-3 Dimension of WindFlip, launch

WindFlip dimensions in launch (85° trim angle)	[m]
Draft	120
Height	40

Figure 2-3 Dimension of WindFlip, transit

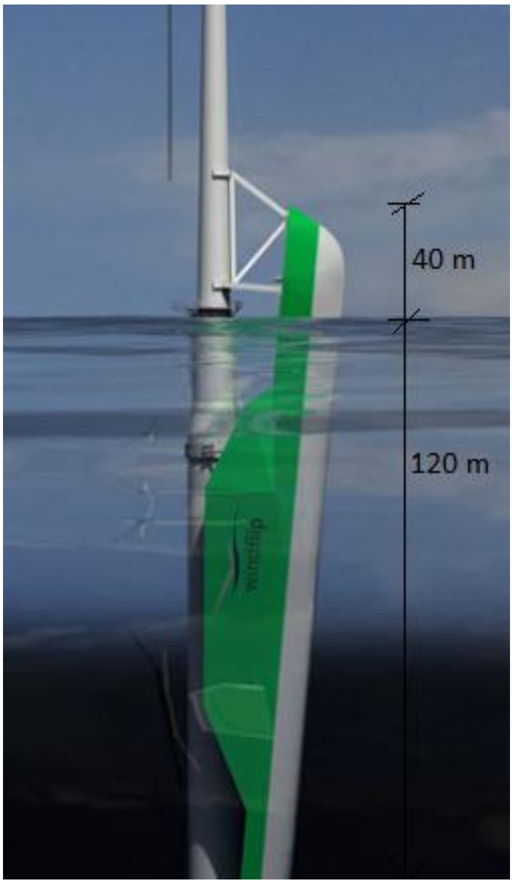


Figure 2-4 Dimension of WindFlip, launch

In this project the transport phase is explored and it aims for finding what sea state that is acceptable for transporting the wind turbine. The total installation operation has not been investigated. The assumed duration of the transport phase is 24 hours. This is a conservative assumption (WindFlip AS, 2010d). This does not include the total time of the installation, which is not given in this project (but it will exceed 24 hours as this is the assumed duration of the transit).

3 Limiting criteria

3.1 Different criteria

When looking at the transportation of the wind turbine, it is the limit of tolerance of the turbine that will lead to the limiting criteria. The nacelle (the part of the wind turbine where the blades are attached) and turbine blades are assumed to be sensitive and it is important to decide what they can sustain during the transportation. The equipment on board is less tender and is not considered as limiting factors (WindFlip AS, 2010d).

Water impact on the blades is thought to mean failure and should be thoroughly looked into. The turbine will be exposed to large forces and moments if a long, thin turbine blade tip is submerged in the seawater. There are also several important components in the nacelle that can be affected if a water impact occurs.

The wind turbine can also be sensitive to large accelerations and sudden movements in the barge. This should be taken into account when deciding the design sea state.

When determine the limit for acceptance it is decided by WindFlip AS that a passable loss of turbines is one of thousand (WindFlip AS, 2010c). This is the limit used when deriving the limiting sea state in later calculations.

3.2 Water impact

The limiting criteria related to water impact on the turbine will be explored by looking at different areas on the turbine. The tip of the turbine blades and the nacelle are the most important spots. In the analyses the coordinates of these spots will be interpreted, and through a given statistical limit the analyses will give a maximum sea states possible for the transport operation. The coordinates for these points are given in Table 3-1.

Table 3-1 Coordinates

Point	x [m]	y [m]	z [m]
Turbine blade tips	172.9	+- 52.2	31.9
Nacelle	157.93	0	18

3.3 Accelerations

WindFlip AS has in some extent looked into what accelerations the turbine can tolerate without experiencing fatigue (See Appendix B for more details). Some assumptions and simplifications have been used. For instance it has only been focused on the turbine tower and the loads it has been exposed to. Other components that can be limiting have been assumed to have the necessary capacity. When this analysis was done the concept of sea-fastening was not yet design and it is assumed that there can be made a sea-fastening system with the right capacity. The stresses on the turbine are assumed to be considerably smaller than the yield stress to avoid low cycle fatigue. The limit recommended from this analysis is that the vertical acceleration of the nacelle should not exceed three tenth of the acceleration of gravity (0.3 G).

3.4 Regulations and standards

For an operation with reference period less than 72 hours is defined as a weather-restricted operation (Det Norske Veritas, 2009)(ISO, 2007). The reference period includes both the expected operation time and an estimated contingency time. The operation of relevance in this master thesis is assumed to last for 24 hours, and it is concluded that it can be categorized as a weather-restricted operation. Table 3-2 shows the differences in criteria with various durations. For an operation lasting for less than 72 hours the specific weather window needs to be defined. This kind of operation should be planned using reliable historical data from a relevant area. The historical data should reach over a period of minimum 5 to 10 years. There should also be added a margin to the design weather criteria. A margin of 20 % is recommended.

Table 3-2 Return period of metocean parameters related to duration, reproduced from regulations (ISO, 2007)

Duration of theoperation	Return periods of metocean parameters
Up to 3 days	Specific weather window to be defined
3 days to 1-week	1 year , seasonal
1 week to 1 month	10 year, seasonal
1 month to 1 year	100 year, seasonal
More than 1 year	100 year, all year

For weather restricted operations Det Norske Veritas (DNV) has some criteria which consider the uncertainties in weather forecast (DNV, 1996). Table 3-3 is reproduced from these rules. It gives a safety value α for the weather forecast in connection with the duration of the operation and the design significant wave height. The operation criteria (Co) gotten from the weather forecast should be equal to or less than the design criteria (Cd) multiplied with the α-value (Co ≤ αCd). From the table it is seen that for an operation of less than 24 hours with a design Hs larger than 4 meter, the forecasted Hs should be 75 % of the design Hs.

Table 3-3 Operation criteria - weather forecast, reproduced from regulations (DNV, 1996)

Operational Period [hours]	**Design wave height (Hs) [m]**		
	1 < Hs ≤ 2	2 < Hs ≤ 4	Hs > 4
Tr < 12	0.68	0.76	0.80
Tr < 24	0.63	0.71	0.75
Tr < 48	0.56	0.64	0.67
Tr < 72	0.51	0.59	0.63

Another operational criterion is the *Beaufort 5* criterion. This implies the limiting start conditions of a towing operation. The wind should not be larger than Beaufort 5, which is the same as 8.0-10.7 m/s (Meteorologisk institutt), when the operation starts (Natskår, 2009).

The ISO regulations (ISO, 2007) say that a time restricted operation, if not able to complete the operation within the limits, should have the possibility to go into a safe condition or abort the operation. A safety condition can for instance mean to stop the vessel and anchor it up against the weather. If this is an option that will reduce the possibility for failure, must be investigated.

4 ShipX Vessel Responses (Veres)

4.1 The program

ShipX - Veres is an analytical program which uses various 2D strip theory formulations to calculate motion responses and loads for different vessel velocities and wave directions (Fathi, 2005). It is possible to make and employ 3D geometry files of the relevant vessel. Before running analyses relevant loading conditions need to be defined. If draught and trim angle are interpreted, ShipX calculates displacement, mass and GM-values. The radiuses of gyration need to be stated. The conditions of interest must also be given; wave directions, vessel speed and range of periods.

The model and its loading conditions are analyzed. When the analysis is finished, ShipX has two post-processors; Transfer function/Statistics and Operability/Regularity. Through the Transfer function/Statistics post-processor it is possible to make relevant transfer functions. Short term statistical analyses like finding response from a given sea state and long term statistical analyses can be done here. The Operability/Regularity post-processor makes it possible to define operational criteria and explore limiting sea states and operability due to given scatter diagrams. Figure 4-1 shows the course of action in the program (Fathi, 2005). In chapter 4.2 the theoretical background of the program will be more thoroughly explained.

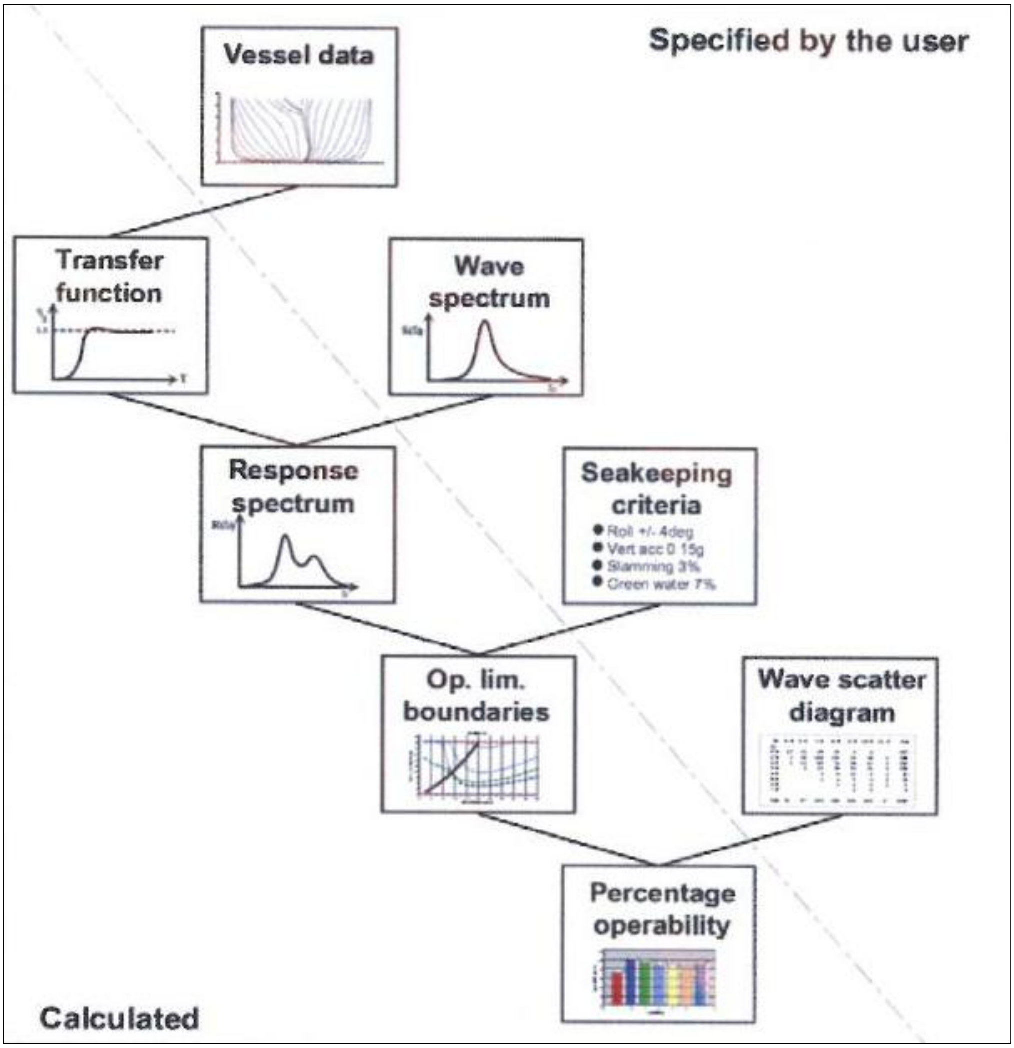


Figure 4-1 Course of action for ShipX – Veres (from manual (Fathi, 2005))

In February 2010 a model testing of WindFlip in the testing facilities at MARINTEK in Trondheim were carried through. There were done tests with regular waves of different frequencies to make transfer functions of the vessel. A comparison of the transfer functions from the model test and transfer functions calculated in ShipX – Veres shows a satisfactory resemblance (Hynne, 2010). An example of this is shown in Figure 4-2. More examples can be found in Appendix C. On this background it is assumed that ShipX – Veres is a sufficient numerical tool when analyzing hydrodynamic responses on WindFlip.

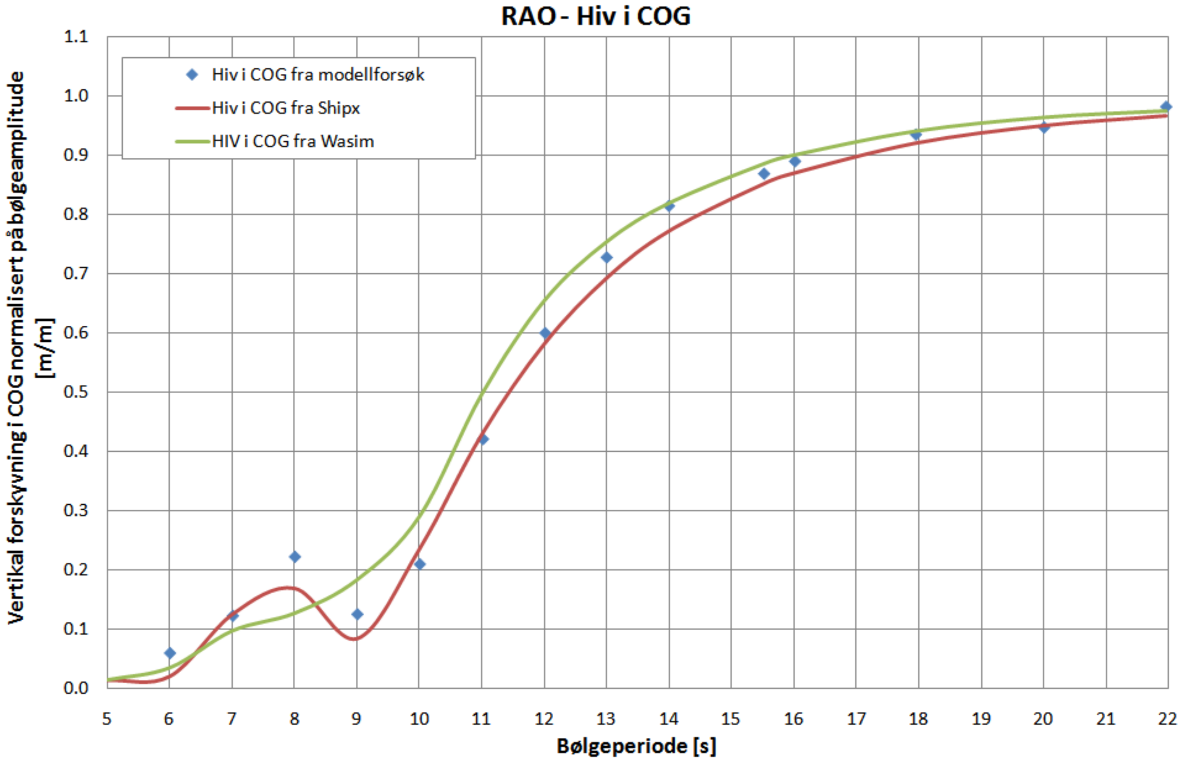


Figure 4-2 Example of comparison of RAOs (Hynne, 2010)

4.2 Theoretical background of the program

The equations and theories in this chapter are, if not stated otherwise, reproduced from or written with basis in the ShipX – Veres manual.

4.2.1 Assumptions

ShipX operates by taking some basic assumptions (Fathi, 2005). One of these is that the vessel oscillates harmonically with the same frequency as the frequency of encounter. Transient effects due to initial conditions and effects due to hydro elasticity are not accounted for. There is also assumed that it is a linear relation between the incident wave amplitude and the responses and that superposition can be used when calculating loads and motions. Potential theory is used which leads the fluid to be homogenous, non-viscous, irrotational and incompressible. Still viscous roll damping can be taken into account through empirical formulas. The form of the vessel is assumed to be slender which means that the length is much larger than the breadth and draught. The vessel is also assumed to be symmetric.

ShipX is based on strip theory. This is a theory which reduces three-dimensional problems to two-dimensional strips (Figure 4-3 illustrates this). There is no interaction between the strips. Total forces can be found by integrating the two-dimensional forces on each strip over the length of the vessel. Three-dimensional effects are neglected. In high speed theory interaction from the strips upstream is accounted for.

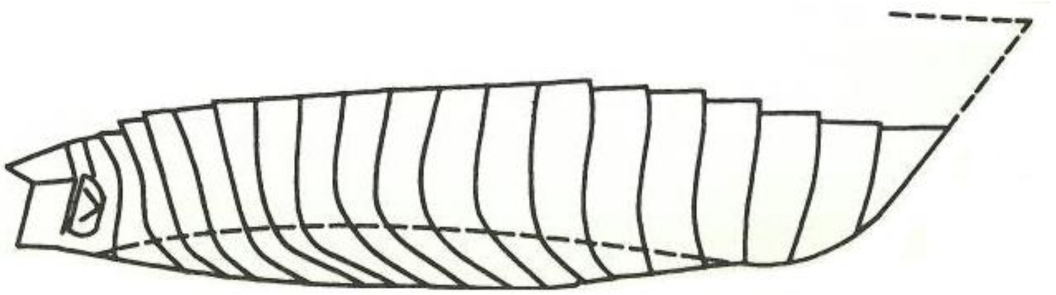


Figure 4-3 Illustration of strip theory for ships (from book (Faltinsen, 1990))

Linear strip theory is based on two assumptions. The first is that the wave amplitude from incoming waves is small compared to the characteristic dimensions of the ship. It is also assumed that the waves are far from breaking; that their steepness is small.

4.2.2 Basic definitions

The program defines a global coordinate system and the vessel motions are denoted with respect to this system. The x-y-plane coincides with the waterline in still water and the x-z-plane is in the symmetry plane of the vessel. The z-axis is passing through COG and with origin in the still water plane. There are defined six degrees of freedom; three translatory and three rotational displacements. These are described in Table 4-1 and Figure 4-4 (Fathi, 2005) shows the connection between degrees of freedom, vessel heading and wave heading. β denotes the angle of the wave heading relative to the ship.

Table 4-1 Description of degrees of freedom

Degree of freedom	Symbol	Description
Surge	η_1	Translation in x-direction
Sway	η_2	Translation in y-direction
Heave	η_3	Translation in z-direction
Roll	η_4	Rotation around x-axis
Pitch	η_5	Rotation around y-axis
Yaw	η_6	Rotation around z-axis

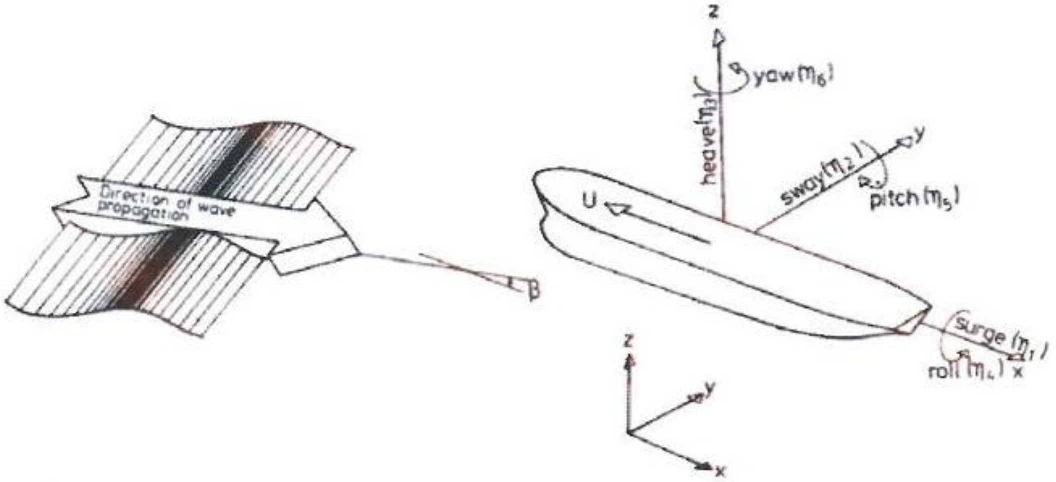


Figure 4-4 Degrees on freedom on ship and wave direction (from manual (Fathi, 2005))

It has been assumed that the ship will oscillate with the same frequency as the frequency of encounter. Equation (4.1) shows this frequency.

$$\omega = \omega_0 + \frac{\omega_0^2 U}{g} cos\beta \tag{4.1}$$

When the responses are assumed to be linear and harmonic the differential equations for each degree of freedom can be written as in equation (4.2).

$$\sum_{k=1}^{6} \left[(M_{jk} + A_{jk})\ddot{\eta}_k + B_{jk}\dot{\eta}_k + C_{jk}\eta_k \right] = F_j e^{i\omega t}, \qquad j = 1, \dots, 6 \tag{4.2}$$

When the different coefficients are determined, the differential equation can be solved numerically after first substituting η_k as in equation (4.3).

$$\eta_k = \tilde{\eta}_k e^{i\omega t} \tag{4.3}$$

The motion transfer function can then be described as in equation (4.4).

$$\eta_k(t) = \eta_{ka} cos(\omega t + \theta_k) \tag{4.4}$$

4.2.3 Viscous roll damping

Veres can include viscous roll damping even though it is not linear. The components that can be included are viscous effects due to skin friction stresses on the hull, eddy damping caused by pressure differences on the hull and bilge keel damping. The roll damping will consist of potential, linear and quadratic terms and the differential equation for roll is solved by using iteration. The method linearizes non-linear effects (Fathi, 2010). This depends on which wave amplitude that is chosen in the program. The chosen amplitude should be near the most typical wave height in the relevant area; significant wave height Hs in a sea state or mean value of Hs in a scatter diagram could be good choices. It will be conservative to choose small amplitudes in preference of larger ones. This is because large amplitudes will lead to large roll damping and maybe too small responses on the ship.

4.2.4 Transfer functions/Statistics

A transfer function is the ratio between the response and the amplitude of excitation. The wave elevation in LCG (the origin) is defined as in equation (4.5), and the motion transfer functions are defined as in equation (4.6). In these equations θ is the phase angle; the phase relation between the motion and the wave. The parameter η_a is the motion amplitude per unit wave amplitude. This amplitude (η_a) is often called response amplitude operator (RAO).

$$\zeta = \zeta_a cos(\omega t) \tag{4.5}$$

$$\eta_k(t) = \eta_{ka} cos(\omega t + \theta_k), \qquad k = 1, \dots, 6 \tag{4.6}$$

To explore slamming and green water the post-processor calculates relative vertical motion between a given position on the ship and the waves. This relative motion is described in equation (4.7). In this equation η is the complex amplitude of the relative vertical motions, η the complex amplitude of the local vertical motions and ζ the undisturbed wave elevation at the relevant position (defined in equation (4.8) where k is the wave number and β the wave heading).

$$\eta_{3r}(x, y, z) = \eta_3(x, y, z) - \zeta(x, y) \tag{4.7}$$

$$\zeta(x, y) = e^{-ik(xcos\beta\ + ysin\beta\ )} \tag{4.8}$$

The hull will cause some distortion in the waves close to it as it passes them. These equations are therefore most reliable in front of the ship. In this project green water is only relevant in points in front of the forward perpendicular (FP) and the equations are expected to give satisfying results.

Regarding wave spectra, the PM-spectrum will be applied in the calculations. This is suitable for fully developed sea, where the wind has been blowing over a relatively large area of water for a period long enough to let the high frequency waves fall into equilibrium. The PM-spectrum was suggested by Dariusz Fathi (Fathi, 2010) as this may give the best linear analyses for the limiting criteria.

In calculations it is possible to choose between long-crested and short-crested seas. For long-crested seas the waves and all their energy approach from one angle. Short-crested seas the energy is distributed over a given angle. The distribution function is proportional with $\cos^{2s}(\theta - \theta_0)$ (Myrhaug, 2007). Figure 4-5 shows the spreading function for an angle of 90 degrees from each side of the main direction. In ShipX it is possible to choose the power of cosine (2s) and the spreading angle.

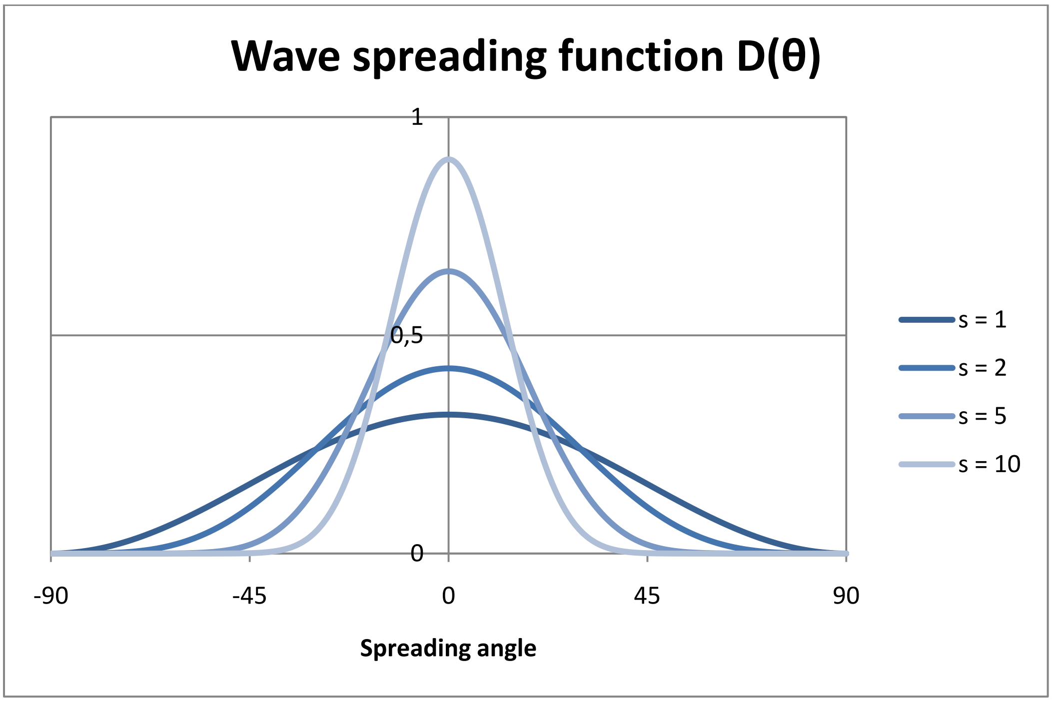


Figure 4-5 Wave spreading function reproduced from compendium (Myrhaug, 2007)

To find the response on the vessel ShipX uses the transfer functions (H(ω)) combined with the wave spectrum (S(ω)) to find the response spectrum ($S_R(\omega)$). To do this equation (4.9) is applied. The statistical values, as the standard deviation, σ_R, (here RMS-value), can be found from the response spectrum as shown in equation (4.10).

$$S_R(\omega) = |H(\omega)|^2 S(\omega) \tag{4.9}$$

$$\sigma_R^2 = \int_0^\infty S_R(\omega)\, d\omega = \int_0^\infty |H(\omega)|^2 S(\omega)\, d\omega \tag{4.10}$$

4.2.5 Operability/Regularity

In the Operability/Regularity post-processor operability limiting boundaries are obtained by combining short-term statistics (wave spectrum) with sea-keeping criteria specified by the user. The relevant criteria in this master thesis are motions and green water, and they will be explained here.

For a given motion criteria (e.g. acceleration) the limiting Hs is calculated directly from the calculation of short-term statistics. The value for the response per meter wave height, g_x (see equation (4.11)), is known from these calculations. Equation (4.12) shows how the limiting significant wave height is obtained (σ_x^{lim} is the limiting motion criteria defined by the user).

$$g_x = \frac{\sigma_x}{H_s} \tag{4.11}$$

$$H_s^{lim}\left(T_p\right) = \frac{\sigma_x^{lim}}{g_x} \tag{4.12}$$

For green water on a specific point on the vessel, the user can define how many occurrences that permitted per hour, n. This is used to calculate the accepted probability, P, of green water at the given point (see equation (4.13) where T_{zR} is the zero-crossing period of the relative motion). To find the limiting Hs for a green water criterion, the probability P is needed together with the user specified vertical distance from the point to the still sea surface, F, and the RMS-value of the relative vertical motion per meter Hs, g_r. The relation between these parameters is shown in equation (4.14).

$$P = \frac{nT_{zR}}{3600} \tag{4.13}$$

$$H_s^{lim}\left(T_p\right) = \frac{F}{g_r\sqrt{-2lnP}} \tag{4.14}$$

The operability results are given in plots, either Cartesian coordinates (xy-plots) or in polar plots. In the xy-plots Tp is the x-coordinate and Hs the y-coordinate. The graph in the plot shows the highest tolerable Hs for each Tp value. The program creates plots for each wave direction. In the polar plots the worst Hs-Tp value for each wave direction is plotted in a circular plot.

4.3 Analyses

A file with the geometry of WindFlip is made of WindFlip AS and is used in this master thesis (WindFlip AS, 2010b). Some parameters must be interpreted in addition to this model to obtain the right loading condition. The draft was taken from the WindFlip main dimensions (see chapter 2). The pitch radius of gyration was measured in the model testing in February (Hynne, 2010). The radii of gyration for roll and pitch were calculated from the equations (Lloyd, 1989) shown below in (4.15) and (4.16).

$$r_{44} \approx 0.3B \tag{4.15}$$

$$r_{66} \approx 0.225L \tag{4.16}$$

Table 4-2 shows the values given and calculated used in the analyses.

Table 4-2 Values for use in ShipX - Veres

Parameter	Symbol	Value
Draught	T	5.7 m
Roll radius of gyration	r_{44}	8.3 m
Pitch radius of gyration	r_{55}	43.3 m
Yaw radius of gyration	r_{66}	31.5 m

Further there were done analyses of the given loading condition with a forward velocity of six knots. The wave directions inserted were from 0 to 330 degrees with steps of 15 degrees. The given period range consisted of 31 values between 4 and 30 seconds to give basis for transfer functions.

Initially there were done analyses both with and without bilge keel. The bilge keel had a breath of 0.5 m and it reached over 30 meters of the vessel. It was seen that the results from the analyses with bilge keel gave better results than those without. The results were better especially at heading 90° where the limiting Hs increased with 87.5 %. This comparison can be seen in Appendix D. The analyses with bilge keel are the most realistic because WindFlip not will be built without a bilge keel(WindFlip AS, 2010d), and it is the results of these analyses that will be emphasized and shown in this report.

Based on the input values and the given conditions an analysis could be implemented. When the analysis was finished successfully the post-processor application could be started. First the post-processor Transfer functions/Statistics were used. Here the transfer functions for the vessel could be produced and it is transfer functions from this post-processor that are compared to the transfer functions from the model tests (see chapter 4.1).

In this post-processor it is possible to define points on the vessel which will be of interest in the analyses to come. As some of the limiting criteria are related to green water or accelerations on specific points, these points were specified in the program. The points are shown in Table 4-3 where the coordinates are related to the coordinate system described in chapter 4.2.2.

Table 4-3 Points of interest

Point	Description	x [m]	y [m]	z [m]
Nacelle	The meeting point of the blades	157.93	0	18
Blade 1	Turbine blade tip, starboard	172.9	52.2	31.9
Blade 2	Turbine blade tip, port	172.9	- 52.2	31.9

The next step was opening the other post-processor; Operability/Regularity. Here the relevant criteria were stated. The criteria used in this analysis is shown in Table 4-4, and there were done analyses for both n=100 and n=1000 to look at the difference between them. The criteria 1/(24*n) mean that one turbine is transported for 24 hours. If 1/n turbines are allowed to fail, the limiting condition can happen 1/(24*n) times per hour.

Table 4-4 Criteria used in ShipX Veres

Criteria	Description
Green water on Nacelle	1/(24*n) occurrences per hour, n: number of wind turbines (e.g. 1000)
Green water on Blade 1	1/(24*n) occurrences per hour
Green water on Blade 2	1/(24*n) occurrences per hour
Vertical acc. of Nacelle	Maximum 0.3 G (three tenth of the acceleration of gravity)

For analyzing the criteria and evaluate the operability PM-spectra were used. The Tp range was set to be 20 values between 5 and 25 seconds. Hs-values up to 20 m were explored. Both long- and short-crested seas were used. The short-crested seas were given a power of cosine of 4 and a wave spreading angle to each side of 90 degrees. The results were plotted in both xy-plots (with Hs and Tp along the axes) and polar plots to get a good look at the tolerable maximum Hs for each wave direction.

There were also done analyses at zero velocity. This was for investigating a safe condition (Ref 3.4). If the weather worsen and exceeds the given limits, there should be a possible condition that would ease the strain. This would typical mean to stop the vessel and position it up against the weather, so especially heading 0 degrees and 180 degrees will be looked into.

4.4 Results

In this chapter the most relevant results are shown. More results can be found in Appendix E.

4.4.1 Limiting Hs

In the following results the dimensioning Hs for different wave directions are stated. The criteria of green water have been varied to look at the importance of them. In ShipX Veres the probability were stated as occurrences per hour. The results are given in Table 4-5, and for a selected number of cases as a polar plot of all criteria. There are results both for long- (Figure 4-6) and short-crested seas (Figure 4-7). For heading 60° the results are displayed in a xy-plot as well as it gave the limiting Hs (Figure 4-8). The xy-plots for other headings can be found in Appendix E. The plots shown in this chapter are from the analyses with failure at one of thousand wind turbines; (1/(24·1000)≈) $4 \cdot 10^{-5}$ occurrences per hour.

Table 4-5 Limiting Hs

Failure at	Sea	Max Hs [m]
1/1000 wind turbines	Long-crested	2.99
1/1000 wind turbines	Short-crested	3.05
1/100 wind turbines	Long-crested	3.22
1/100 wind turbines	Short-crested	3.28

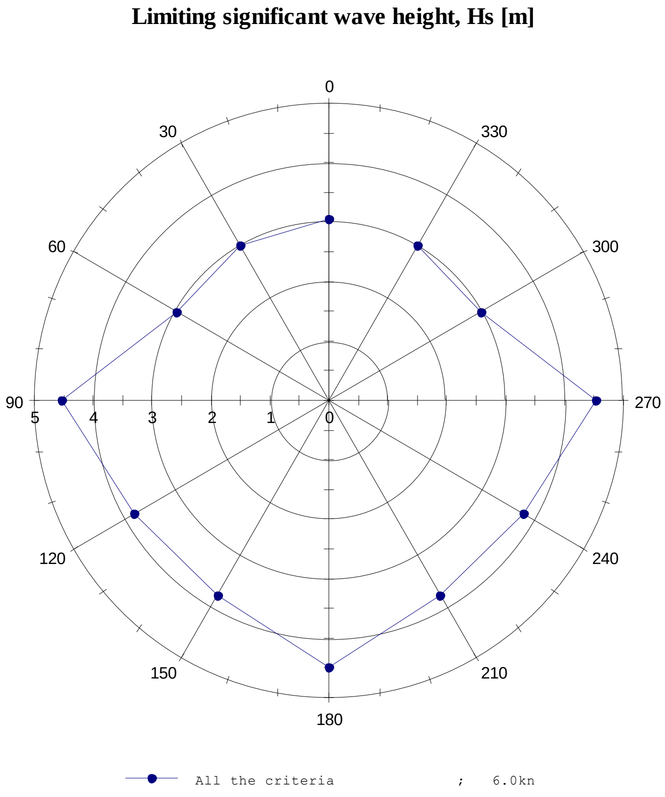


Figure 4-6 Limiting Hs, long-crested seas, 1/1000 wind turbines

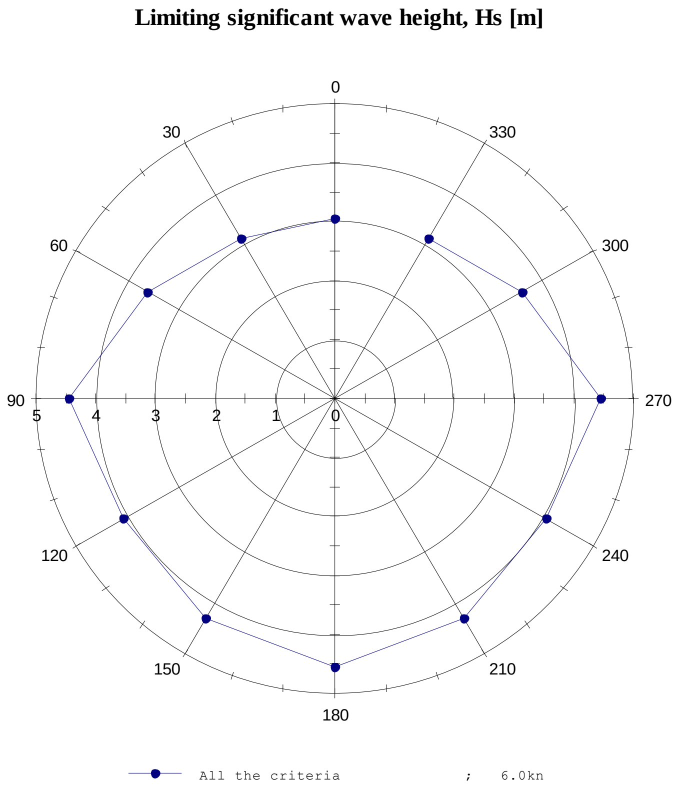


Figure 4-7 Limiting Hs, short-crested seas, 1/1000 wind turbines

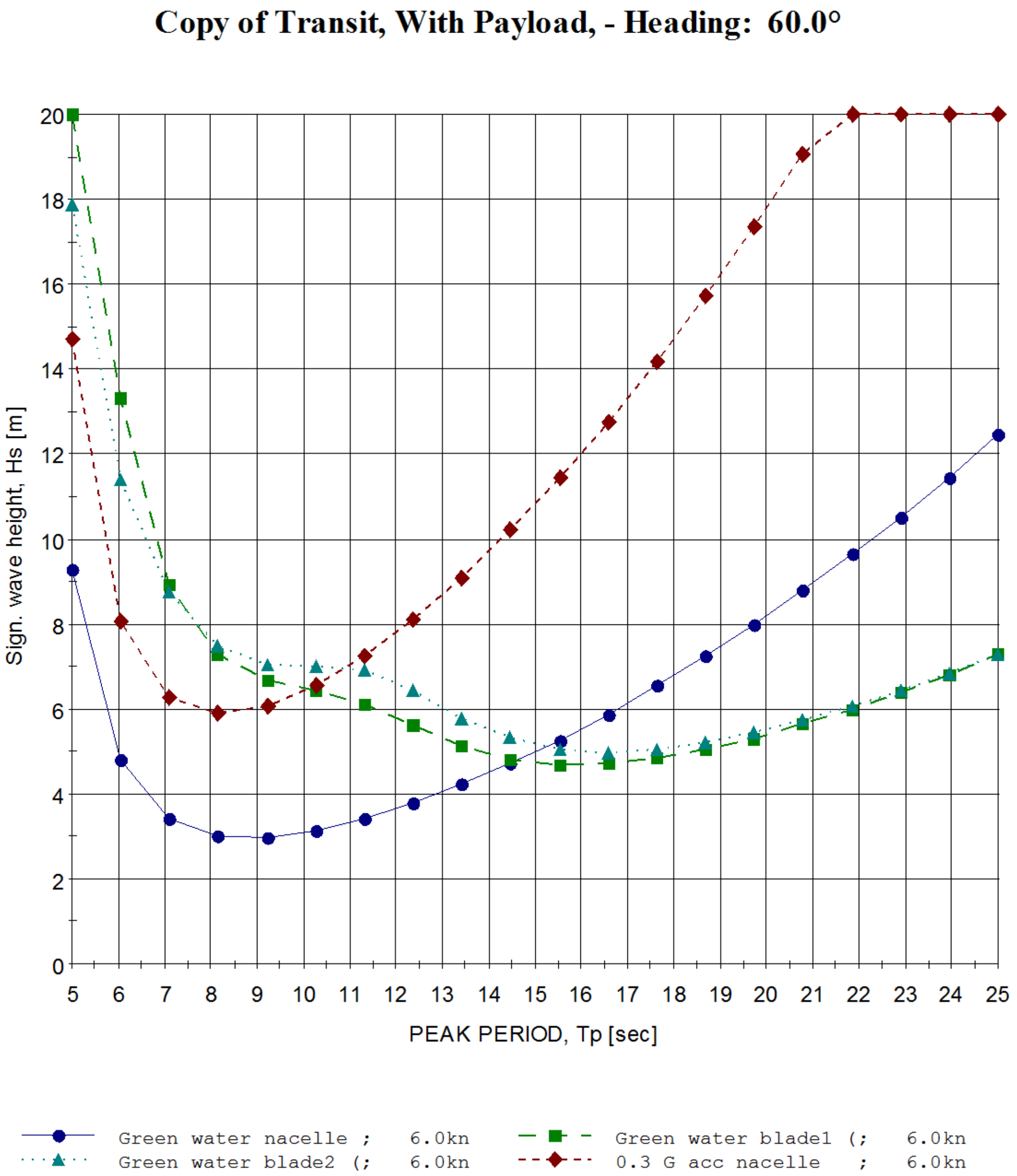


Figure 4-8 Heading 60°, xy-plot of limiting Hs, 6 kn

4.4.2 Limiting lines

Figure 4-9 shows the limiting Hs-Tp curve for both 1/100- and 1/1000-failure. The accepted sea states are found in the area under the curves.

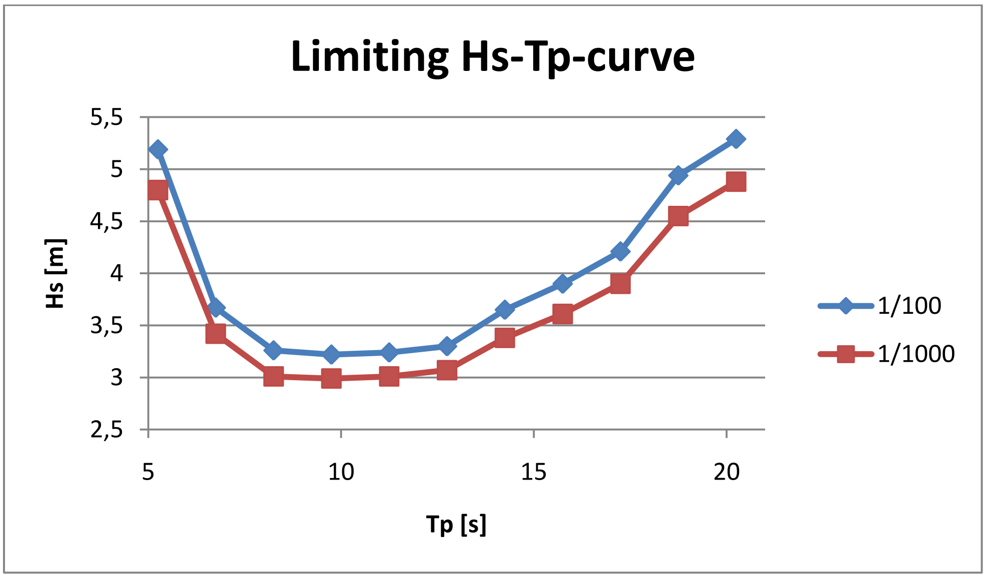
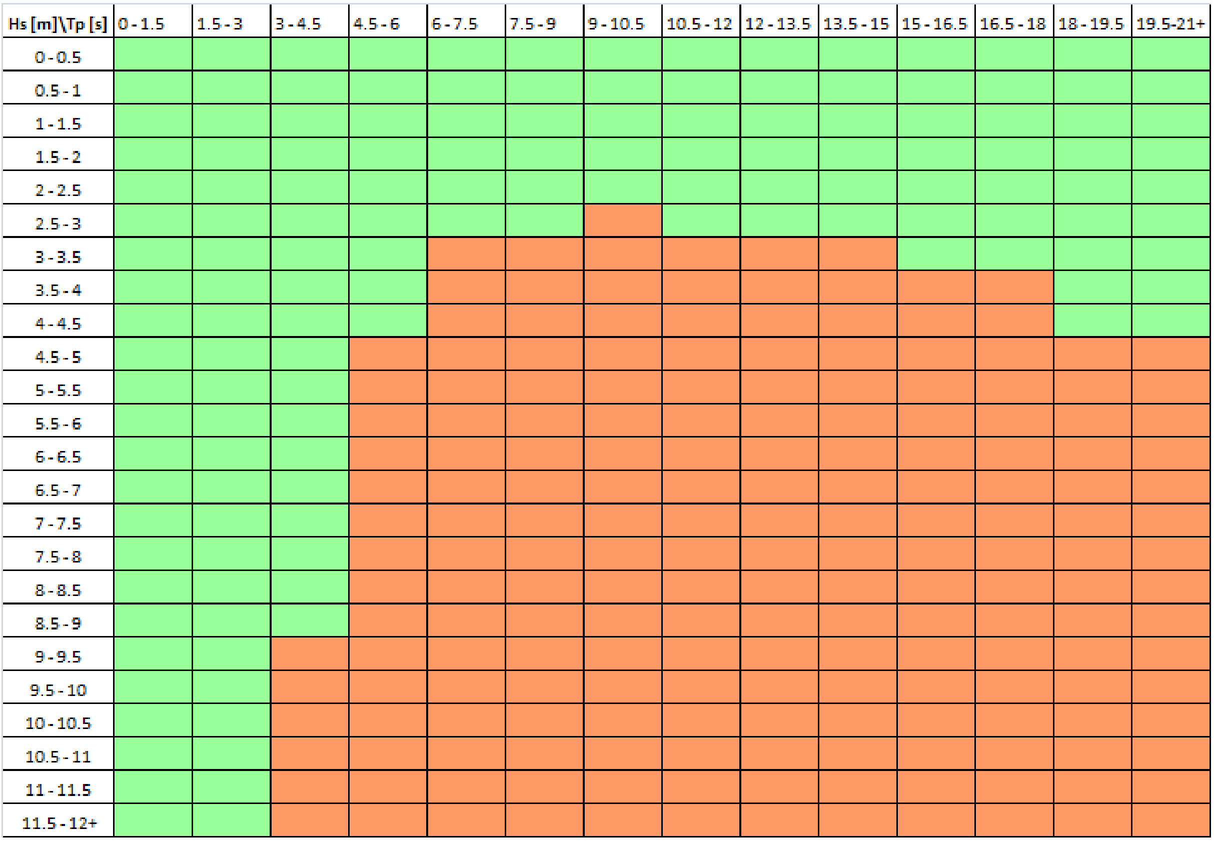


Figure 4-9 Limiting Hs-Tp-curve

Figure 4-10 shows the approved sea states when failure at 1/1000 wind turbines is accepted. Green is accepted, red is not.



Hs [m]\Tp [s]	0 - 1.5	1.5 - 3	3 - 4.5	4.5 - 6	6 - 7.5	7.5 - 9	9 - 10.5	10.5 - 12	12 - 13.5	13.5 - 15	15 - 16.5	16.5 - 18	18 - 19.5	19.5-21+
0 - 0.5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
0.5 - 1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
1 - 1.5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
1.5 - 2	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
2 - 2.5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
2.5 - 3	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩
3 - 3.5	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩
3.5 - 4	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩
4 - 4.5	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩
4.5 - 5	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
5 - 5.5	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
5.5 - 6	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
6 - 6.5	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
6.5 - 7	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
7 - 7.5	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
7.5 - 8	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
8 - 8.5	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
8.5 - 9	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
9 - 9.5	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
9.5 - 10	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
10 - 10.5	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
10.5 - 11	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
11 - 11.5	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
11.5 - 12+	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥

Figure 4-10 Accepted sea states when failure at 1/1000 turbines

4.4.3 Safe condition

For exploring a possible safe condition the limiting Hs for zero velocity has been derived. The results for all headings can be seen in Figure 4-11 (long-crested seas) and Figure 4-12 (short-crested seas). The exact results for the two headings 0° and 180° can be found in Table 4-6.

Table 4-6 Limiting Hs for zero velocity

	Heading [degrees]	Limiting Hs [m]
Long-crested seas	0	3.30
	180	4.26
Short-crested seas	0	3.28
	180	4.41

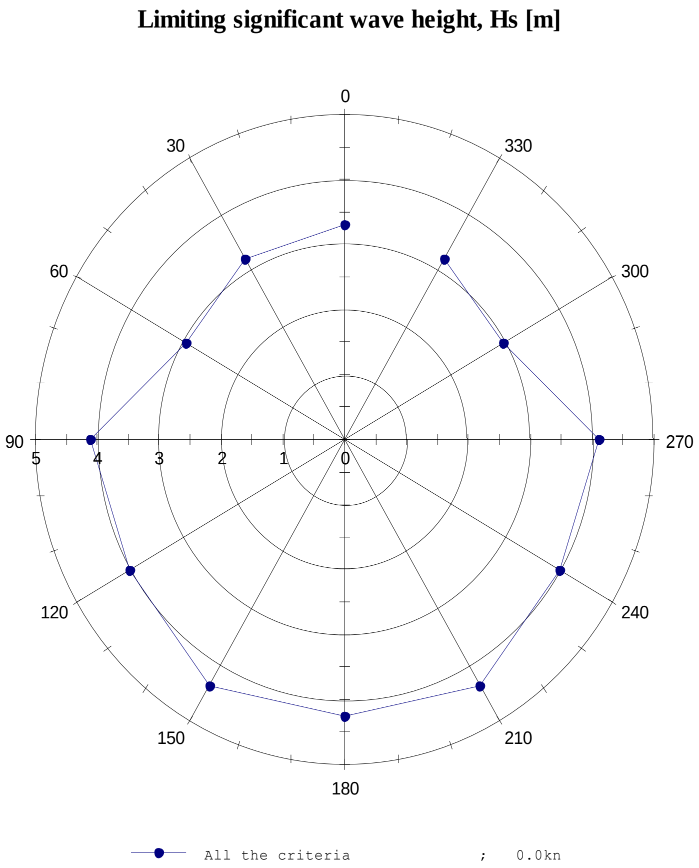


Figure 4-11 Limiting Hs, long-crested seas, 1/1000 wind turbines, zero velocity

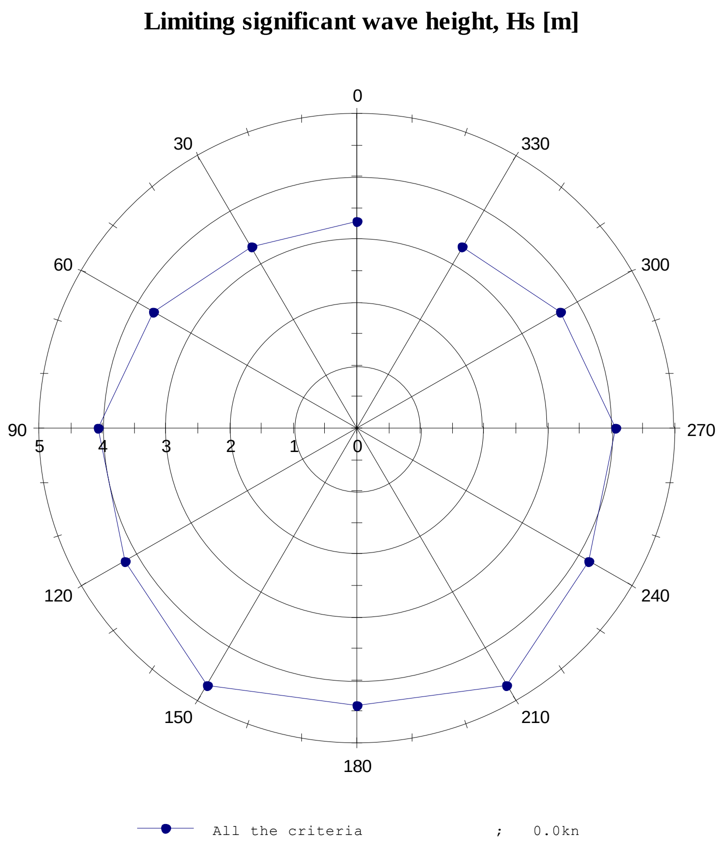


Figure 4-12 Limiting Hs, short-crested seas, 1/1000 wind turbines, zero velocity

4.5 Discussion of results from ShipX – Veres

When comparing the results from analyses with and without bilge keels, it is seen that the roll damping produced by bilge keels is significant (Appendix D). The most realistic analyses are those with bilge keel and these are the ones of interest in further discussions and calculations.

Concerning short- or long-crested seas, it is seen that short-crested seas gives larger maximum tolerable Hs than long-crested. It looks like having all the energy from the waves coming from one direction is worse than having it spread out to each side. Because of this the results from the analyses with long-crested waves will be used in further work.

When looking at the condition with bilge keel and long-crested seas, and a probability limit of failure at 1/1000 wind turbines, it is discovered that the limiting Hs is 2.99 m. The critical wave angle is 60 degrees on either side of the vessel (see Figure 4-6).

In the regulations and standards it is recommended to use a safety margin on the limiting Hs (see chapter 3.4). If a limiting significant wave height of 2.5 m is used in further work it includes a safety margin of 16 %. This is a little less than 20 % as was suggested, but is still a relatively good margin. In further work a limit of 2.5 m coincides well with a scatter diagram with a partition of Hs of 0.5 m.

When looking at each wave direction in the xy-plots it is possible to find the limiting Hs for each Tp. The curve for this is shown in Figure 4-9 and Figure 4-10 and it is seen that the worst Hs values appear for Tp values between 6 and 15. The limit becomes higher on each side of this Tp range.

Regarding safe condition it is clear that having the weather coming at the vessel from astern (heading 180°) is better than meeting it with the bow (heading 0°). This is concluded as the limiting Hs is about one meter higher for 180° than for 0° heading. It looks like waves with the headings 150° or 210° will give a higher limiting significant wave height, but this is not practical. If anchored up because of sudden change in weather during operation, the vessel will either be heading the weather or meet it with the stern. If positioned up with the stern against the weather it looks like the vessel can experience waves with Hs of 4.26 m with a probability of failure at one of thousand wind turbines. This is 1.27 m higher than the calculated operational limiting Hs of 2.99 m, and could be used as a safe condition if necessary.

5 Seasonal variation and weather windows

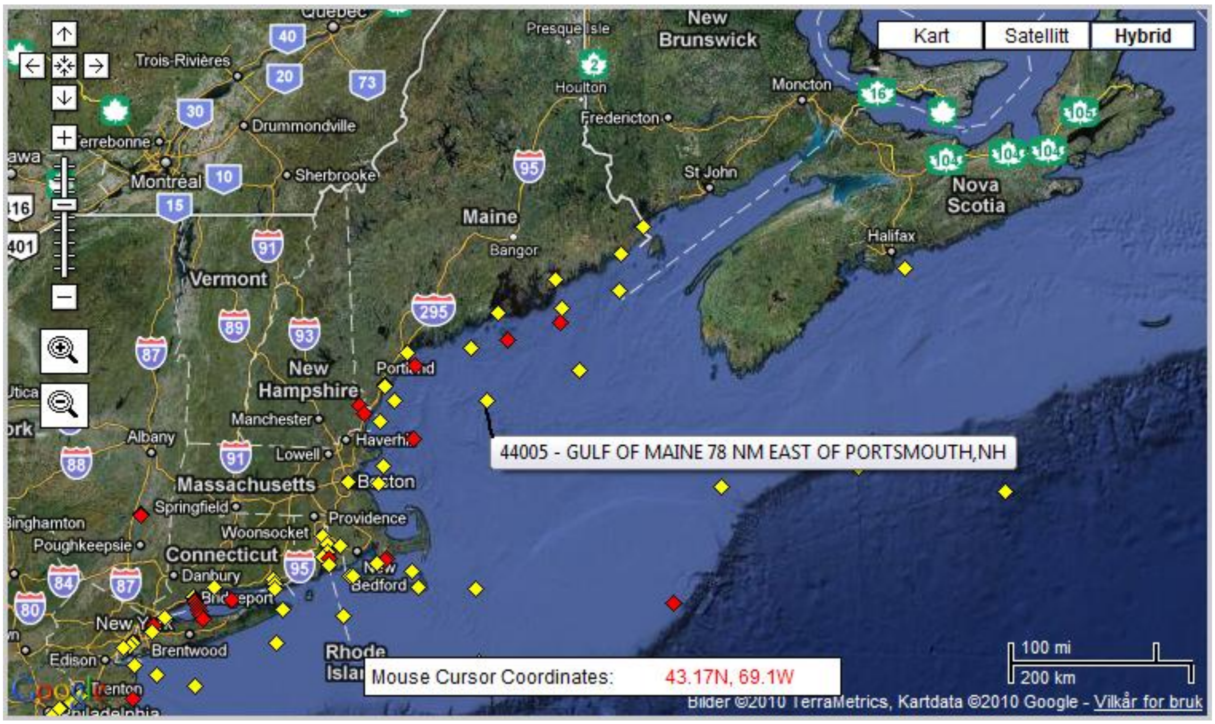
5.1 Background

Concerning operability it is of interest to explore the seasonal variation in a relevant area. It is important to look into what parts of the year that can be adequate for operation. Firstly the seasonal variation in measured metocean data will be examined. Then the operability related to the limiting sea state for the operation and the wave data will be looked into.

5.2 Metocean data

In this master thesis measurements from the ocean outside Maine north-east in the United States of America are used. This is at the moment one of the most relevant areas to start installing floating wind turbines. It is also good metocean data from this area ranging over several years, and these data can be found on the Internet (U. S. Government, 2010). The most relevant buoy (Buoy 44005 in Figure 5-1) is positioned in the Gulf of Maine and it has measured metocean data through the years 1979-2008. The period between each measurement is one hour, but the measurements through a year are seldom complete. Consequently there are holes in the data. The required data for the further analyses are significant wave height, Hs, peak period, Tp, and time. The measured data from the Gulf of Maine consists of these parameters among others.

When looking at the data it was found that the data from 1982 to 2008 were usable. The only exception was the data from 2000. The data from this year were not used. Still the usable data range over 26 years which is much more than the recommended minimum of five to ten years (see chapter 3.4).



44005 - GULF OF MAINE 78 NM EAST OF PORTSMOUTH,NH

Mouse Cursor Coordinates: 43.17N, 69.1W

Figure 5-1 Map that shows the position of the measuring buoy (U. S. Government, 2010)

5.3 MatLab

To analyze and use the found data from Maine, MatLab was used. A script given from WindFlip AS (Mannsåker, 2010) was edited to find weather windows and statistical values for the measured significant wave heights. The finished scripts used in this master thesis can be found in Appendix F. Figure 5-2 shows the course of action in the MatLab scripts.

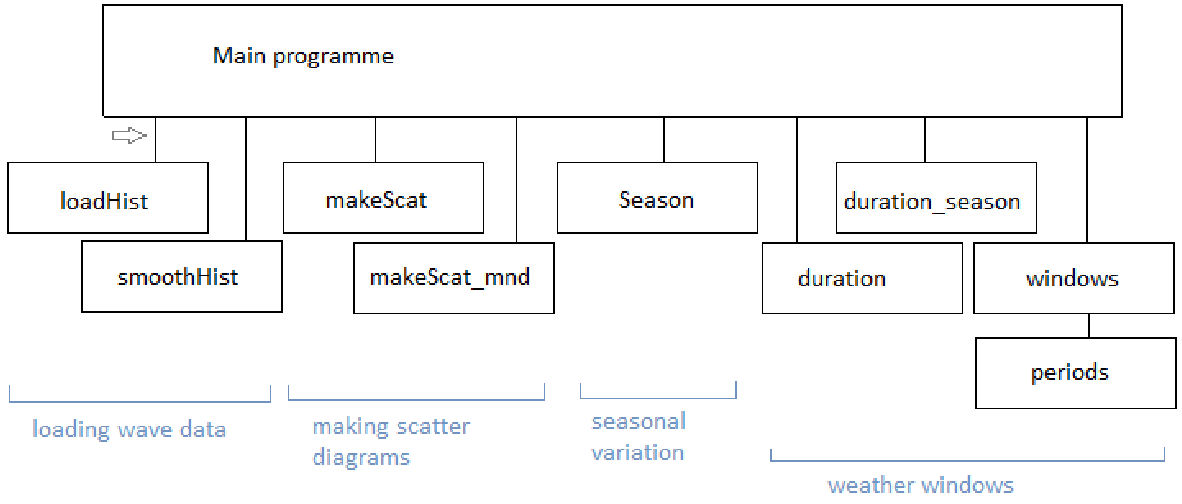


Figure 5-2 Flow diagram of the MatLab scripts

The program reads the data for all relevant years. It is programmed to take in all data even if there are holes in them. If desired, Hs as a function of time can be plotted for each year. Possible missing data and the trend in the data can then be explored.

For each year the mean value of Hs and Tp per month are calculated to discover seasonal variations. The mean values are taken for all months over the data for all the years. These results will indicate how these values change through the year and if there is a trend of seasonal variation.

The program makes a scatter diagram for all measured data. It also makes monthly scatter diagrams by collecting the data for the different months in twelve different scatter diagrams. This is also a possible way to indicate seasonal variation.

By dividing the data in groups related to the significant wave height with a given step size (typical 0.1 m), the MatLab script can identify the weather windows for the different years and seasons. The average weather window through the year and for the different seasons was found by conveying the data from MatLab to Excel. The corresponding standard deviation was also calculated.

When inserted the maximum accepted Hs (2.5 m) and the length of the operation (24 hours), the program can detect the possible windows that corresponds to this. It finds every unique possible period for the transportation, and divides the large weather windows into 24 hour periods. This means that a weather window of 100 hours will be counted as 4 windows, each of 24 hours (24·4=96).

The operation time of 24 hours only includes the transportation time, and the total WindFlip operation will last significantly longer. As this report only explores the transport to site, this total operation time will not be considered. When dividing larger windows into 24 hour periods, the total period has not been taken into account. Then a weather window of 100 hours should be divided by the total operation time. The script only finds the possible 24 hour openings for the transportation. The number of this will indicate the operability of the transport operation through the year. The script counts the number of 24 hour weather windows for each year, and calculates the mean value and the standard deviation for these numbers.

There were also made a verification script to investigate whether or not there could be found a correspondence in the variation of Tp and Hs. This will be described in chapter 5.4.

5.4 Verification and exploring the wave data

It was of interest to see if the significant wave height Hs and the peak period Tp varied in a corresponding pattern. This was done by making a MatLab script to choose a random year and a random time of this year. Figure 5-3 shows the course of action for these MatLab scripts.

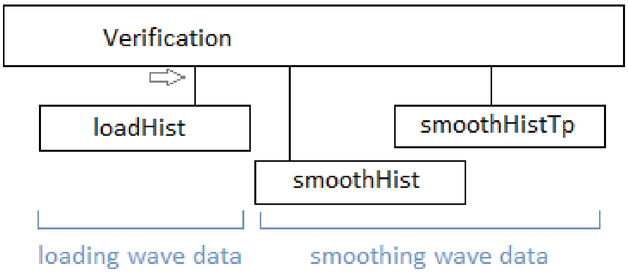


Figure 5-3 Flow diagram for verification MatLab scripts

The year of choice should preferably have continuous wave data through the whole year. The wave data for both 1985 and 1987 were convenient regarding this. By choosing different time periods in both years the correspondence of Hs and Tp could be investigated. The mean of Hs and Tp were calculated for the chosen time interval. The number of times the data crossed the mean level were counted for both Hs and Tp, and the mean crossing period were derived. From both examples it was clear that Tp varied with a higher frequency than Hs. The results from some chosen time intervals are shown in Table 5-1.

Table 5-1 Variation of Hs and Tp

Data	Mean crossing period, Hs [hours]	Mean crossing period, Tp [hours]
1985 (data: 1000-2000)	27.4	21.8
1985 (data: 3000-5000)	46.1	19.3
1987 (data: 1000-2000)	41.6	20.6
1987 (data: 3000-5000)	75.3	18.9

The conclusion from this is that the data of Hs and Tp not can be assumed to vary in the same rhythm. It may be difficult to look at the metocean limits for the operation through both Hs and Tp as it looks like Tp varies faster than Hs. The safest way to define the limits is to only look at the limiting Hs values and use the worst case. In this case this will mean a limiting significant wave height of 2.5 m.

In chapter 5.5 this has not been considered and the operability related to both Hs and Tp is explored by using the limiting curves found from the ShipX analyses.

5.5 Seasonal variation

By analyzing the metocean data from Maine for 1979-2008 it is possible to get an idea of how the weather conditions vary over the year. Firstly the average of Hs and Tp over each month has been found. The results from this are shown in Figure 5-4 and Figure 5-5.

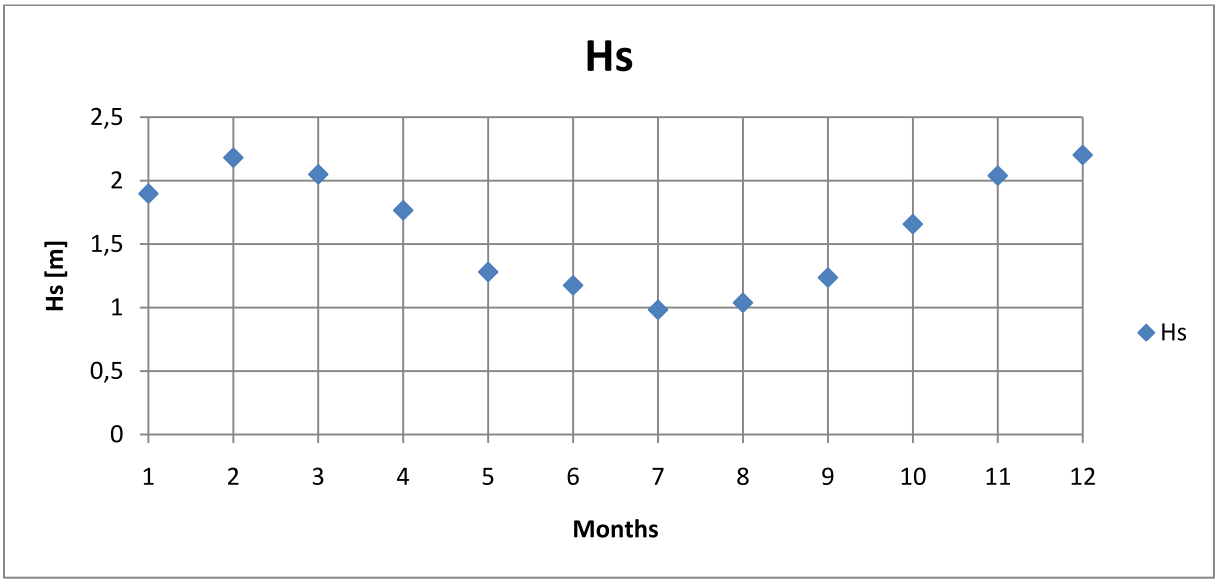


Figure 5-4 Monthly variation of average Hs

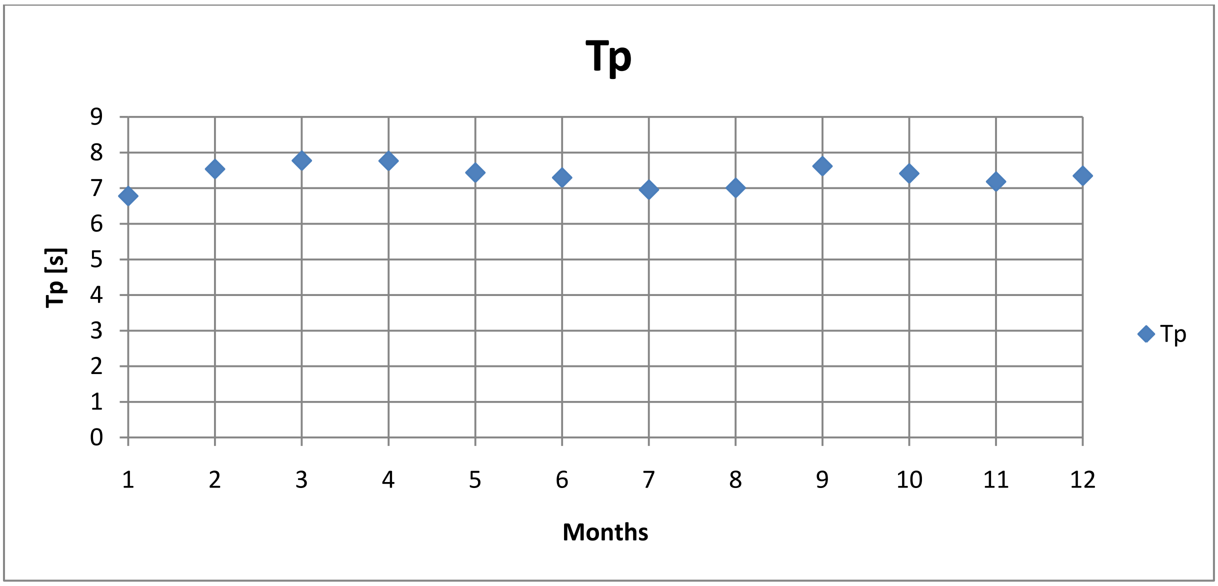
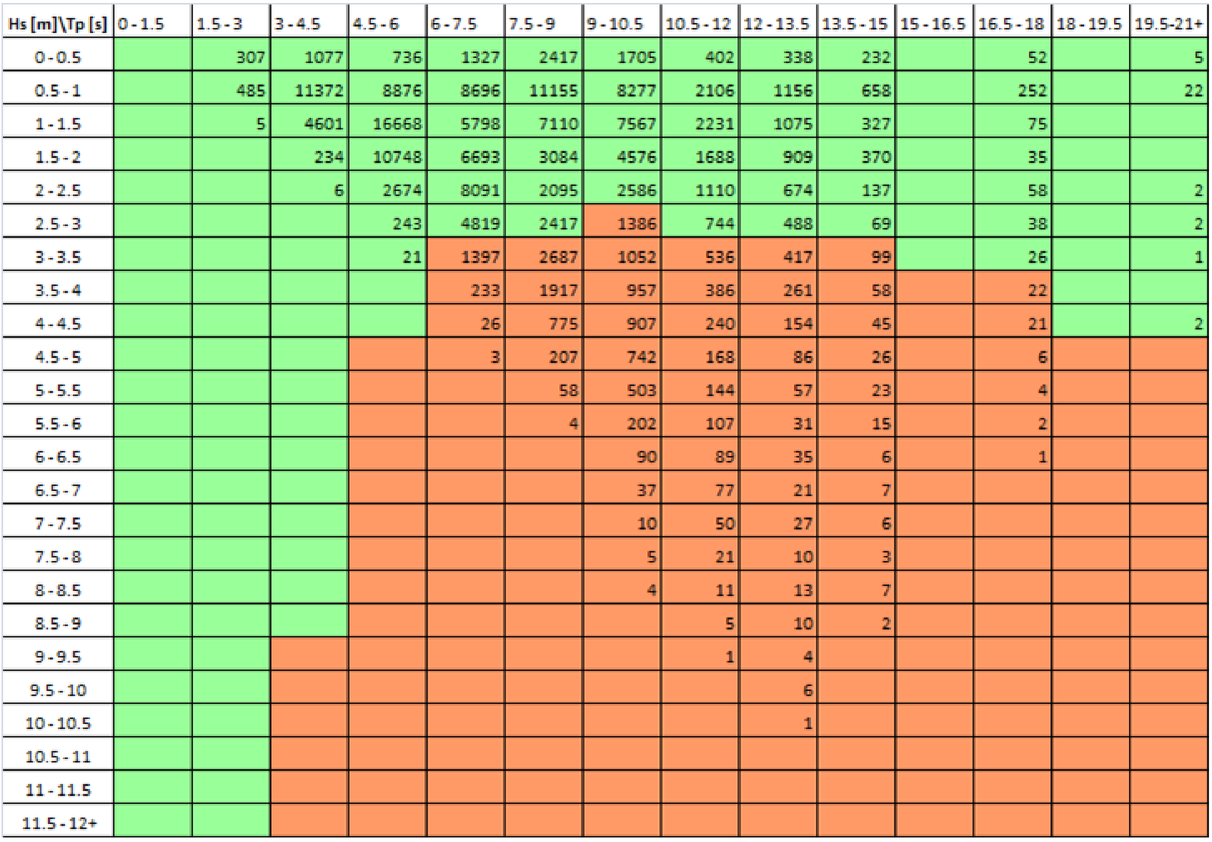


Figure 5-5 Monthly variation of average Tp

From these figures it is observed that the significant wave height, Hs, varies through the year with the highest mean Hs in February and December, and the lowest July. The period from May to September comes out as the calmest season of the year. The average peak period Tp varies less in percentages and it does not follow Hs evenly.

From the wave data it was also possible to create scatter diagrams. Both annual and monthly scatter diagrams were established. The limiting curve related to Hs and Tp (See chapter 4.4.2 and 4.5) were added to the scatter diagrams. The annual diagram is shown in Figure 5-6 and monthly scatter diagrams can be found in Appendix G.

It can be observed that the Hs values are distributed evenly over the Hs range while there are holes in the Tp values. There are no measurements with Tp between 15 s and 16.5 s or between 18 s and 19.5 s.



Hs [m]\Tp [s]	0-1.5	1.5-3	3-4.5	4.5-6	6-7.5	7.5-9	9-10.5	10.5-12	12-13.5	13.5-15	15-16.5	16.5-18	18-19.5	19.5-21+
0-0.5		307	1077	736	1327	2417	1705	402	338	232		52		5
0.5-1		485	11372	8876	8696	11155	8277	2106	1156	658		252		22
1-1.5		5	4601	16668	5798	7110	7567	2231	1075	327		75		
1.5-2			234	10748	6693	3084	4576	1688	909	370		35		
2-2.5			6	2674	8091	2095	2586	1110	674	137		58		2
2.5-3				243	4819	2417	1386	744	488	69		38		2
3-3.5				21	1397	2687	1052	536	417	99		26		1
3.5-4					233	1917	957	386	261	58		22		
4-4.5					26	775	907	240	154	45		21		2
4.5-5					3	207	742	168	86	26		6		
5-5.5						58	503	144	57	23		4		
5.5-6						4	202	107	31	15		2		
6-6.5							90	89	35	6		1		
6.5-7							37	77	21	7				
7-7.5							10	50	27	6				
7.5-8							5	21	10	3				
8-8.5							4	11	13	7				
8.5-9								5	10	2				
9-9.5								1	4					
9.5-10									6					
10-10.5									1					
10.5-11														
11-11.5														
11.5-12+														

Figure 5-6 Annual scatter diagram

The percentage of the data that was within the accepted area was determined for each month by dividing the number of data in the green area by the total number of data. Table 5-2 and Figure 5-7 shows the results of this. It is clear that the period from May to September is the most calm and reliable period of the year. The percentages of tolerable data for these five months are all over 97 %, which is significantly higher than for the rest of the year. This corresponds well to the calm period found from the monthly average Hs.

Table 5-2 Acceptable data

Month	Total data	Acceptable data	Percentage
January	16417	13244	80,7 %
February	14167	11624	82,0 %
Mars	15566	13173	84,6 %
April	14696	13362	90,9 %
May	15604	15250	97,7 %
June	16481	16252	98,6 %
July	15972	15918	99,7 %
August	15744	15586	99,0 %
September	14336	13950	97,3 %
October	13816	12445	90,1 %
November	13668	11528	84,3 %
December	11806	9418	79,8 %
All year	**178273**	**161750**	**90,7 %**

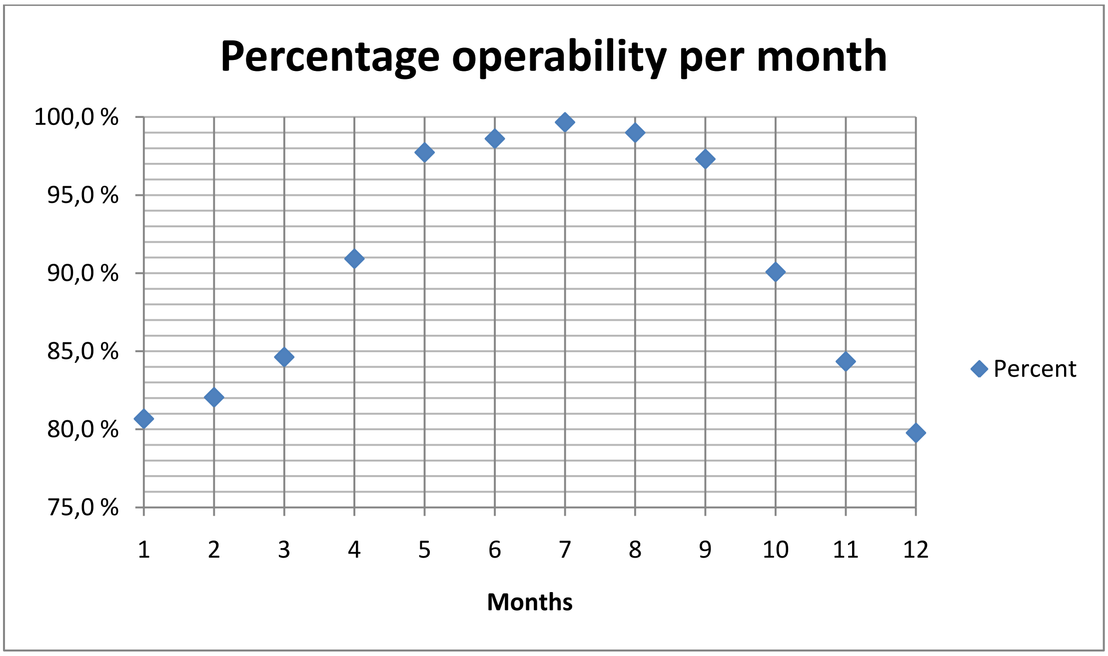


Figure 5-7 Percent monthly operability

On this background the year will be divided into two seasons; summer and winter. The summer season includes the five month from May at to September, and the winter season the rest of the months. When exploring weather windows in the next chapter this distribution of the year will be employed.

5.6 Weather windows

When the limiting criterion for the significant wave height is established it is possible to combine it with the metocean data to look at weather windows for the operation. After dividing the year into seasons, it is also possible to look at the seasonal variations in weather windows. This is to explore the operability of the operation through the year.

When given maximum Hs of 2.5 m, the weather windows fulfilling this demand were found. The average duration and the standard deviation for the duration were found, both annual and seasonal. The results of this are found in Table 5-3.

Table 5-3 Average weather windows, annual and seasonal

Period	Average weather window [hours]	Standard deviation [hours]
All year	85,6	206,3
Summer season	264,9	427,9
Winter season	47,6	64,8

From these results it is clear that the weather windows in the summer season generally larger than in the winter. The large standard deviations are a result of a large spread in the duration of the weather windows.

When given an operation time of 24 hours, the program finds the number of possible weather windows for this specific duration. This is done for both summer and winter season. The results from this are shown in Table 5-4.

Table 5-4 Average number of weather windows per season

Season	Average # weather windows per season	Standard deviation
Summer	103,0	37,1
Winter	80,1	30,6

From these results it is seen that most of the weather windows are to be found during the summer season. The difference between summer and winter is considerable as the winter season exists of seven months and the summer season of only five months. The average number of weather windows divided on the representative number of months gives about 20 windows per summer month and about 11 per month the rest of the year.

5.7 Safe condition

Through the analyses in ShipX – Veres a safe condition was suggested (4.4.3 and 4.5). This condition was to anchor up with the stern against the weather. In this way the limiting Hs were 4.26 m with a probability of failure at one of thousand wind turbines. By count the measured sea states below this criterion it was possible to calculate the percentage of data within 4 m. 4 m were used rather than 4.26 m to be able to use the scatter diagrams. This also gives a small safety margin. It is seen that for all months more than 92 % of the sea states have a significant wave height lower than 4 m. For all five summer months the percentage is higher than 99 %. This is shown in Figure 5-8.

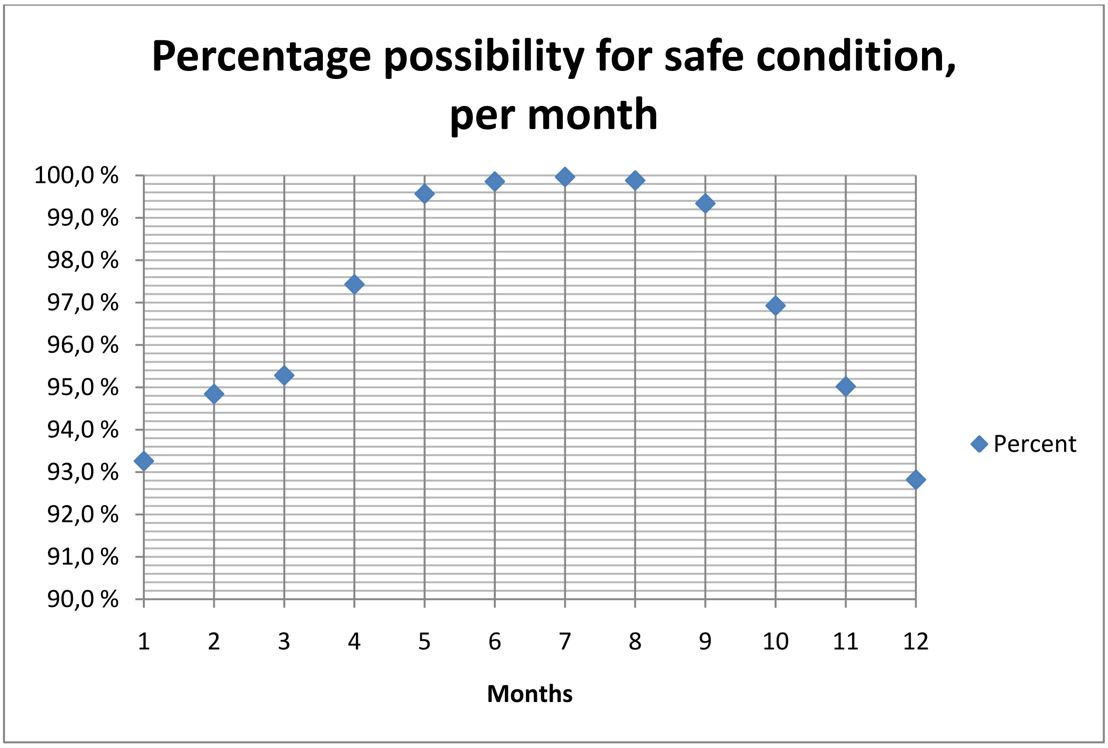


Figure 5-8 Percentage possibility for safe condition

6 Discussion

Firstly it is reasonable to discuss the discovered regulations and the limitation these contribute to. The most important issue related to this is whether or not the operation can be defined as weather restricted, i.e. with duration shorter than 72 hours. When only looking at the transportation which is assumed to last for 24 hours as in this master thesis, the transit operation can be called weather restricted. However the transit operation is only the start of the total installation operation, and it all should be accounted for. This is because a longer operation may exceed 72 hours and enter the category of weather-unrestricted operations. For weather-unrestricted operations other rules and regulations need to be taken into consideration.

The regulations advise a safety margin on design sea state of 20 %. In this master thesis a safety margin of 16 % were used. This a little less than the recommended value, but was chosen as it was a better number to work with in further calculations. It should also be mentioned that a safety margin of 16 % gave a limiting Hs of 2.5 m while a margin of 20 % would give a limiting Hs of 2.4 m. The difference is not significant, and a margin of 16 % will not give hazardous results.

In the regulations it is also recommended to have a safe condition in case there is a sudden change in weather. Through calculations in ShipX – Veres a suggested safe condition were found. This was to anchor the vessel with its stern against the weather. In this way the limiting Hs increases from 2.5 m to 4 m. By looking at the metocean data it is seen that the percentage of sea states below this limit is over 92 % for all months. For the summer months the percentage never gets beyond 99 %. From this it can look like the proposed safe condition is acceptable. Worse weather than this could of course occur, but it must be assumed that the weather forecasts can predict this with a relatively good precision. It can also be assumed that when the weather forecasts look good enough to go through with the operation, the change in weather will not be so big that the safe condition limit is exceeded.

Regarding weather forecast and the regulations for when to begin an operation, the limit depends on the length of the operation. In Table 3-3 the weather forecast needed for letting the operation start related to the duration and design Hs are shown. When the duration is set to be 24 hours, the category less than 48 hours must be used. This combined with a design Hs of 2.5 m gives a requisite weather forecast of 0.64 % of design Hs, i.e. 1.6 m. This may change when looking at the total installation operation.

When looking at the application of ShipX – Veres the basic assumptions must be discussed. The program is built on linear 2D strip theory which transforms a 3D problem into 2D strips. Interaction between the strips and other three-dimensional effects are neglected. Effects due to hydro elasticity are neither taken into account. Potential theory is used which means the fluid is defined as homogenous, non-viscous, irrotational and incompressible, but viscous roll damping can still be included through empirical formulas. Even though some of the assumptions may be speculative, the linear theory seams to give good results compared to three-dimensional programs and model tests. The model testing of the WindFlip concept strengthens this theory as the comparison between RAOs from the model tests and ShipX – Veres shows good similarities.

In the analyses PM-spectra were used. This was done for getting the best results from the limiting criteria analyses. If PM-spectra give a good impression of the sea states developing in the Gulf of Maine is not certain. If there are both swell and wind seas another spectrum should be used, i.e. Torsethhaugen.

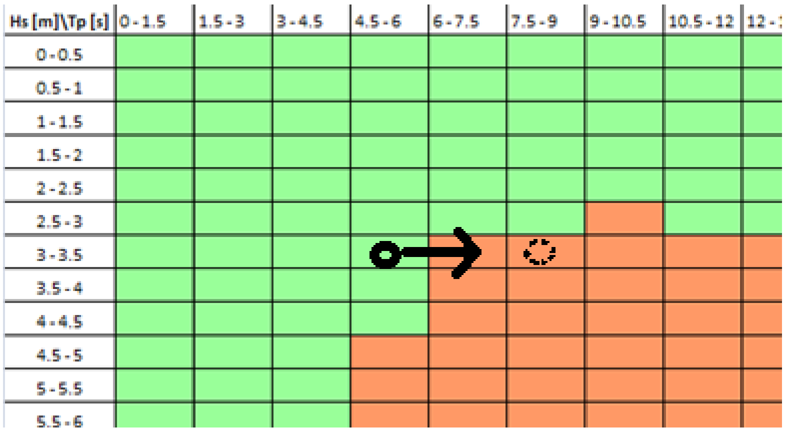
Both long-crested and short-crested seas were used in the analyses. The results from long-crested seas were used as basis in later calculations as it was seen that this gave worse results than short-crested. When the long-crested seas are worst it means that the vessel experiences the worst responses when the all wave energy approaches from one angle. In reality both long- and short-crested seas may occur and the worst case must be used as basis for further work.

The issue of whether or not use bilge keel was clarified by WindFlip AS who said the barge not would be built without a bilge keel. In account to this the results shown in this report come only from analyses with bilge keel. There were initially done analyses both with and without bilge keel, and it was seen that a bilge keel with 30 m length and 0.5 m breadth gave a significant roll damping. There was an increase in limiting Hs for heading 90° of 87.5 %. The variation in results due to different bilge keel with respect to length and breadth should be investigated in later analyses.

The quality of the results from ShipX due to the given criteria should also be discussed. In the curve in Figure 4-9, there are some but not very large differences between the results for failure at one of hundred and one of thousand wind turbines. This small variation could be because it is a steep variation in the relevant area, but it could also be caused by limitations in the program. When given as number of accepted occurrences per hour a criterion for failure at one of thousand wind turbines means $4 \cdot 10^{-5}$ accepted occurrences per hour. Whether or not this gives the right results is an important source of error which should be clarified. The manual of ShipX – Veres does not give a clear explanation of this.

When it comes to the metocean data from the Gulf of Maine, there are data from a large enough number of years, but the quality of the data must be considered. The data of Hs look like they are evenly distributed over a natural range of values. The data of Tp are more uncertain. They are not evenly distributed and they seem to accumulate on specific values. This is seen in the scatter diagrams were some of the Tp- columns do not contain any data. The measurements of Tp may be constructed based on the wave energy, or other weather conditions that are easier to measure, in a way that specific values are more probable to be made than others. This will prevent the Tp values to be evenly distributed over a natural Tp-range.

In the chapter about verification of data the variation of Hs and Tp was compared. It was seen that Tp had a relatively even variation in different seasons and different years while there were big differences in the way Hs varied. In general Tp varied faster than Hs and there was nothing that indicated a corresponding variation between the two parameters. In the figures describing limiting curves there are some variation of limiting Hs depending on Tp. As Tp varies faster than Hs these curves may be dangerous to employ. This because a quick change in Tp may make the condition to go from acceptable to unacceptable as shown in Figure 6-1. Due to this the best solution may be to use the lowest limiting Hs and apply it for all Tp-values.



Hs [m]\Tp [s]	0 - 1.5	1.5 - 3	3 - 4.5	4.5 - 6	6 - 7.5	7.5 - 9	9 - 10.5	10.5 - 12	12 -
0 - 0.5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
0.5 - 1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
1 - 1.5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
1.5 - 2	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
2 - 2.5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
2.5 - 3	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟩	🟩
3 - 3.5	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟧
3.5 - 4	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟧
4 - 4.5	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟧
4.5 - 5	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟧	🟧
5 - 5.5	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟧	🟧
5.5 - 6	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟧	🟧

Figure 6-1 Result of quick variation of Tp

When it comes to seasonal variation the area of interest in the Gulf of Maine has a relatively calm weather throughout the year with a mean wave height not exceeding 2.5 m for any month. In the same time there are five months, from May to September, that stand out as the calmest of the year. This is seen both in the curve of average Hs for each month and in the curve of percentage operability. For the five months that have been defined as the summer season the mean Hs never exceed 1.5 m and the percentage operability related to the measured data and the limiting curves never gets below 97 %. In these months the percentage of the data below the limit for the suggested safe condition is over 99 %. There should in other words be good possibilities to go through with the operation in these months. Nevertheless the rest of the months have relatively large percentages for operation as well, especially if it is possible to stop and wait for better weather in the safe condition.

The weather windows found were divided into 24 hour partitions to see how many possibilities there were for the transportation operation to be performed. The average number of windows during the five summer months was 103 while during the winter season the average of windows were 80. This shows that it is in general best chance for performing the operation during the summer season. To divide the windows into parts of 24 hours may not give the best results with a view to the total installation procedure, but it gives a picture on the possibilities for transportation.

7 Conclusion

In this master thesis the object investigated has been the transportation phase of installing floating wind turbines with the WindFlip concept. The concept is about transporting a fully assembled floating wind turbine lying horizontally, with a 5° slope, on a specially made barge. When arriving at the operation site, the barge flips 85° until the wind turbine is standing vertically in the water. Then it is released.

There are for the present few regulations that apply to floating wind turbines and transporting them. The relevant existing regulations for this transit are regulations for towing operations within marine operations. The regulations found in this thesis concern duration of the operation and weather forecast. The limit between weather-restricted and weather-unrestricted operation is defined as the duration of 72 hours. There are more regulations to be accounted for when the operation time exceeds 72 hours and the operation with that is defined as weather-unrestricted. For a weather-restricted operation a specific weather window must be defined. The limiting sea states should also have a safety margin, and a margin of 20 % is recommended. When it comes to weather forecast there are also margins to take into account. For durations of 24 hours and a limiting significant wave height of 2.5 m, the forecasted Hs should be 64 % of the given value of 2.5 m. There is also a start criterion for towing operations. It is called the Beaufort 5-criterion and states that the wind should not be larger than 5 on the Beaufort scale (8.0-10.7 m/s) when the operation starts. The regulations also recommend having a safe condition to settle into if the weather builds up during the operation. A possibility could be to anchor up against the weather, if this position can take a larger sea state, and wait for it to calm.

To determine the limiting Hs the MARINTEK software ShipX Vessel Responses (Veres) were used. With bilge keel and a velocity of six knots it was possible to find limiting Hs-value given various Tp-values. The lowest limiting Hs-value was 2.99 m. With a margin of 16 % the limiting Hs is 2.5 m. This value was used in further calculations. This result came from calculations with long-crested seas. Short-crested seas were also tried, but it seemed like the worst condition was to get all wave energy from one direction. The results from the project thesis written in the fall 2009 on the same subject suggested a limiting sea state with a Hs-value around 3 m. This corresponds relatively well with the more processed conclusions in this master thesis.

When exploring possible safe conditions it was observed that for zero velocity and a wave heading of 180° (from behind) the limiting Hs increased to 4 m. This means that if anchoring up with the stern against the weather, the barge can endure sea states with a more than one meter higher Hs-value than during regular transit.

When looking at measured wave data from the Gulf of Maine at the north-east coast of the USA, it generally looks like this may be a good place to install floating wind turbines with WindFlip. The average Hs varies over the year, but does not exceed 2.5 m for any month. The five months from May to September stand out as calmer than the rest of the year with an average Hs lower than 1.5 m. The percentage of data within the accepted sea states is also generally large. For the five summer months it stays above 97 %. The percentage of data within the boundaries of the found safe condition is over 99 % from the summer season. The numbers are a little lower for the rest of the year.

Regarding weather windows, in the summer months there are longer windows and larger possibilities for performing installations than during the rest of the year. The average weather window for the summer period last for 264.9 hours while for the rest of the year the same value is 47.6 hours. For the transportation that is said to last for 24 hours it should be possible to carry through during both summer and winter. When taken into account that the total installation time will be significantly longer, and possibly need calmer weather, the winter months may be less relevant. At least there may be longer periods of waiting between each possible weather window. In the summer there should be good possibilities to perform the total installing operation.

The weather windows were divided in parts of 24 hours. This does not give a good indication of the real number of weather windows for the total installation, but it gives a view on how many transport possibilities there are in each season; 103 in the summer and 80 in the winter. The conclusion is that there should be good possibilities to install floating wind turbines in the Gulf of Maine. The installations should preferably take place from May to September, but there are good chances to find openings during the rest of the year as well.

8 Further work

In this master thesis it is only the transport of the wind turbines that has been looked into. The assumed operation time for the transportation has been 24 hours which comes under the 72 hours limit the regulations define as weather-restricted. This means that the operation is dependent of a satisfying weather forecast. In further work it may be detected that the whole operation including both transit and installation may exceed this 72 hours limit. If this is the case, the operation will be defined as a weather-unrestricted operation. For these operations there are other regulations and recommendations which should be looked into.

If the duration of the operation exceeds 72 hours the value with one year seasonal return period should be the limiting criteria. To find this a distribution of the sea states should be made from the scatter diagrams. A good distribution may be a three-parameter Weibull distribution (Haver, 2010). The cumulative version of this distribution is shown in (8.1). The different values of α should be tried out when finding the relevant parameters.

$$F_{Hs}(h) = 1 - exp\left\{-\left(\frac{h-\alpha}{\beta}\right)^{\lambda}\right\} \tag{8.1}$$

If the WindFlip concept is established in the United States for installing wind turbines in the sea outside Maine, the essential rules and regulation for this area must be clarified; both related to the vessel and to the operation.

The typical sea state in the Gulf of Maine should be explored. In the analyses in this master thesis PM-spectra were used. If this represent the relevant conditions sufficiently should be cleared.

Regarding bilge keel on the vessel, various sizes and positions of it should be tried. As a bilge keel made a significant difference in the analyses it is an important parameter in the design of the barge.

9 References

Det Norske Veritas. 2009. *Recommended Practice, DNV-RP-H103, Modelling and analysis of marine Operations.* Høvik : Det Norske Veritas, 2009.

DNV. 1996. *Rules for planning and execution of Marine Operations.* Høvik : Det Norske Veritas, 1996.

Faltinsen, Odd M. 1990. *Sea loads on ships and offshore structures.* Cambridge : Cambridge University Press, 1990.

Fathi, Dariusz. 2010. *Questions about ShipX Vessel Responses (Veres).* [interv.] Idunn Olimb. 30 April 2010.

—. 2005. *ShipX Vessel Responses (Veres), Ship Motions and Global Loads, Users' Manual.* Trondheim : MARINTEK, 2005.

Haver, Sverre. 2010. Questions about distribution of Hs. Trondheim : Idunn Olimb, 12 May 2010.

Hynne, Anders. 2010. *Master thesis: Sea fastening of the Hywind turbine during transportation with Windflip.* Trondheim : Department of Marine Technology, NTNU, 2010.

—. 2010. Values for use in ShipX. Trondheim : WindFlip AS, April 2010.

ISO. 2007. *FINAL DRAFT PreFDIS-10-29-07, Petroleum and natural gas industries — Specific requirements for offshore structures — Part 6: Marine operations.* s.l. : ISO, 2007.

Lloyd, A R J M. 1989. *Seakeeping: Ship Behaviour in Rough Weather.* Sussex : Ellis Horwood Ltd, 1989.

Mannsåker, Torbjørn. 2010. Matlab script. Trondheim : Windflip AS, April 2010.

Meteorologisk institutt. Meteorologisk institutt. *Vind.* [Internett] [Sitert: 16 May 2010.] http://met.no/?module=Articles;action=Article.publicShow;ID=720.

Myrhaug, Dag. 2007. *Kompendium for TMR4180 Marin Dynamikk - Uregelmessig sjø.* Trondheim : Department of marine techology, NTNU, 2007.

Natskår, Asle. 2009. *Questions about regulations for Marine Operations.* [interv.] Idunn Olimb. 1 December 2009.

Olimb, Idunn. 2009. *Project thesis: Operational crtieria for transporting wind turbine with WindFlip.* Trondheim : Department of Marine Technology, NTNU, 2009.

Oljedirektoratet. 2009. OD studie 190609: Mulighetsstudie, Vurdering av vindkraft offshore til reduksjon av klimagassutslipp. *Oljedirektoratet.* [Internett] 19 June 2009. [Sitert: 9 May 2010.] http://www.npd.no/Global/Norsk/1%20-%20Aktuelt/Nyheter/%5BPDF-vedlegg%5D/Foredragene%20til%20Klimakur%202020/OD%20studie%20190609.pdf.

—. 2010. Sokkelåret 2009 - Petroleumsproduksjon . *Oljedirektoratet.* [Internett] 15 January 2010. [Sitert: 9 May 2010.] http://www.npd.no/no/nyheter/nyheter/2010/sokkelaret-2009/sokkelaret-2009---petroleumsproduksjon/.

Statoil. 2008. Hywind_04. *Statoil.* [Internett] 22 May 2008. [Sitert: 30 May 2010.] http://www.statoil.com/no/NewsAndMedia/News/2008/Downloads/hywind_04.jpg.

U. S. Government. 2010. National Oceanic and Atmospheric Administration. *National Data Buoy Center.* [Internett] 2010. [Sitert: 19 April 2010.] http://www.ndbc.noaa.gov/.

WindFlip AS. 2010c. *Acceptable loss of turbines.* Trondheim : s.n., 2010c.

—. 2010d. *Design of WindFlip.* Trondheim : s.n., 2010d.

—. 2010b. ShipX model of WindFlip. Trondheim : WindFlip AS, Mars 2010b.

—. 2010a. WindFlip - Photo Gallery. *WindFlip.* [Internett] 2010a. [Sitert: 30 May 2010.] http://windflip.com/gallery.aspx.

Appendices

Appendix A: Main dimensions WindFlip

Appendix B: Limiting acceleration

Appendix C: Comparison of RAOs from model test and MatLab

Appendix D: Comparison of results with and without bilge keel

Appendix E: Results from ShipX – Veres

Appendix F: MatLab scripts

Appendix G: Scatter diagrams

Appendix H: Electronic appendices

Appendix A: Main dimensions WindFlip

WindFlip Local Coordinate System (WLC):

X, longitudinal, 0 at stern

y, transverse, 0 on CL

z, normal on baseline, 0 on baseline

WindFlip Global Coordinate system (WGC):

Same origin as local coordinate system. But rotated so n_z is normal to free surface

Hywind Local Coordinate system (HLC):

Origin on centre axis and keel level. n_z parallel with the centre axis

Hywind Global Coordinate System (HGC):

Origin on centre axis and at keel level. n_z normal to free surface

Hywind CG Coordinate System (HCGC)

Origin in the Centre of Gravity. N_z normal to free surface

ShipX Coordinate System (SXC):

Placed with z-axis passing through COG and with origin in the still water plane. X-axis is positive towards bow.

HyrdoD Global coordinate System (HGC)

Placed so that the z-axis goes through origin of HydroD input coordinate system.

The HydroD input coordinate system is for WindFlip equivalent to the windflip local coordinate system.

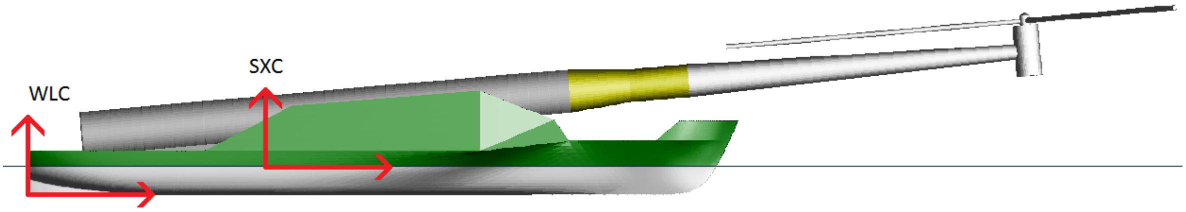


Figure - SXC and WLC coordinate systems

Transit (WLC):
Length: 140 m
Beam: 27.8 m
Draft: 5.7 m
Height (keel to top tanks): 20.7 m
Displacement, volume: 11 615 m^3
Displacement, mass: 11 906 tons
Transit Speed: 6 knots
COB: (51.818, 0, 3.241) m
COG: (51.79, 0, 12.30) m
GML: 1.79 m
GMT: 248.16 m
Pitch, Moment Of Inertia: 59.57 ***

Launch (WLC):
Draft: 120 m
Height: 40 m
Displacement, Volume: 27 777 m^3*
Displacement, Weight: 28 472 tons*
Trim Angle: 85 deg
COB: (61.814, 0, 8.901)
COG: (53.83, 0, 8.22)
GML: 8.17 m
GMT: 8.03 m
Pitch, R.gyr: 71.67 m ***

Wind Turbine on WindFlip (WLC):
Inclination angle: 5 deg
COG: (40.3041, 0, 14.7766) m
Weight: 6500 tons
Blade tip pos: (228, +-52.2, 37.6) m
Nacelle pos: (210.1, 0, 23.7) m

In SXC
Blade Tip pos: (172.9, 0, 31.9) m
Nacelle Pos: (157.93, 0, 18) m

Wind Turbine, free floating (HLC):
Draft: 110 m
Height: 80 m
Blade Length: 60 m
Displacement, Volume: 6341.46 m^3
Displacement, Weight: 6500 tons
Diameter, Substructure= 8.75 m
Height, Substructure= 98 m
Diameter, Waterline=6.5 m
COG: (0, 0, 30)
COB: (0, 0, 52.86) m
GMT: 22.86 m**
GML: 22.86 m**
Pitch, R.gyr=47.96 m

Test Model, Transit (WLC):
Scale Ratio: 1:45
Length: 3.11 m
Beam: 0.62 m
Draft: 0.13 m
Model weight: 57.28 kg
Displacement, volume: 0.126 m^3
Displacement, mass: I26.87 kg
COB: (1.151, 0, 0.072) m
COG: (1.151, 0, 0.273) m, includes turbine
GML: 0.0398 m
GMT: 5.515 m
Pitch, R$_{GYR}$: 1.324 ***

Test Model, Launch (WLC):
Draft: 2.67 m
Height: 0.889 m
Displacement, Volume: 0.304 m^3*
Displacement, Weight: 304 kg*
Trim Angle: 85 deg
COB: (1.374, 0, 0.1978)
COG: (1.196, 0, 0.183)
GML: 0.182 m
GMT: 0.178 m
Pitch, R$_{Gyr}$: 1.593 m ***

* Displacement of ship alone. Not including the displaced volume of wind turbine

** Only the difference between COB and COG, no addition from waterline

*** Both ship and wind turbine

Appendix B: Limiting acceleration

Operasjonskriterier for transport av Hywind-turbinen med Windflip

1 Resultater

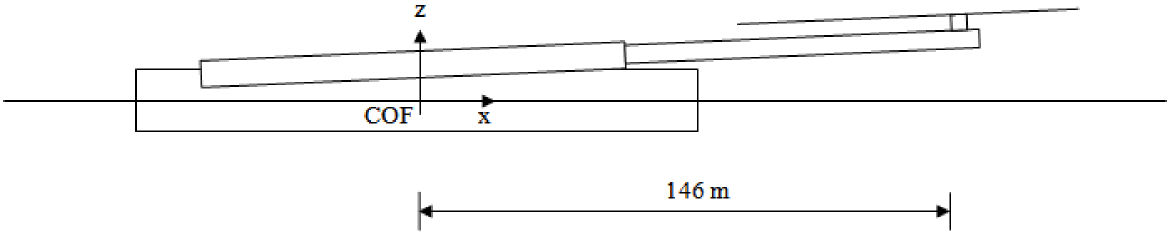
Kritisk akselrasjon for nacelle i vertikal retning	0,3 G

Tabell 1 – Kritisk aksellerasjon

2 Introduksjon

I denne analysen av operasjonskriterier begrenser vi oss til kun å se på belastningene som selve tårnet på vindturbinen blir utsatt for. Det betyr at vi antar at alle andre komponenter som kan være begrensende har stor nok kapasitet. Eksempel på andre komponenter som kan være begrensende er sea-fastning og nacelle.

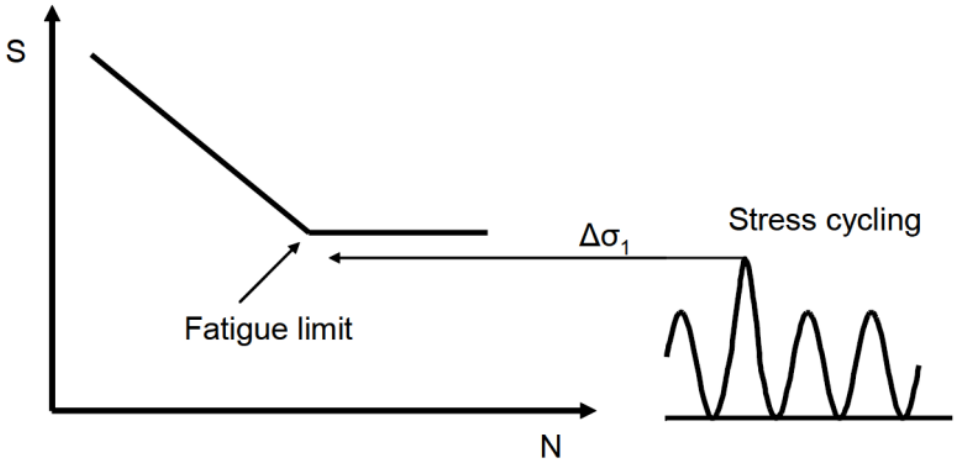
For eksempel vil sea-fastningen bli utsatt for store krefter under transport, og det har ikke blitt gjennomført beregninger som slår fast hvor store disse kreftene blir. På bakgrunn av at sea-fastningen ikke har blitt designet på nåværende tidspunkt antar vi at det vil være mulig å designe et sea-fastning system som har stor nok kapasitet til å ta opp de belastningene det blir utsatt for.



Figur 1 – Definisjon av koordinatsystem

3 Valg av kritisk spenning

Spørsmålet er hvilken kritisk spenning vi bør velge. Ut fra et rent praktisk resonnement forstår vi at spenningen må være vesentlig lavere enn flytespenningen for å unngå lavsyklus utmatting. Fra side 20 i dokumentet ”Recommended practice, DNV-RP-C203, Fatigue Design of offshore Steel Structures” har vi at det ikke er nødvendig med en detaljert beregning av utmatting så lenge maksimal spenning er mindre enn maksimal spenning ved 10^7 sykler i S-N-diagrammet. Denne grensa er kalt ”Fatigue limit” og er vist i Figur 2.



Figur 2 – Fatigue limit

Fra side 52 i den tidligere nevnte ”Recommended practice” har vi at den øvre delen av Hywind-turbinen kan klassifiseres i utmattingklasse C. Bakgrunnen for dette er at vi har et rør med stor diameter som vil ha sveiser som er jevnt med røret.

Ved å gå inn i Tabell 2 for S-N kurve C finner vi at maksimal spenningsvidde må være mindre enn 73 MPa for å unngå utmatting.

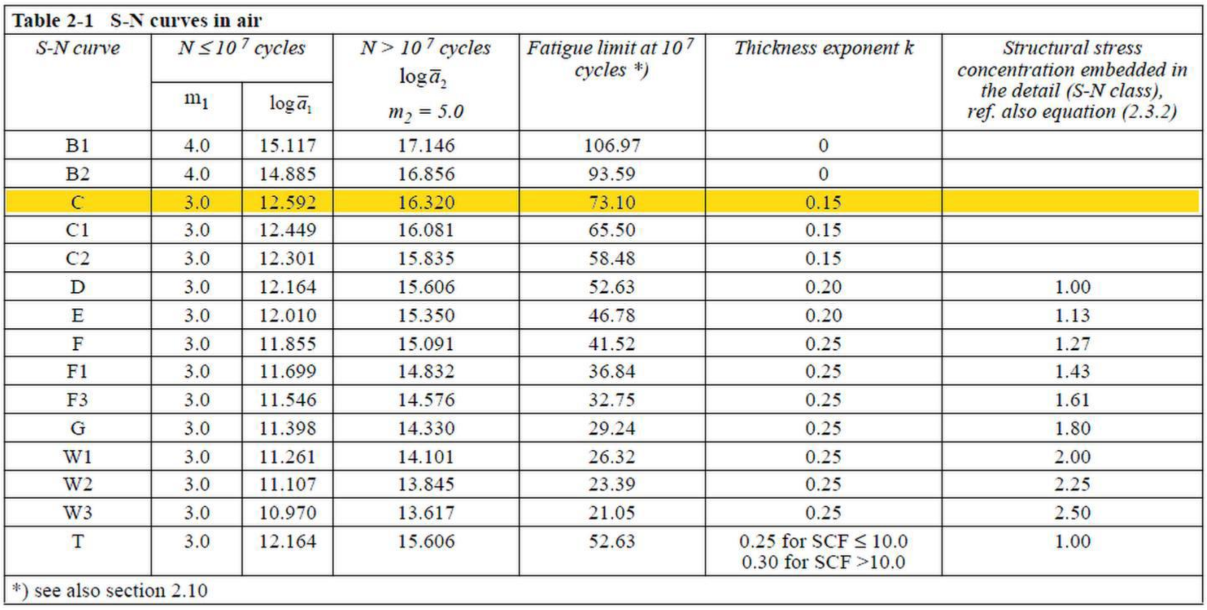


Table 2-1 S-N curves in air

S-N curve	*$N \leq 10^7$ cycles*		*$N > 10^7$ cycles* $\log \bar{a}_2$	*Fatigue limit at 10^7 cycles *)*	*Thickness exponent k*	*Structural stress concentration embedded in the detail (S-N class), ref. also equation (2.3.2)*
	m_1	$\log \bar{a}_1$	$m_2 = 5.0$			
B1	4.0	15.117	17.146	106.97	0	
B2	4.0	14.885	16.856	93.59	0	
C	3.0	12.592	16.320	73.10	0.15	
C1	3.0	12.449	16.081	65.50	0.15	
C2	3.0	12.301	15.835	58.48	0.15	
D	3.0	12.164	15.606	52.63	0.20	1.00
E	3.0	12.010	15.350	46.78	0.20	1.13
F	3.0	11.855	15.091	41.52	0.25	1.27
F1	3.0	11.699	14.832	36.84	0.25	1.43
F3	3.0	11.546	14.576	32.75	0.25	1.61
G	3.0	11.398	14.330	29.24	0.25	1.80
W1	3.0	11.261	14.101	26.32	0.25	2.00
W2	3.0	11.107	13.845	23.39	0.25	2.25
W3	3.0	10.970	13.617	21.05	0.25	2.50
T	3.0	12.164	15.606	52.63	0.25 for SCF ≤ 10.0 0.30 for SCF >10.0	1.00

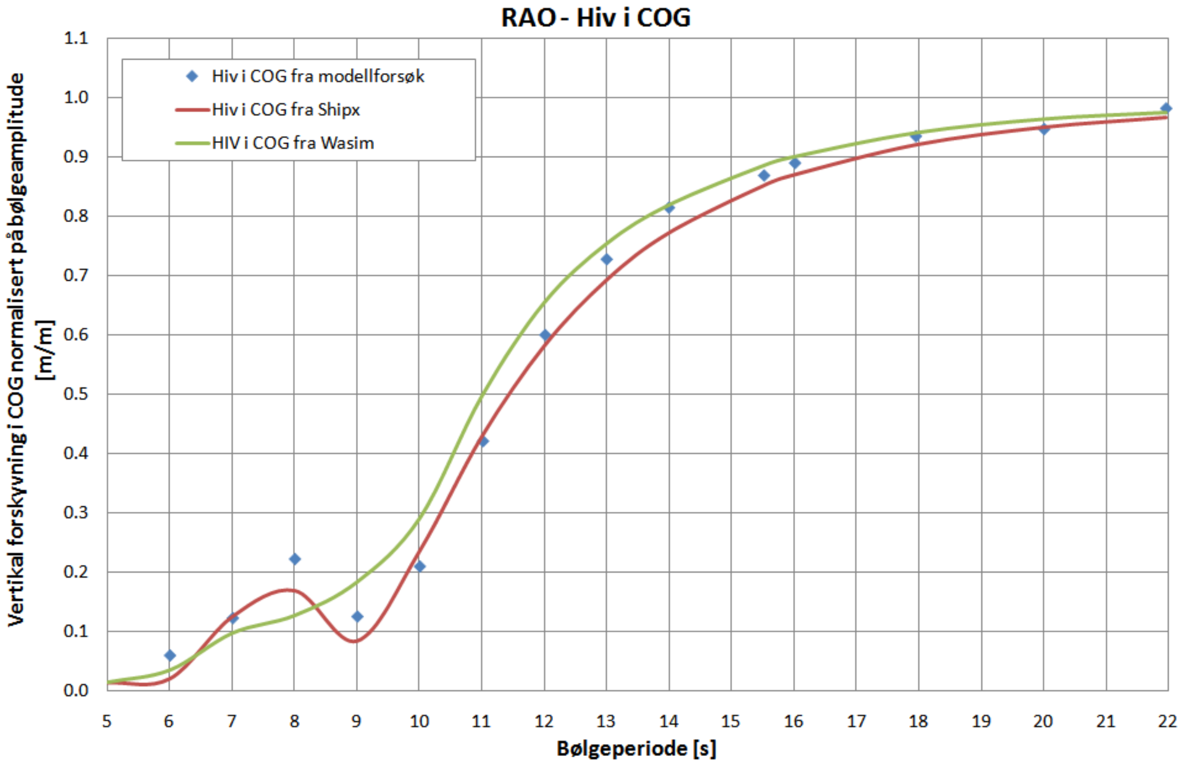
*) see also section 2.10

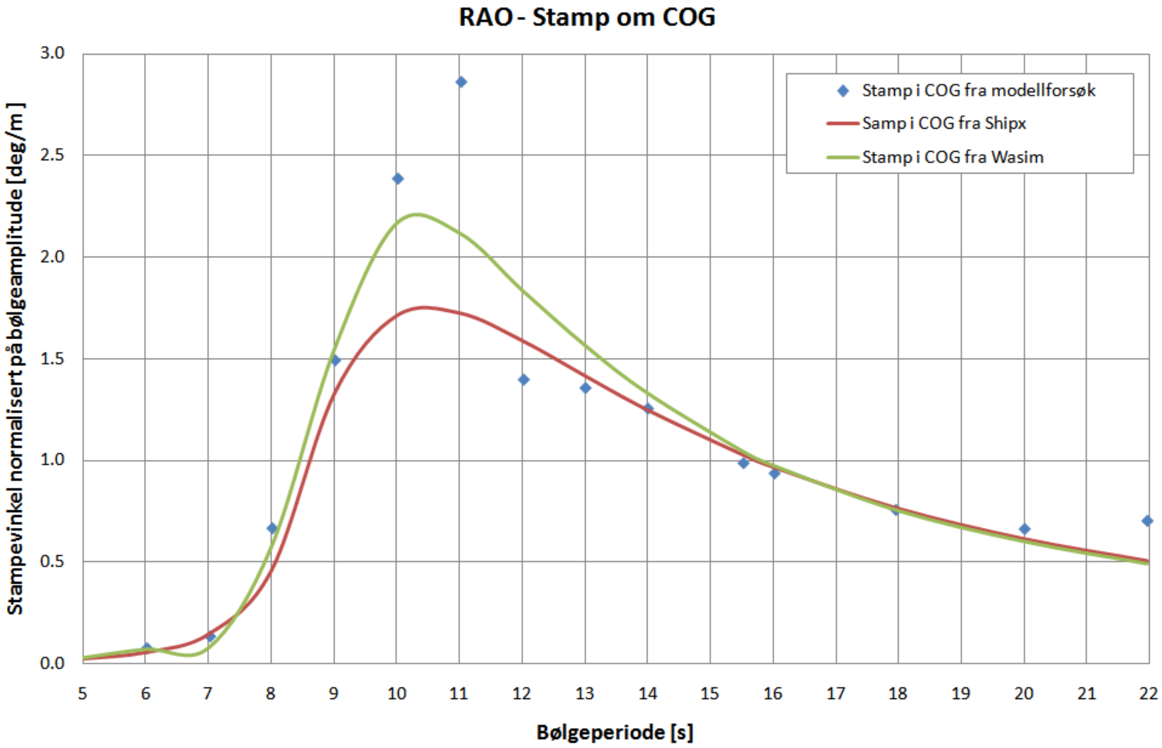
Tabell 2 – S-N kurver i luft

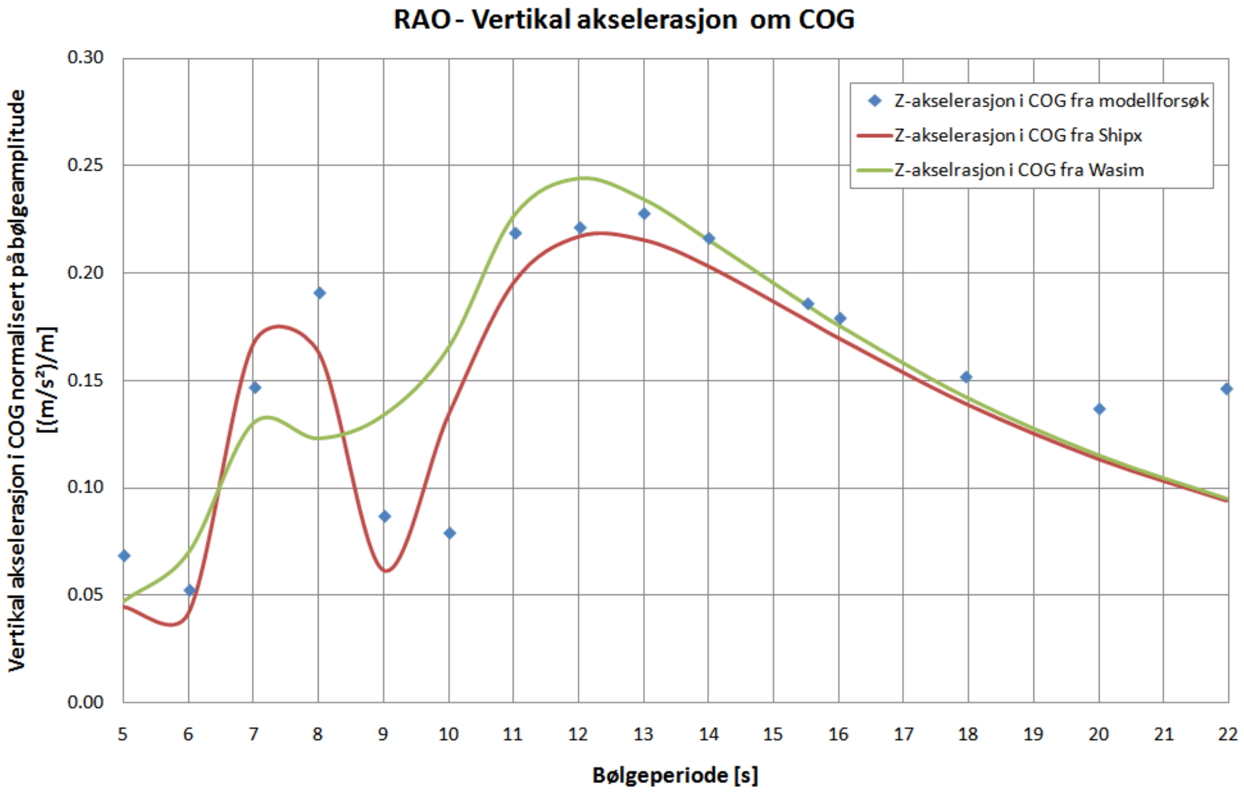
Fra analysene i 3D Beam får vi at maksimal vertikal akselrasjon i nacellen blir 0,3 G hvis maksimal spenning i røret under transport skal være 70 MPa.

Appendix C: Comparison of RAOs from model test and MatLab

Comparison of RAOs of displacement and acceleration for heave and pitch in COG. From the master thesis of Anders Hynne (Hynne, 2010).






RAO - Vertikal akselerasjon om COG
Vertikal akselerasjon i COG normalisert på bølgeamplitude [(m/s²)/m]
0.30
0.25
0.20
0.15
0.10
0.05
0.00
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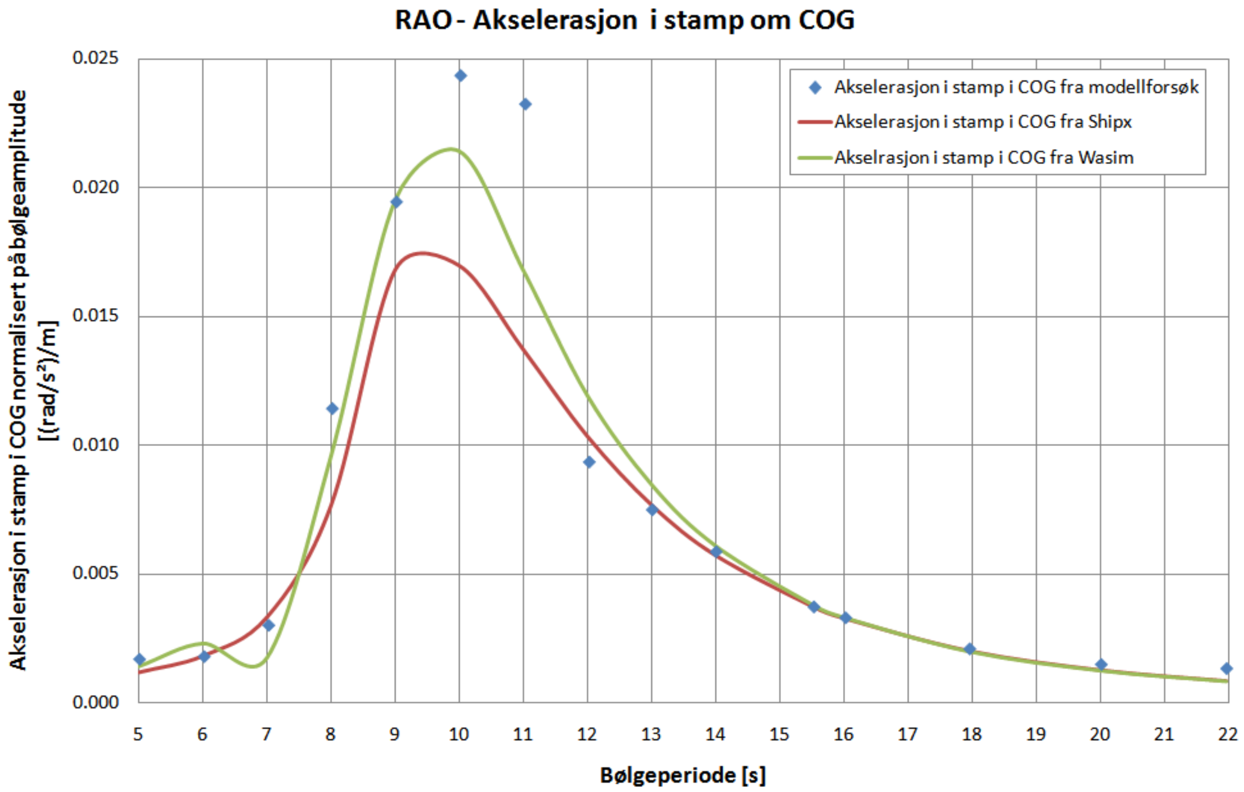
22
Bølgeperiode [s]
Z-akselerasjon i COG fra modellforsøk
Z-akselerasjon i COG fra Shipx
Z-akselrasjon i COG fra Wasim


RAO - Akselerasjon i stamp om COG
Akselerasjon i stamp i COG normalisert på bølgeamplitude [(rad/s²)/m]
0.025
0.020
0.015
0.010
0.005
0.000
5
6
7
8
9
10
11
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14
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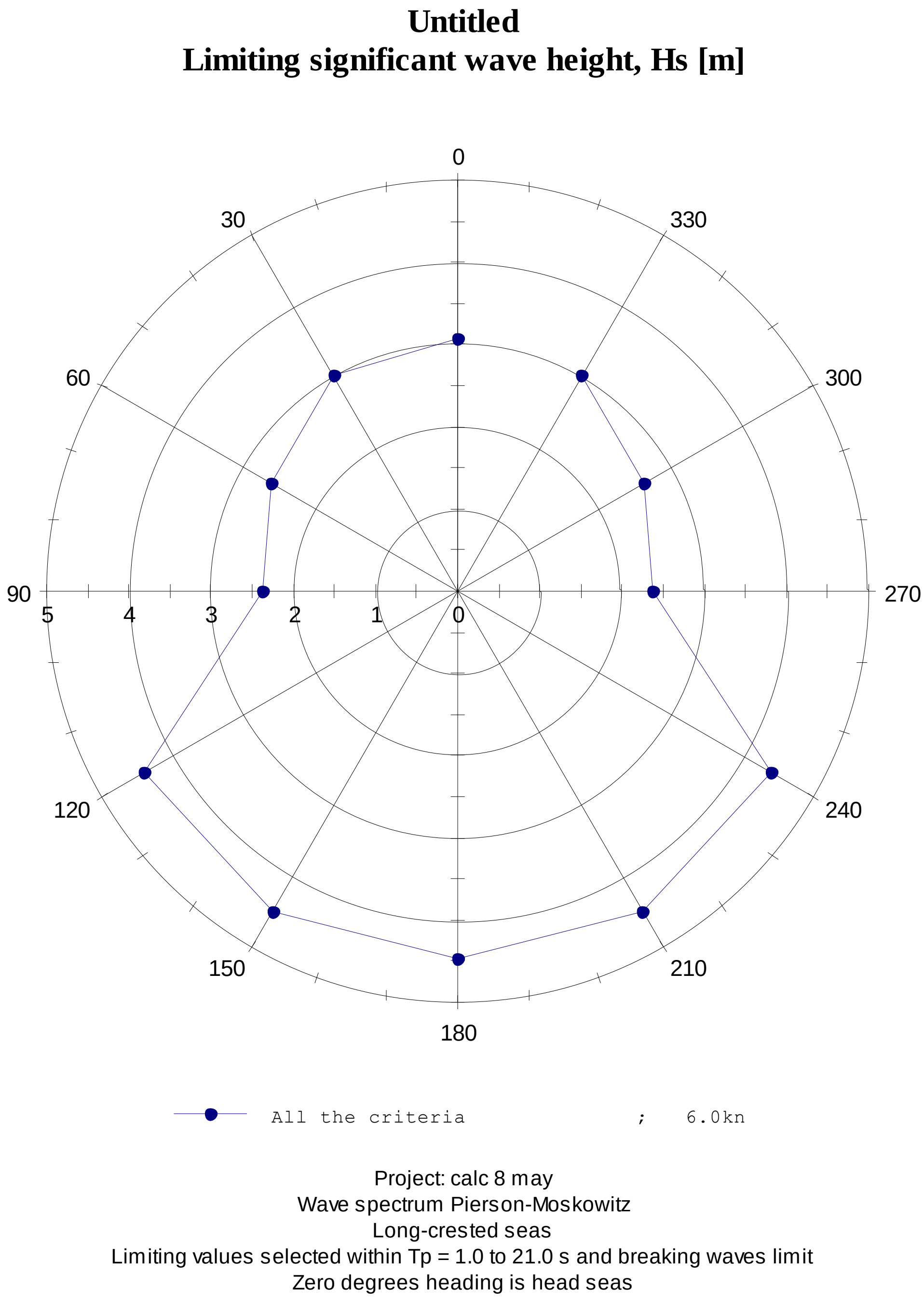
18
19
20
21
22
Bølgeperiode [s]
Akselerasjon i stamp i COG fra modellforsøk
Akselerasjon i stamp i COG fra Shipx
Akselrasjon i stamp i COG fra Wasim

Appendix D: Comparison of results with and without bilge keel

The following results were done early in the analysis phase. There are some errors in the values due to wrong inputs, but they work as a comparison between analyses with and without bilge keel. The same inputs and conditions have been used in both analyses. The only difference is the bilge keel. It is observed that a bilge keel with length 30 m and breadth 0.5 m makes a significant difference for especially heading 90°. For this heading the limiting Hs goes from about 2.4 m without bilge keel to 4.5 m with bilge keel. This is an enhancement of 87.5 %. Due to this and that WindFlip AS stated that the barge would not be built without a bilge keel, the further analyses were done with bilge keel.

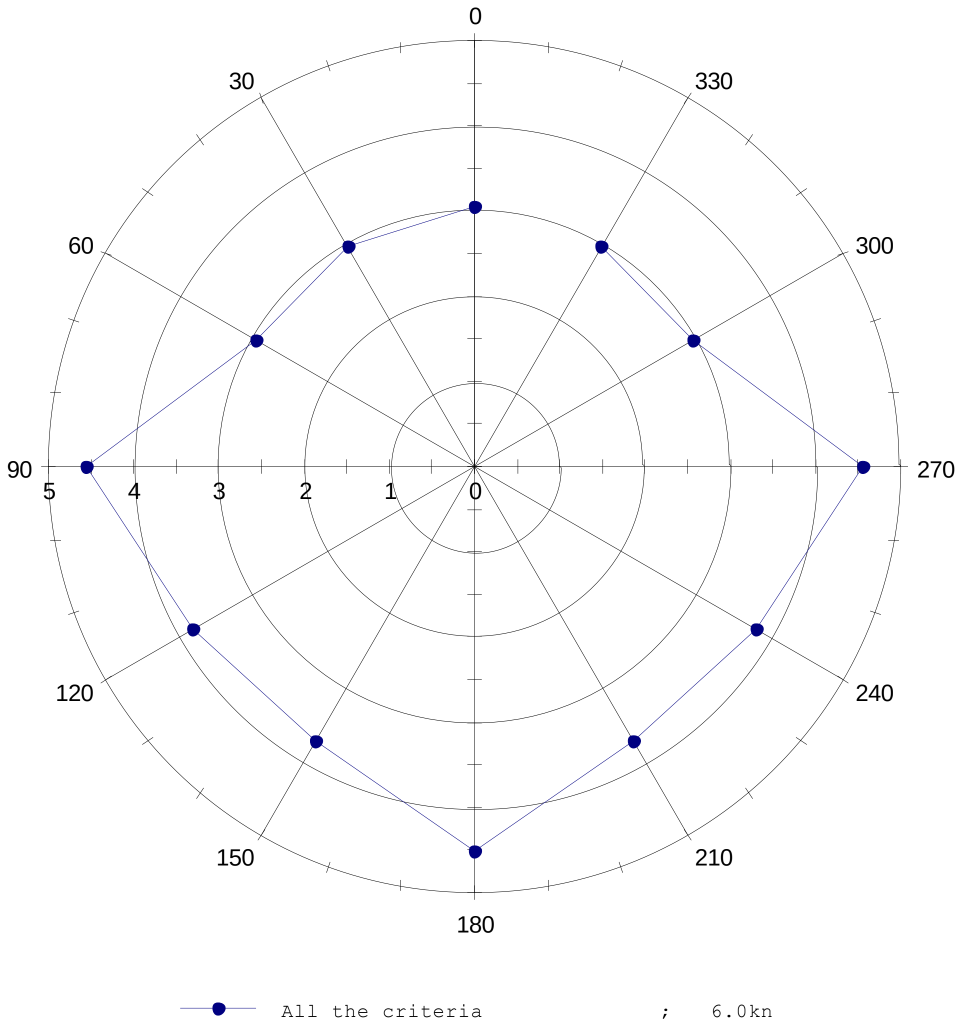
Without bilge keel


Untitled
Limiting significant wave height, Hs [m]

Project: calc 8 may
Wave spectrum Pierson-Moskowitz
Long-crested seas
Limiting values selected within Tp = 1.0 to 21.0 s and breaking waves limit
Zero degrees heading is head seas

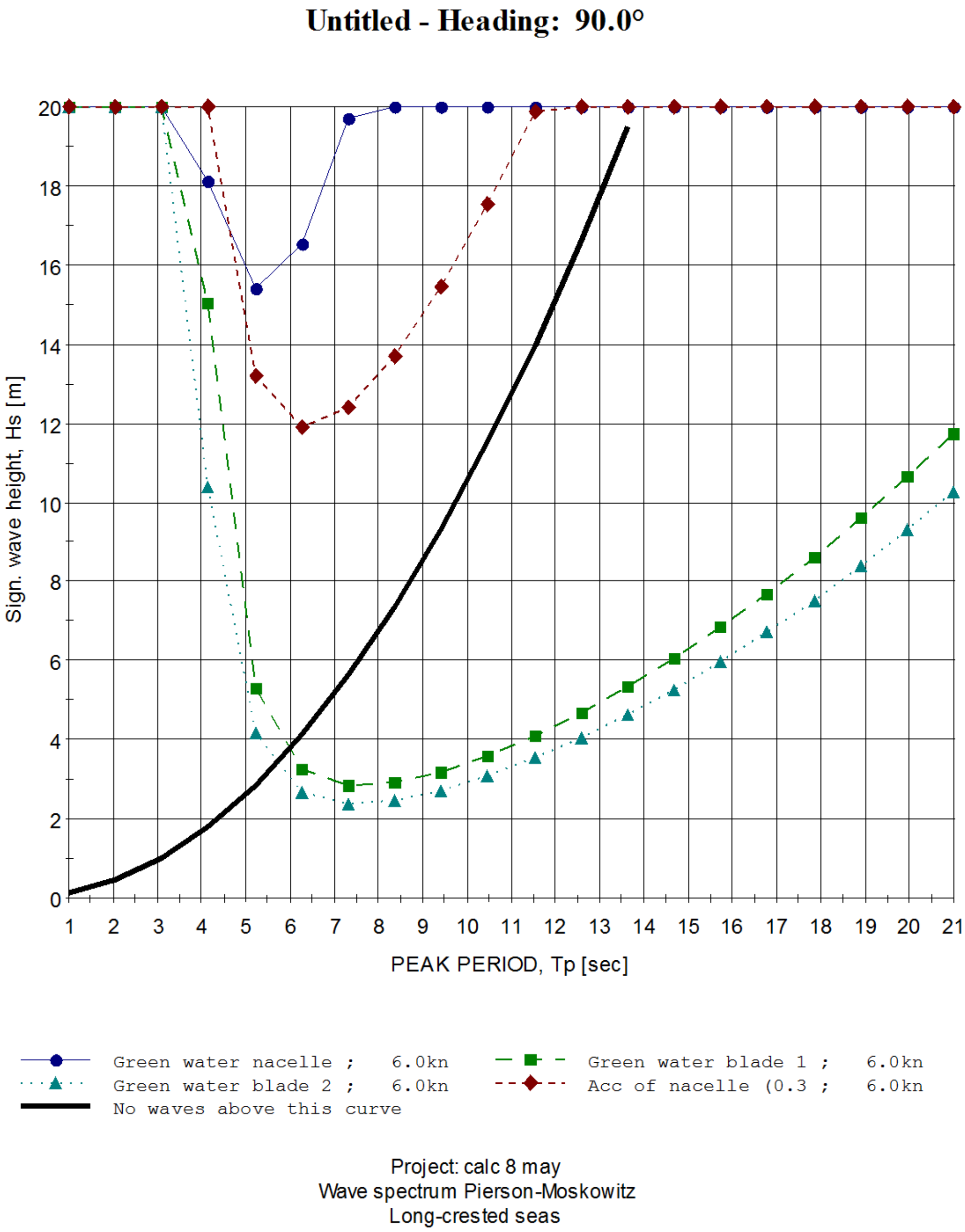
With bilge keel

Copy of Transit, With Payload, Limiting significant wave height, Hs [m]

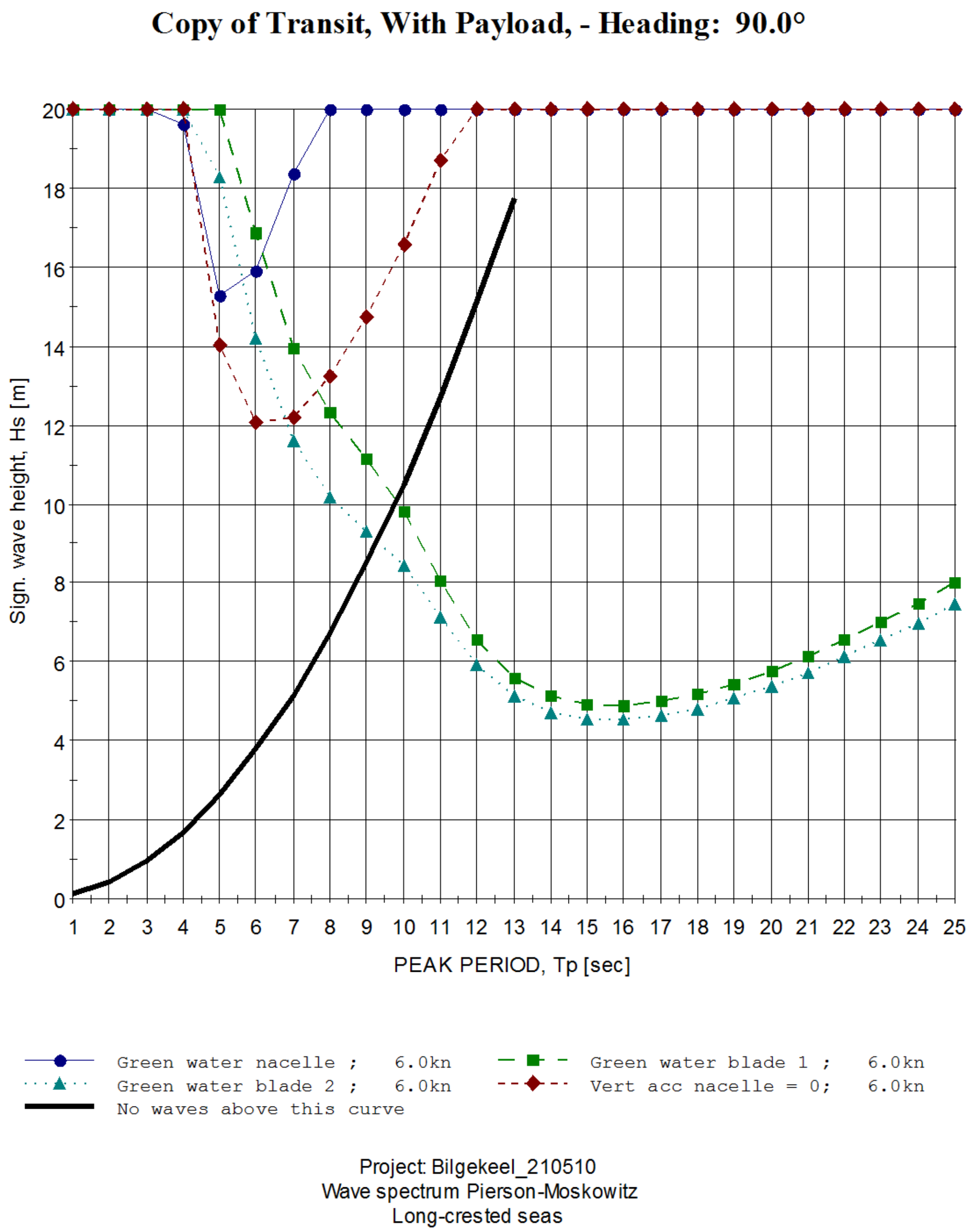


Project: Bilgekeel_210510
Wave spectrum Pierson-Moskowitz
Long-crested seas
Limiting values selected within Tp = 1.0 to 25.0 s and breaking waves limit
Zero degrees heading is head seas

90 degrees without bilge keel



90 degrees with bilge keel



Appendix E: Results from ShipX – Veres

In this appendix the result plots for the limiting criteria are shown. There are results both for 6 knots and 0 knots, for long- and short-crested seas and for 1/100 and 1/1000 criteria.

Contents:

Results for velocity 6 knots, failure at one of thousand wind turbines:

- Polar plot long-crested seas
- Polar plot short-crested seas
- xy-plots for all directions, long-crested seas

Results for velocity 6 knots, failure at one of hundred wind turbines:

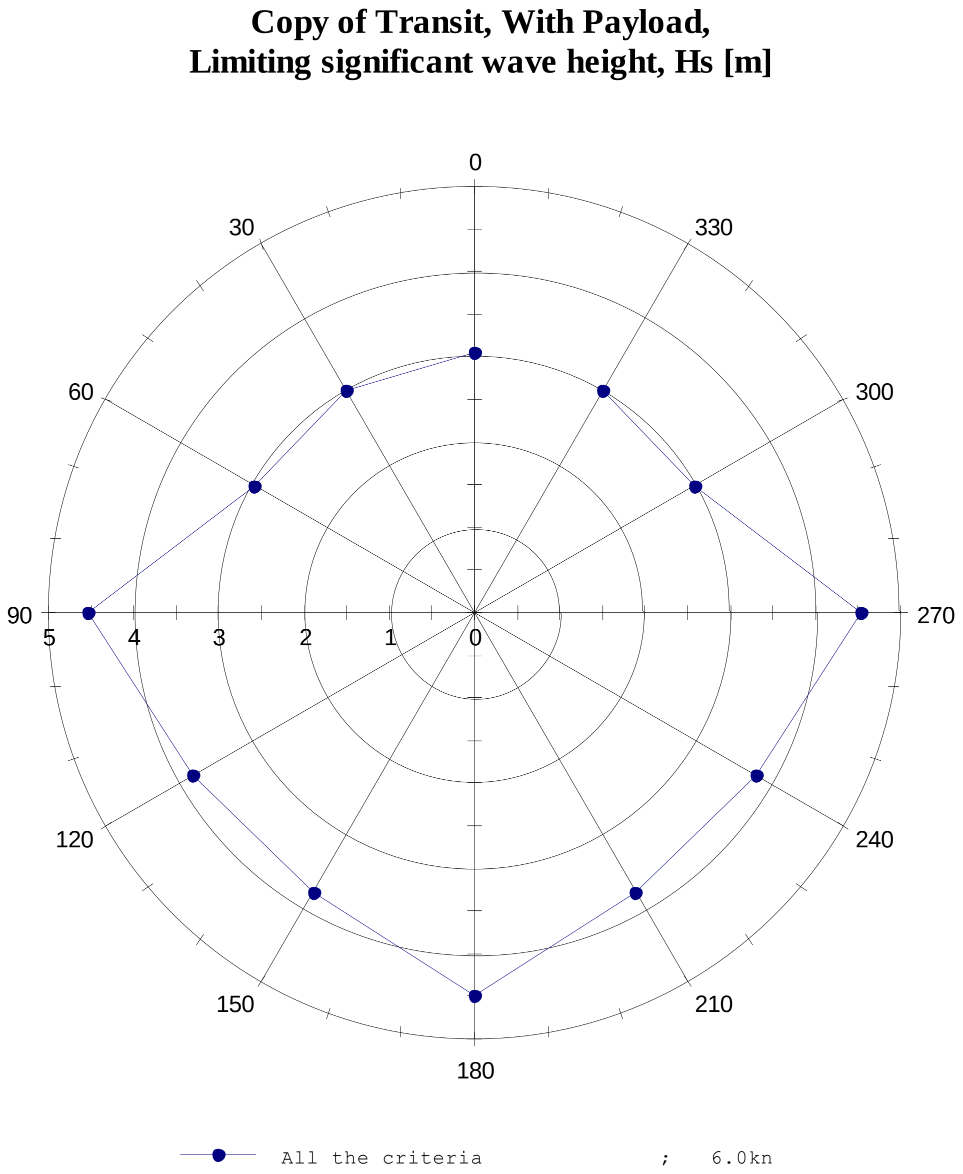
- Polar plot long-crested seas
- Polar plot short-crested seas
- xy-plots for all directions, long-crested seas

Results for velocity 0knots, failure at one of thousand wind turbines:

- Polar plot long-crested seas
- Polar plot short-crested seas
- xy-plots for all directions, long-crested seas

Results for velocity 6 knots, failure at one of thousand wind turbines

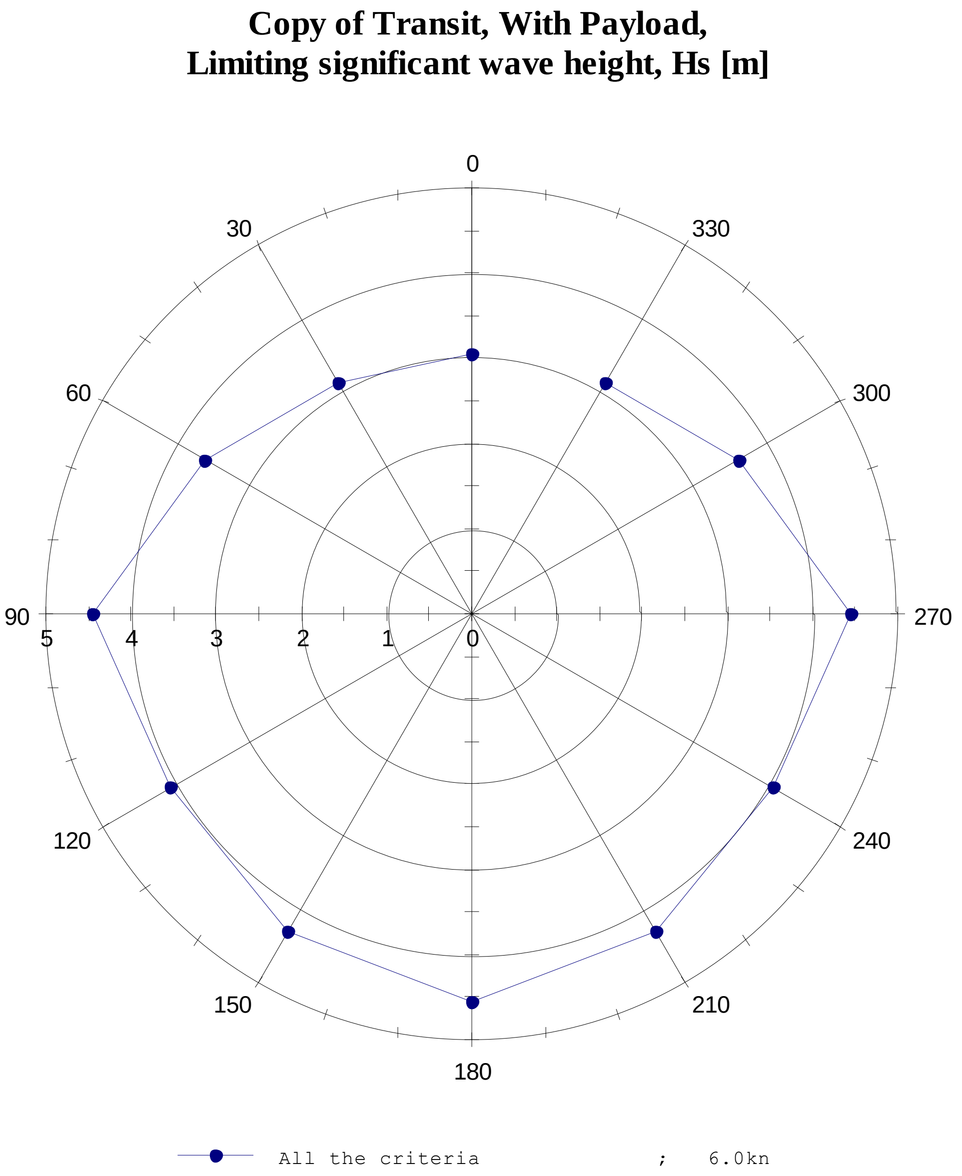
Polarplot long-crested seas



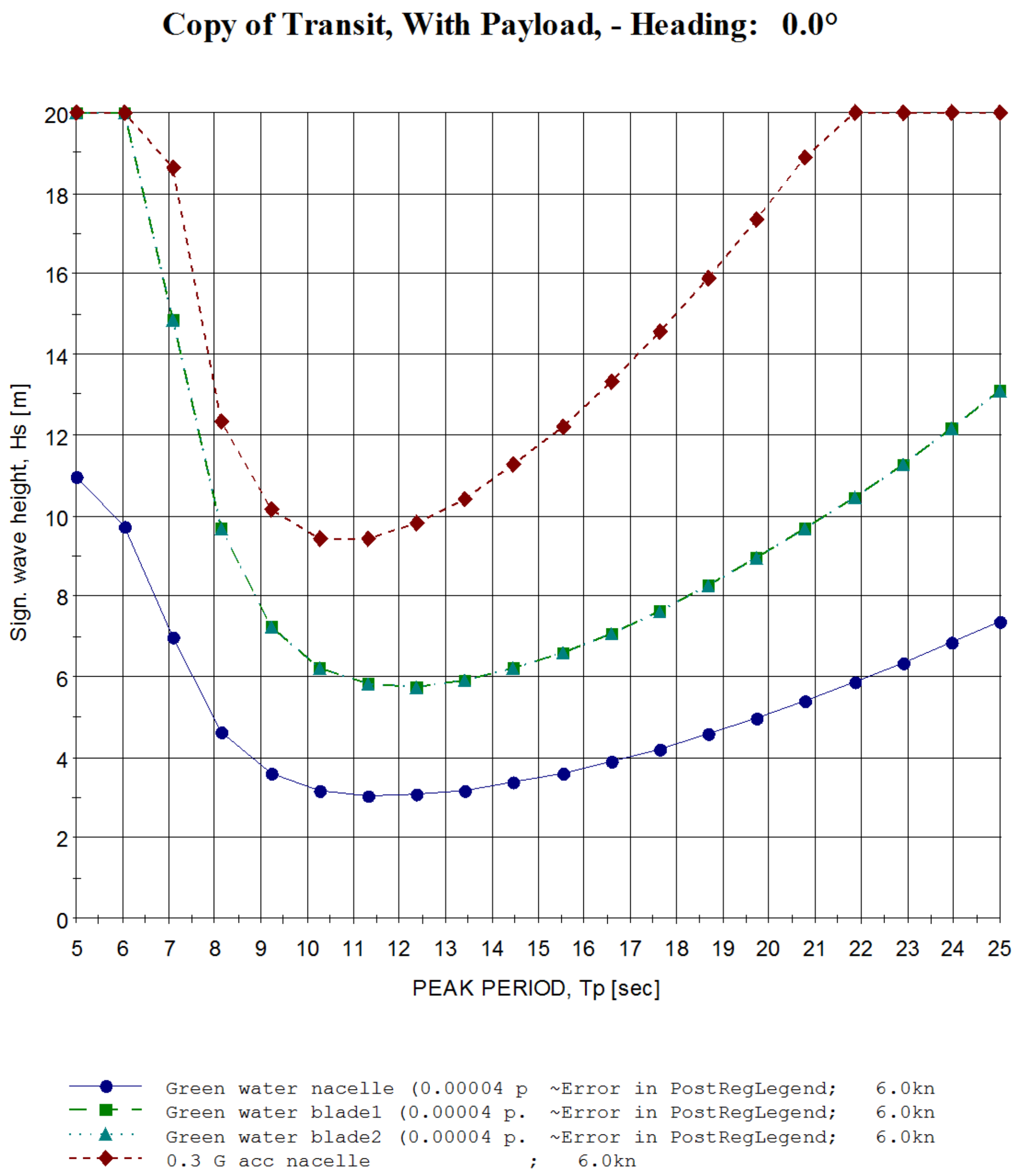
Copy of Transit, With Payload,
Limiting significant wave height, Hs [m]

Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas
Limiting values selected within Tp = 5.0 to 25.0 s and breaking waves limit
Zero degrees heading is head seas

Polarplot short-crested seas



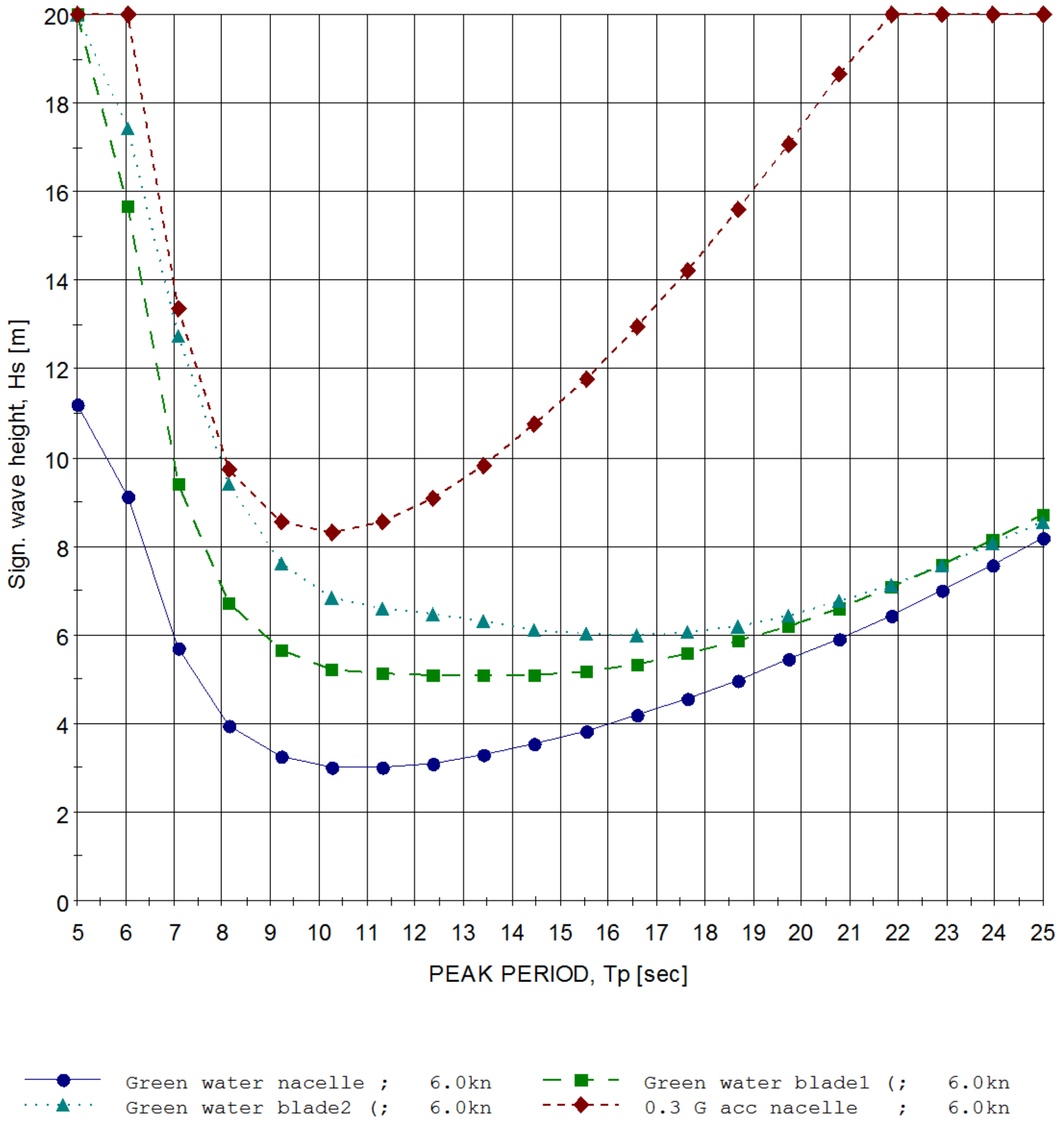
Project: zero velocity
Wave spectrum Pierson-Moskowitz
Short-crested seas (Power of cosine = 4, wave spreading angle = ±90.0°)
Limiting values selected within Tp = 5.0 to 25.0 s and breaking waves limit
Zero degrees heading is head seas



Copy of Transit, With Payload, - Heading: 0.0°

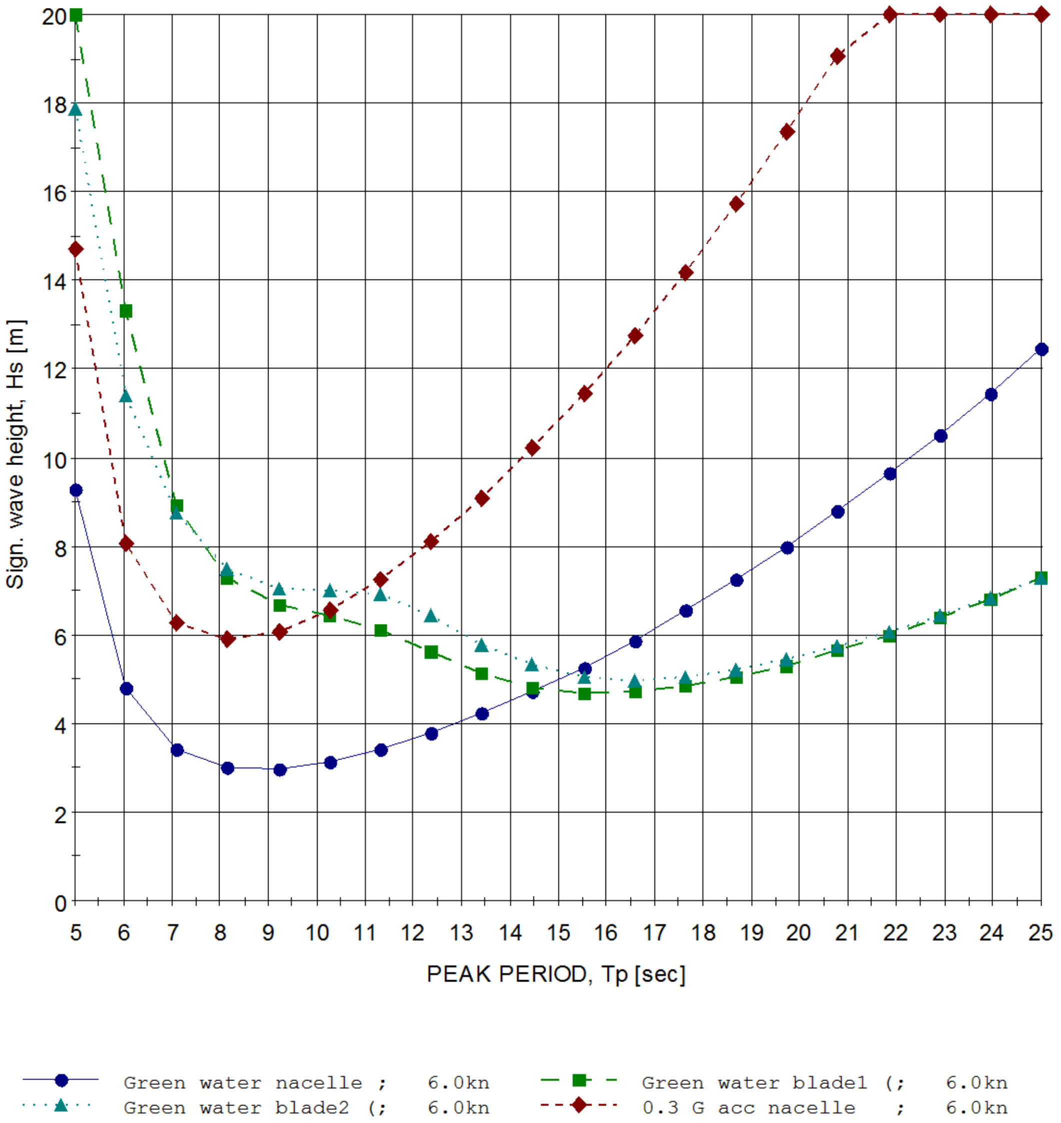
Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas

Copy of Transit, With Payload, - Heading: 30.0°



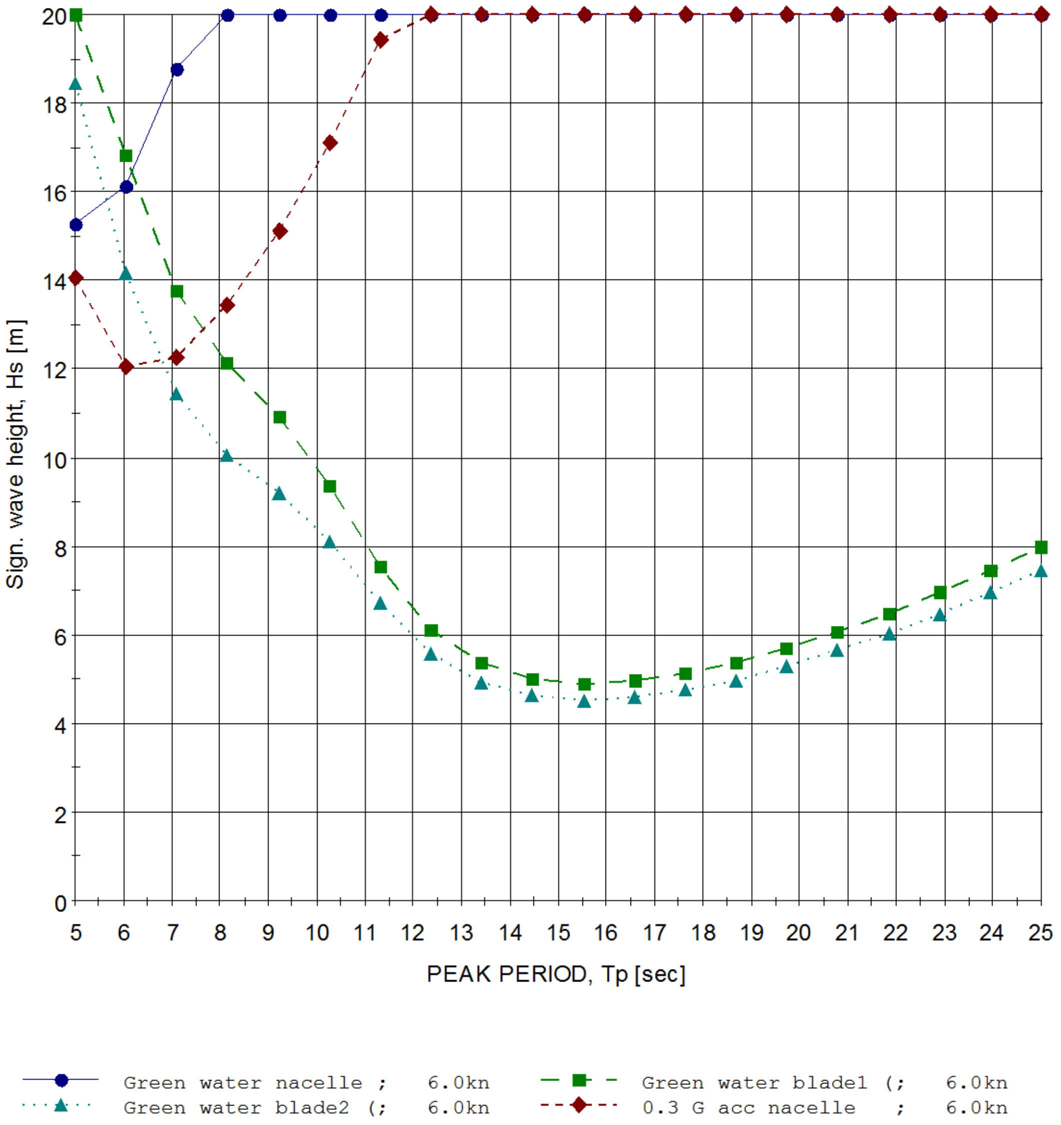
Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas

Copy of Transit, With Payload, - Heading: 60.0°



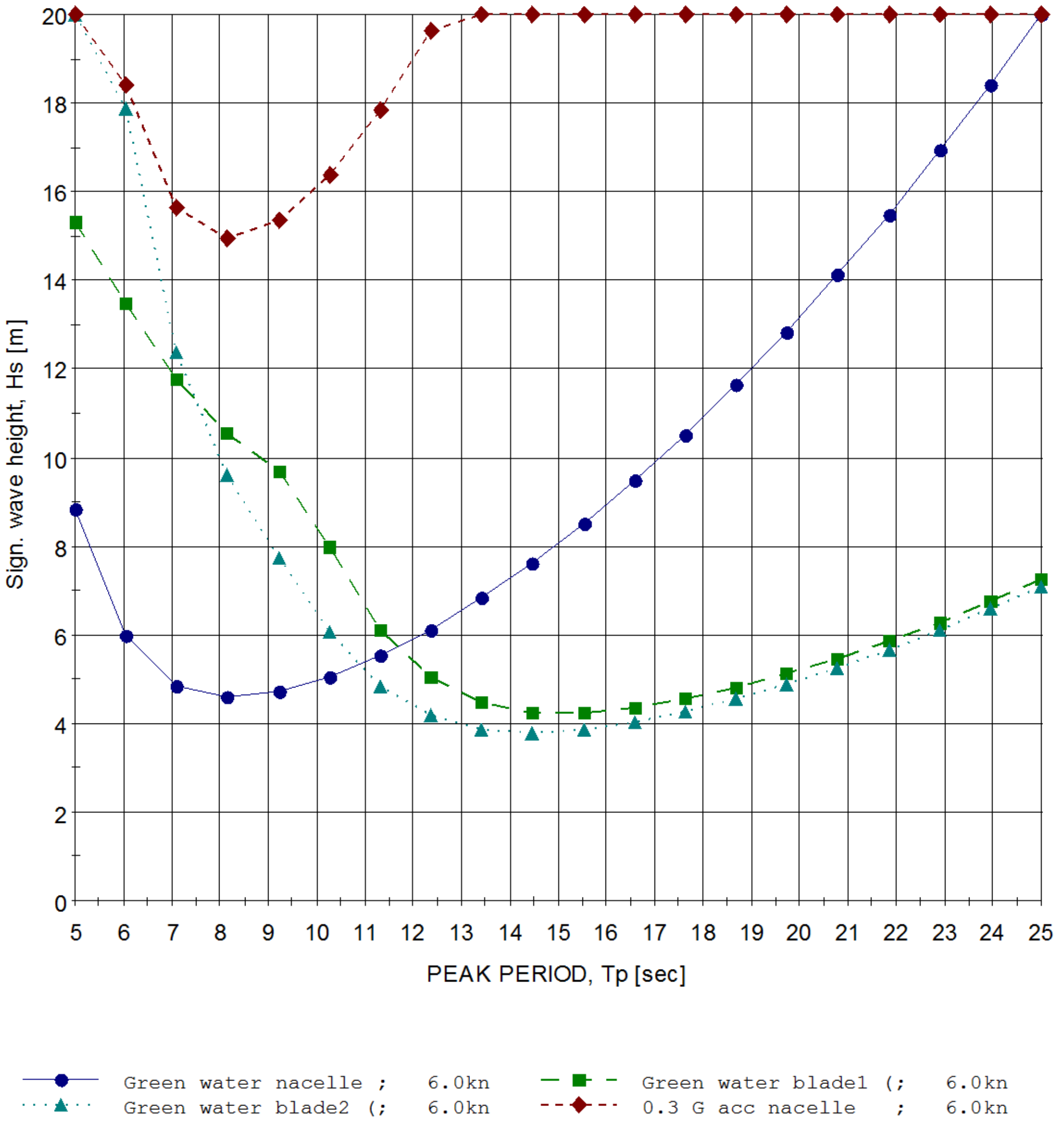
Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas

Copy of Transit, With Payload, - Heading: 90.0°

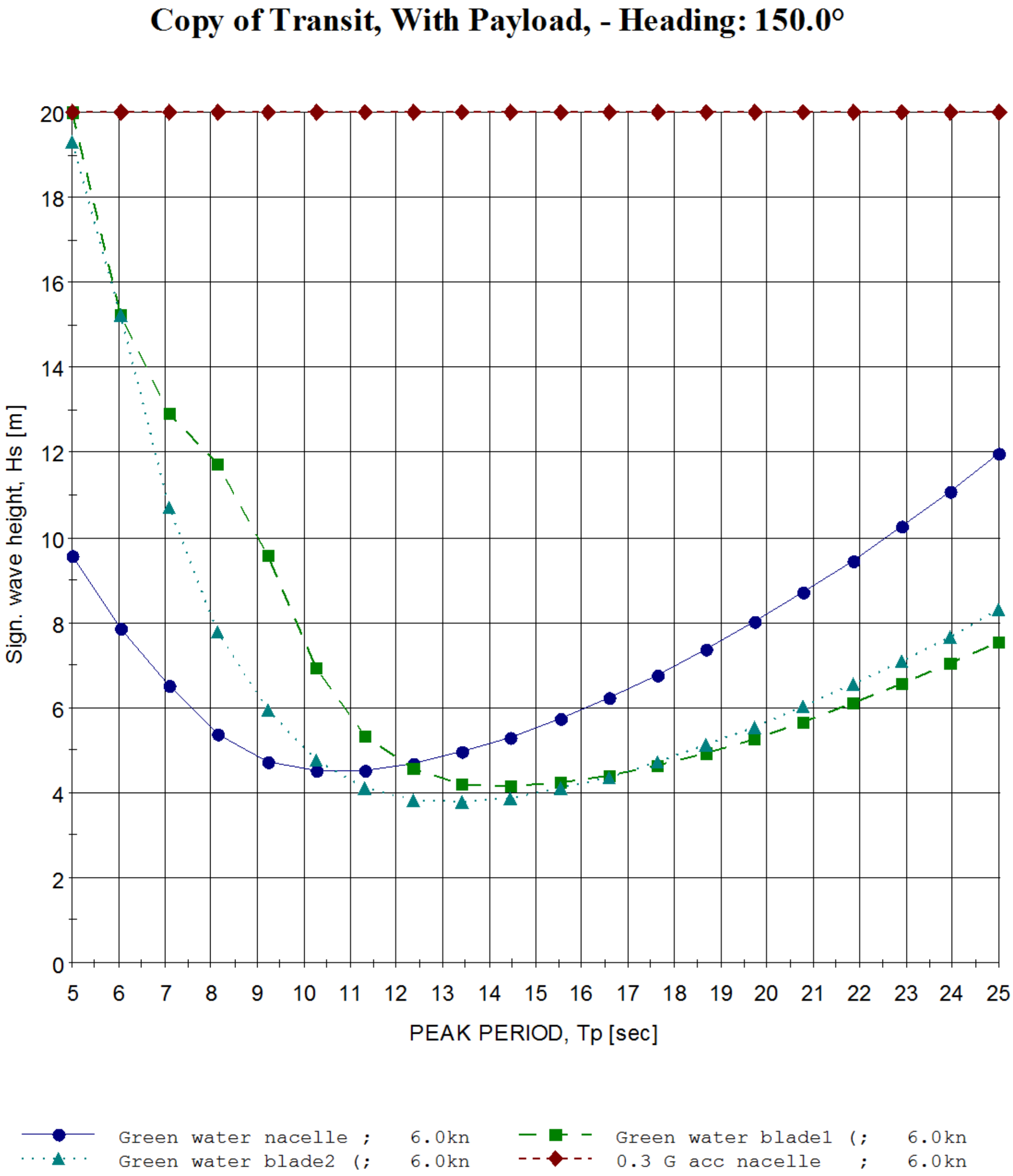


Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas

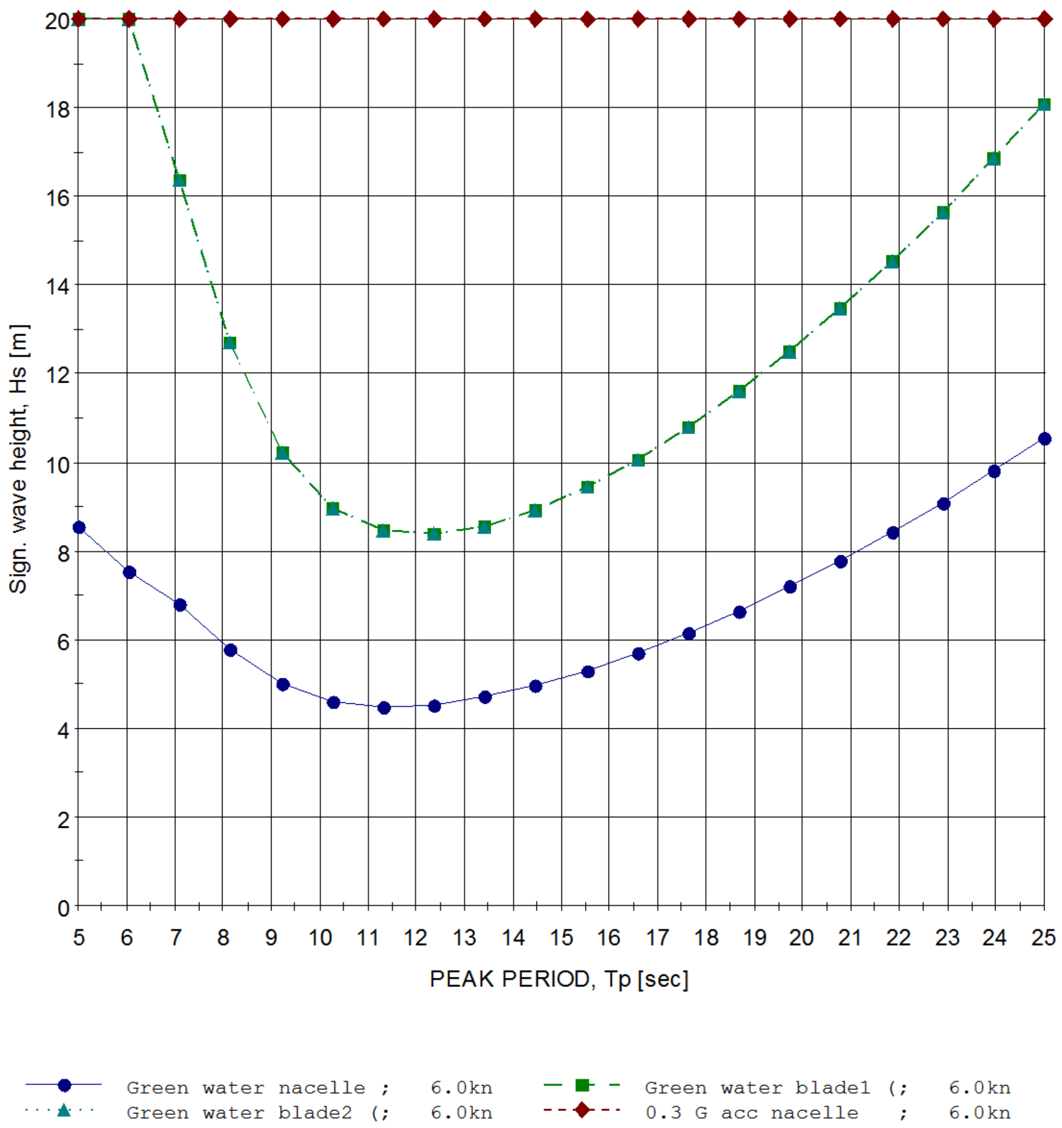
Copy of Transit, With Payload, - Heading: 120.0°



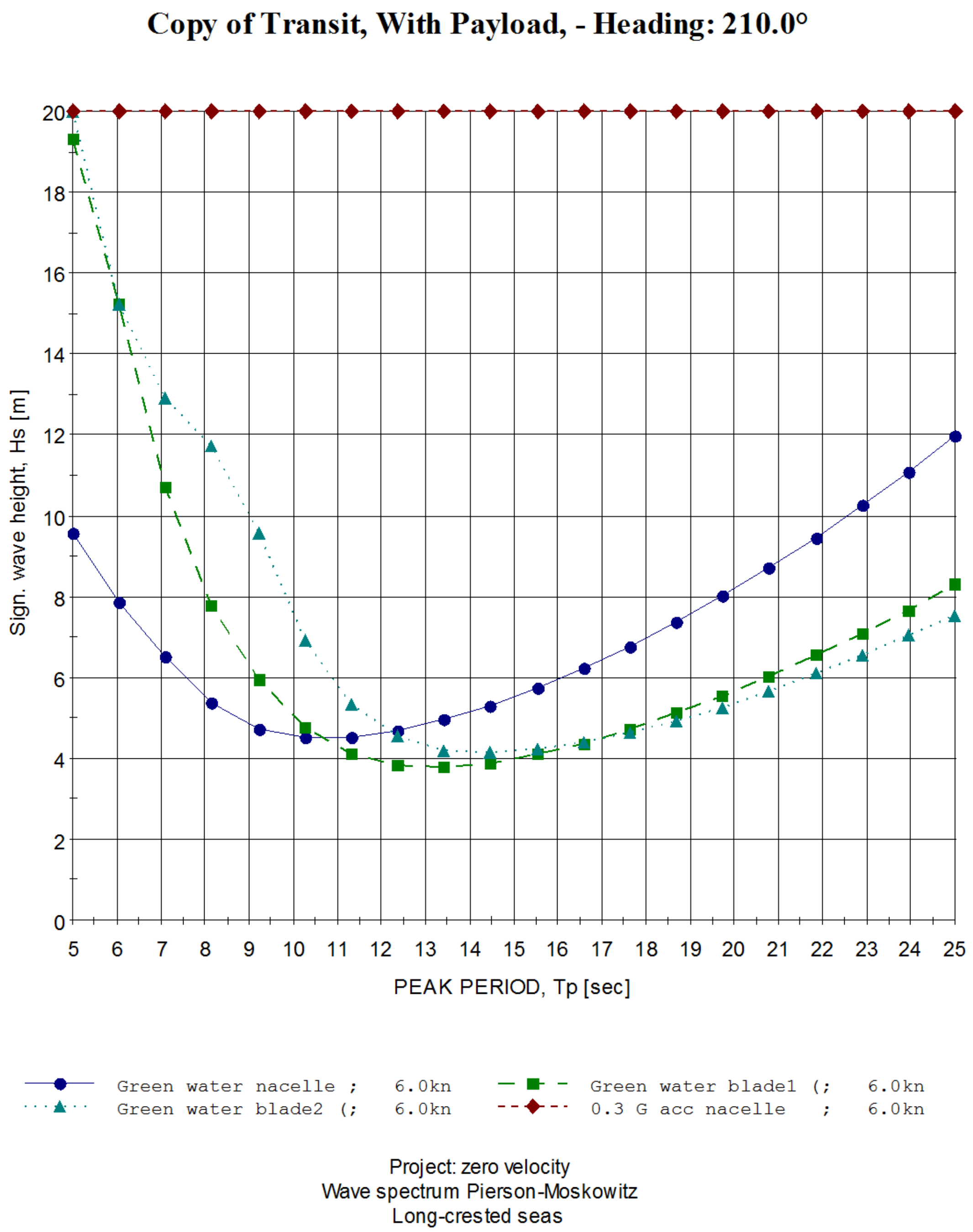
Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas



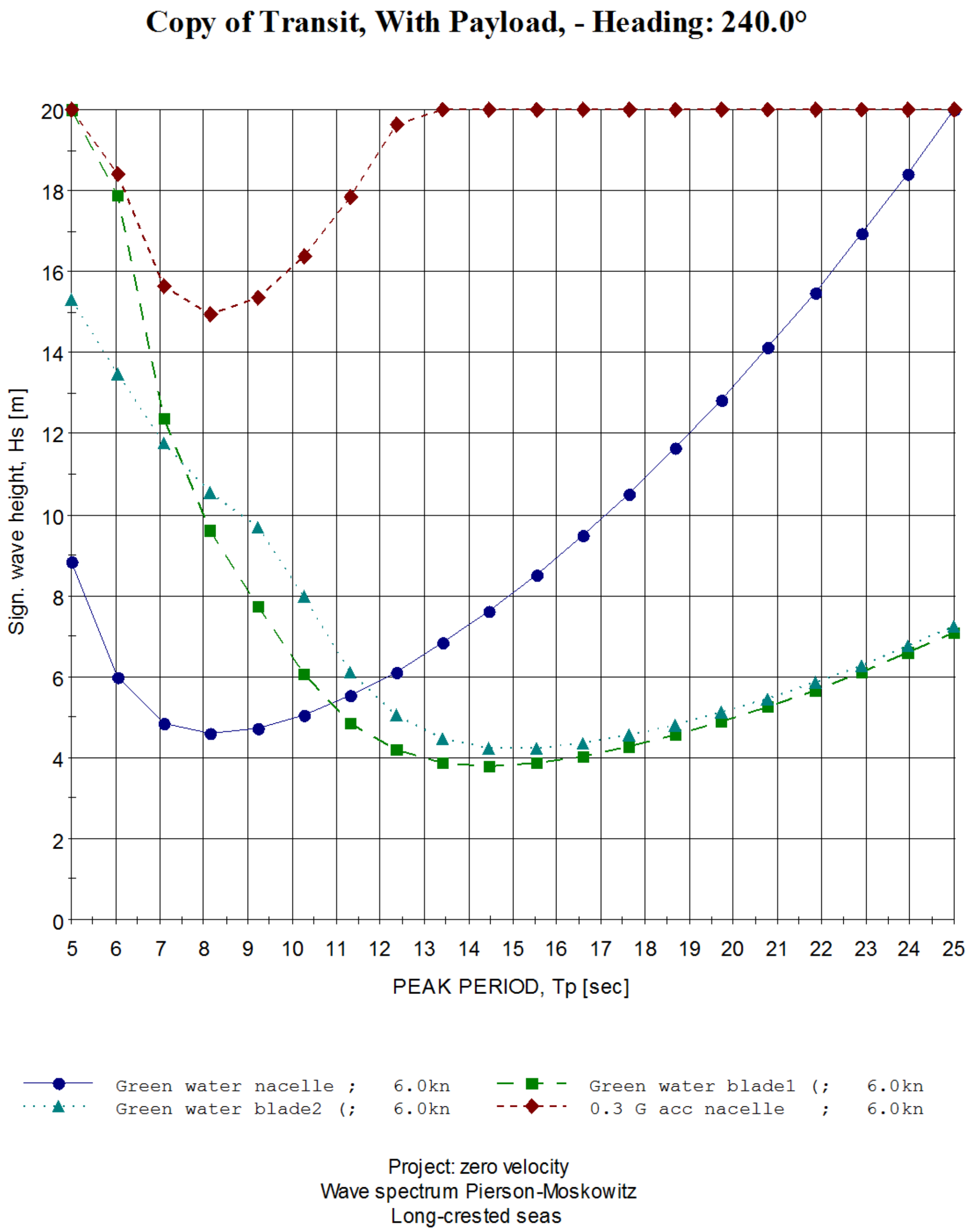
Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas


Copy of Transit, With Payload, - Heading: 180.0°

Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas



Copy of Transit, With Payload, - Heading: 210.0°


Copy of Transit, With Payload, - Heading: 240.0°
Sign. wave height, Hs [m]
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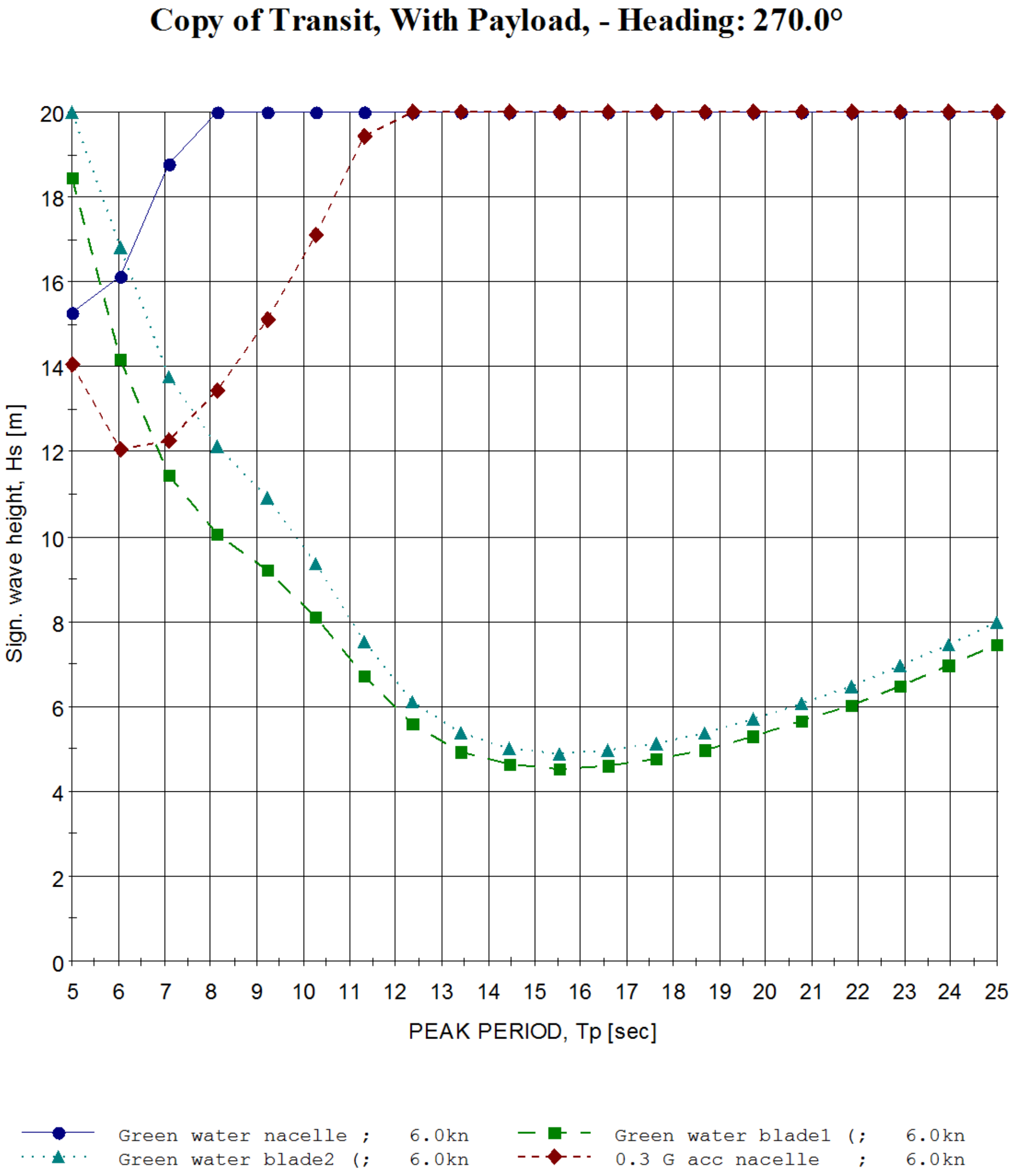
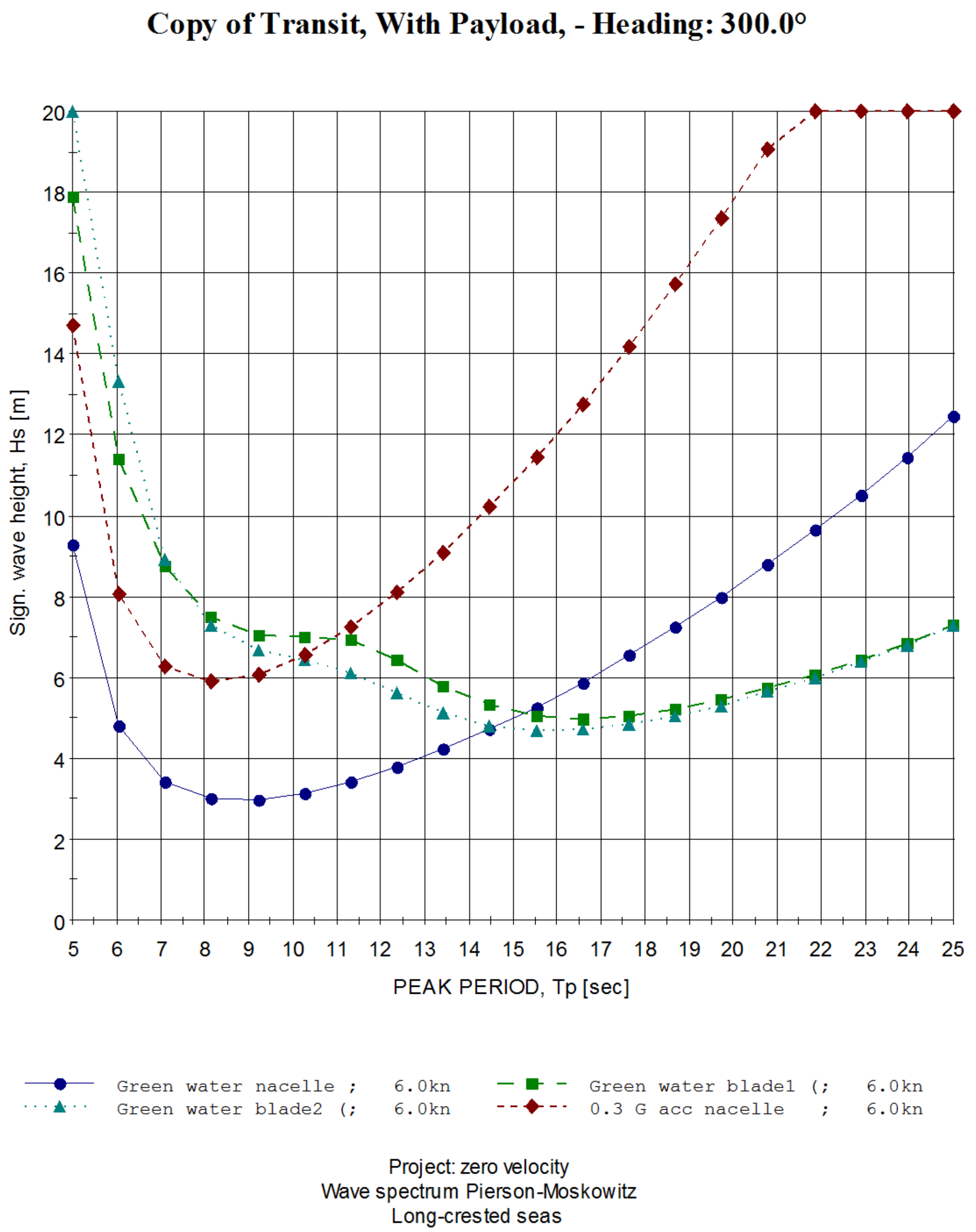
PEAK PERIOD, Tp [sec]
Green water nacelle ; 6.0kn
Green water blade1 (; 6.0kn
Green water blade2 (; 6.0kn
0.3 G acc nacelle ; 6.0kn
Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas

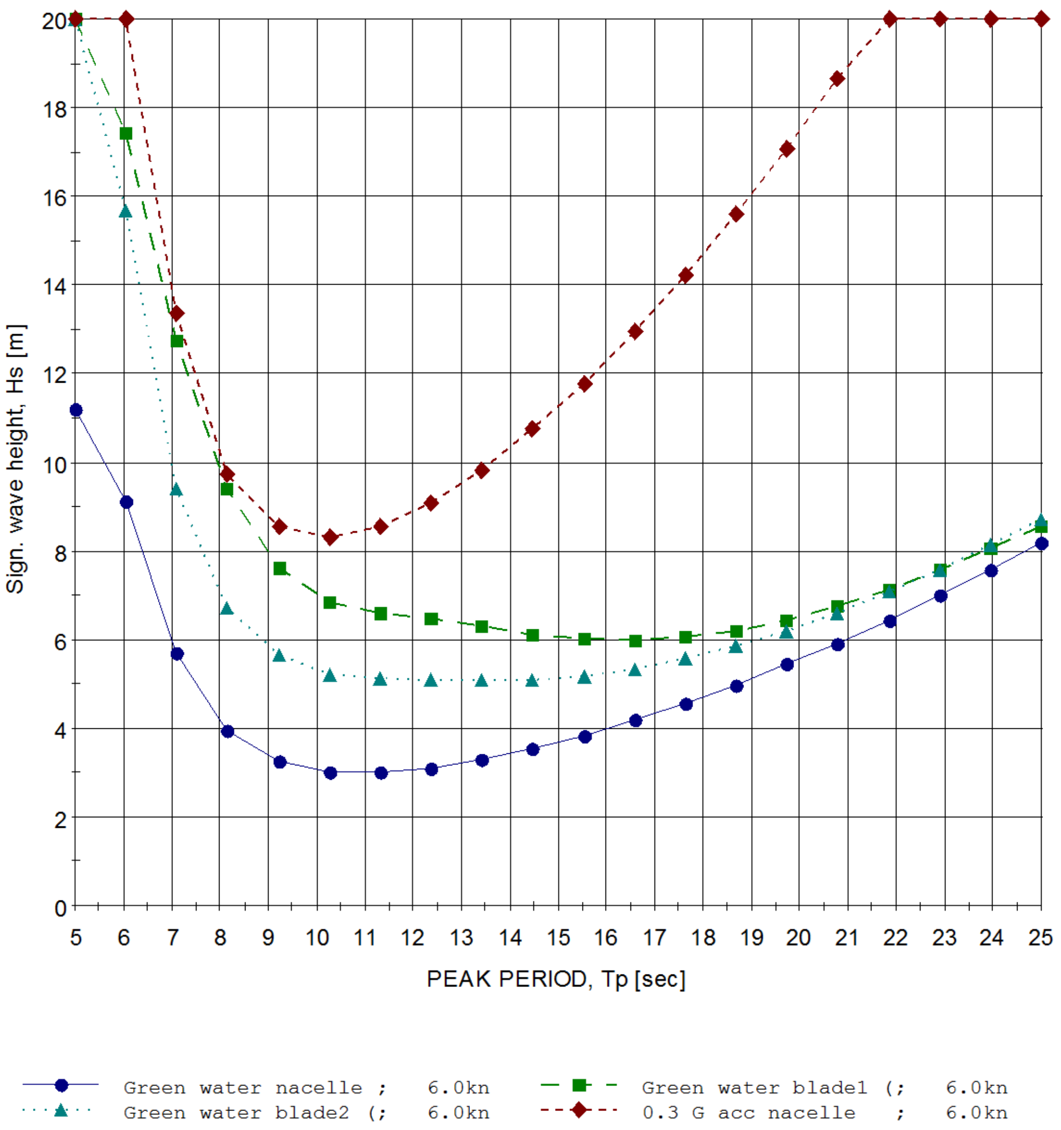


Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas



Copy of Transit, With Payload, - Heading: 300.0°

Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas



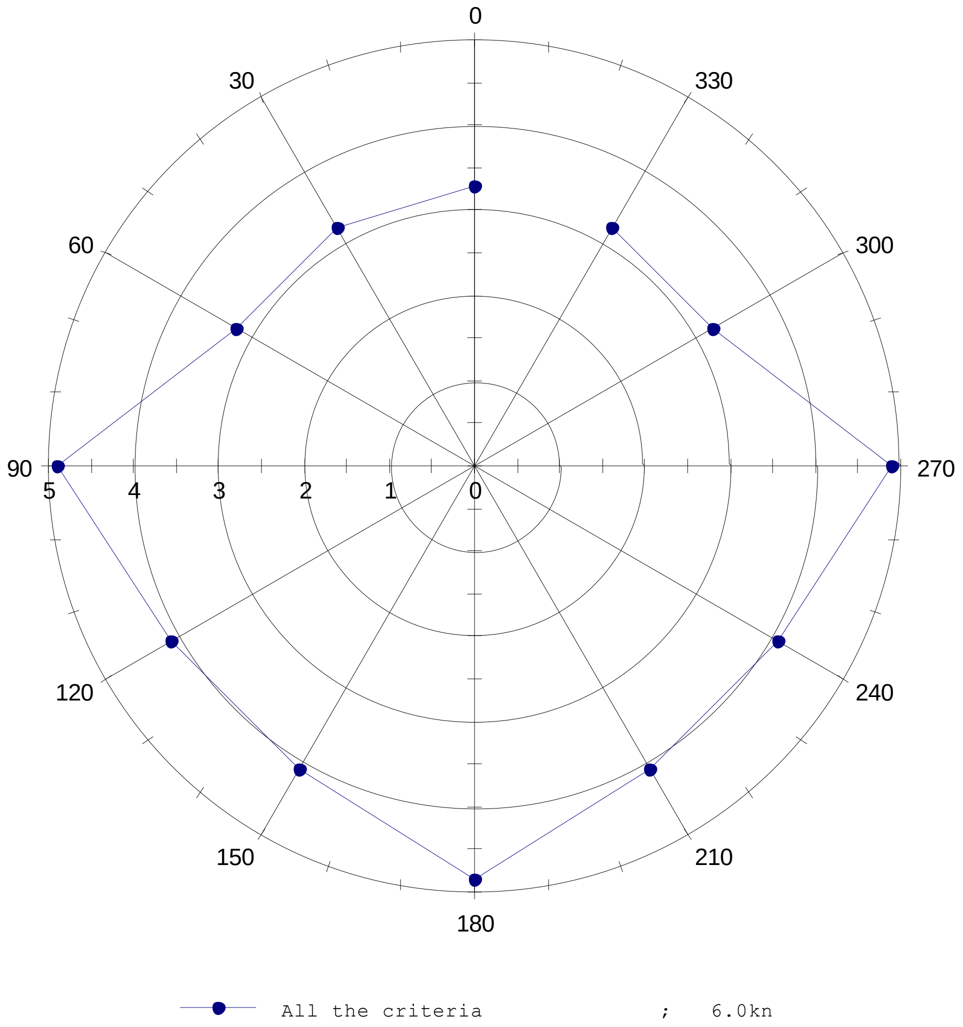
Copy of Transit, With Payload, - Heading: 330.0°

Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas

Results for velocity 6 knots, failure at one of hundred wind turbines

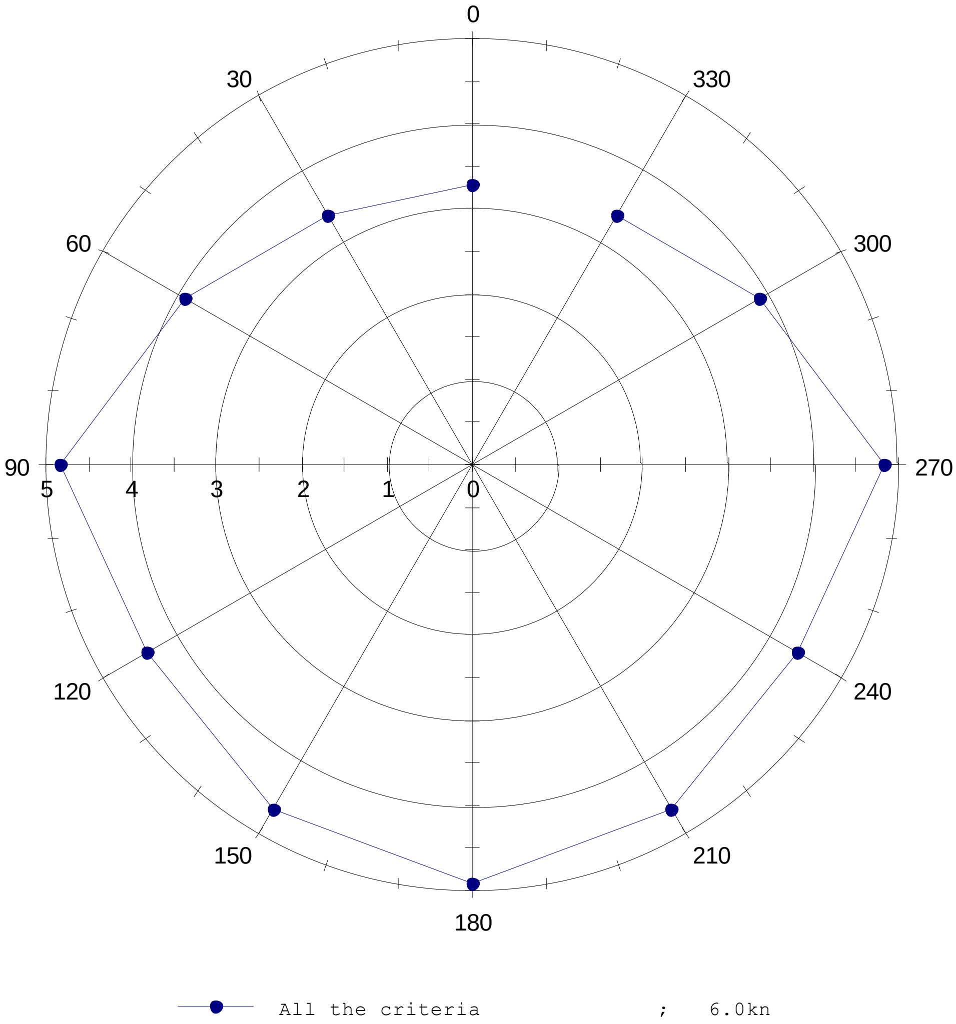
Polarplot long-crested seas

Copy of Transit, With Payload,
Limiting significant wave height, Hs [m]

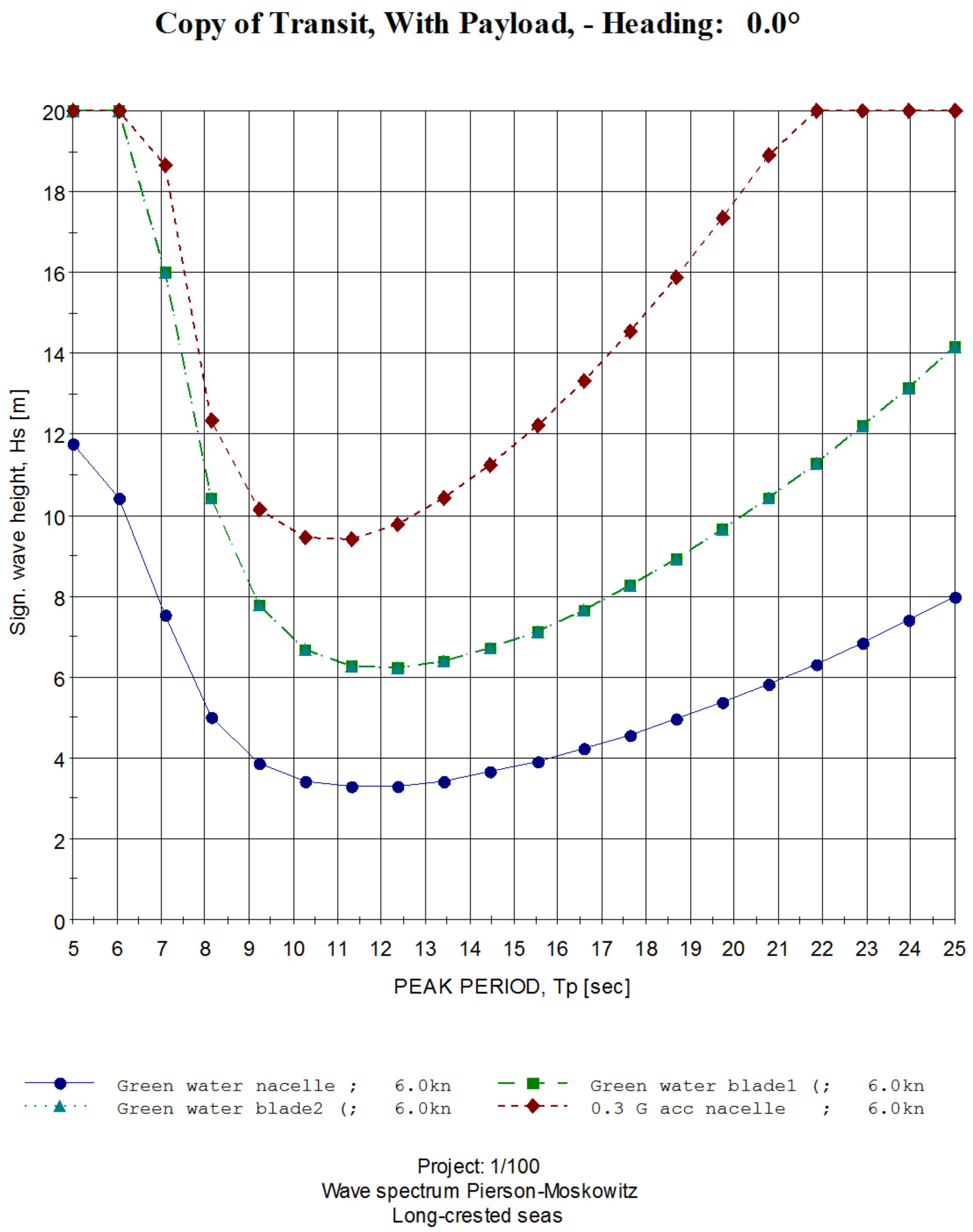


Project: 1/100
Wave spectrum Pierson-Moskowitz
Long-crested seas
Limiting values selected within Tp = 5.0 to 25.0 s and breaking waves limit
Zero degrees heading is head seas

Copy of Transit, With Payload,
Limiting significant wave height, Hs [m]



Project: 1/100
Wave spectrum Pierson-Moskowitz
Short-crested seas (Power of cosine = 4, wave spreading angle = ±90.0°)
Limiting values selected within Tp = 5.0 to 25.0 s and breaking waves limit
Zero degrees heading is head seas


Copy of Transit, With Payload, - Heading: 0.0°
Sign. wave height, Hs [m]
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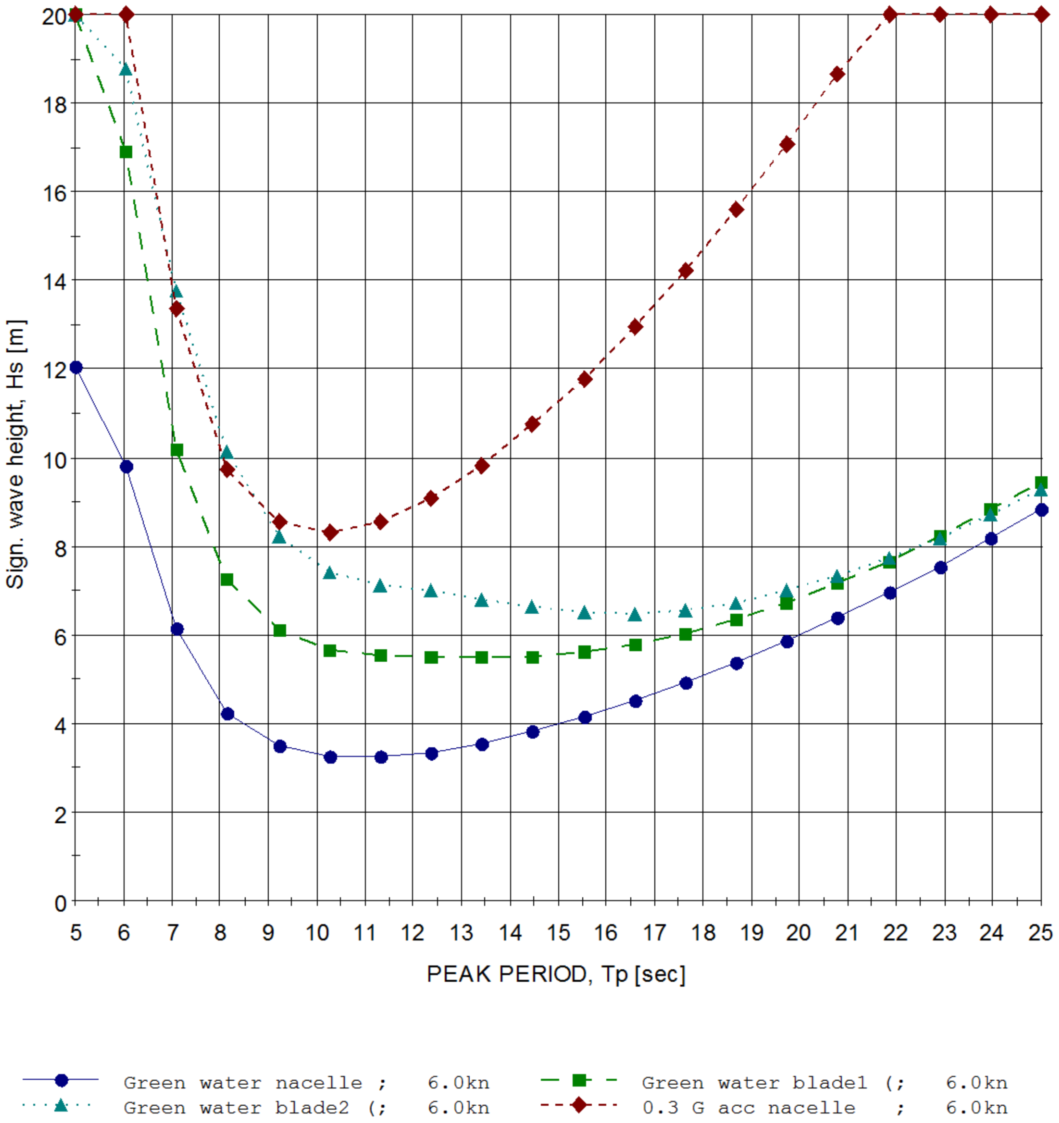
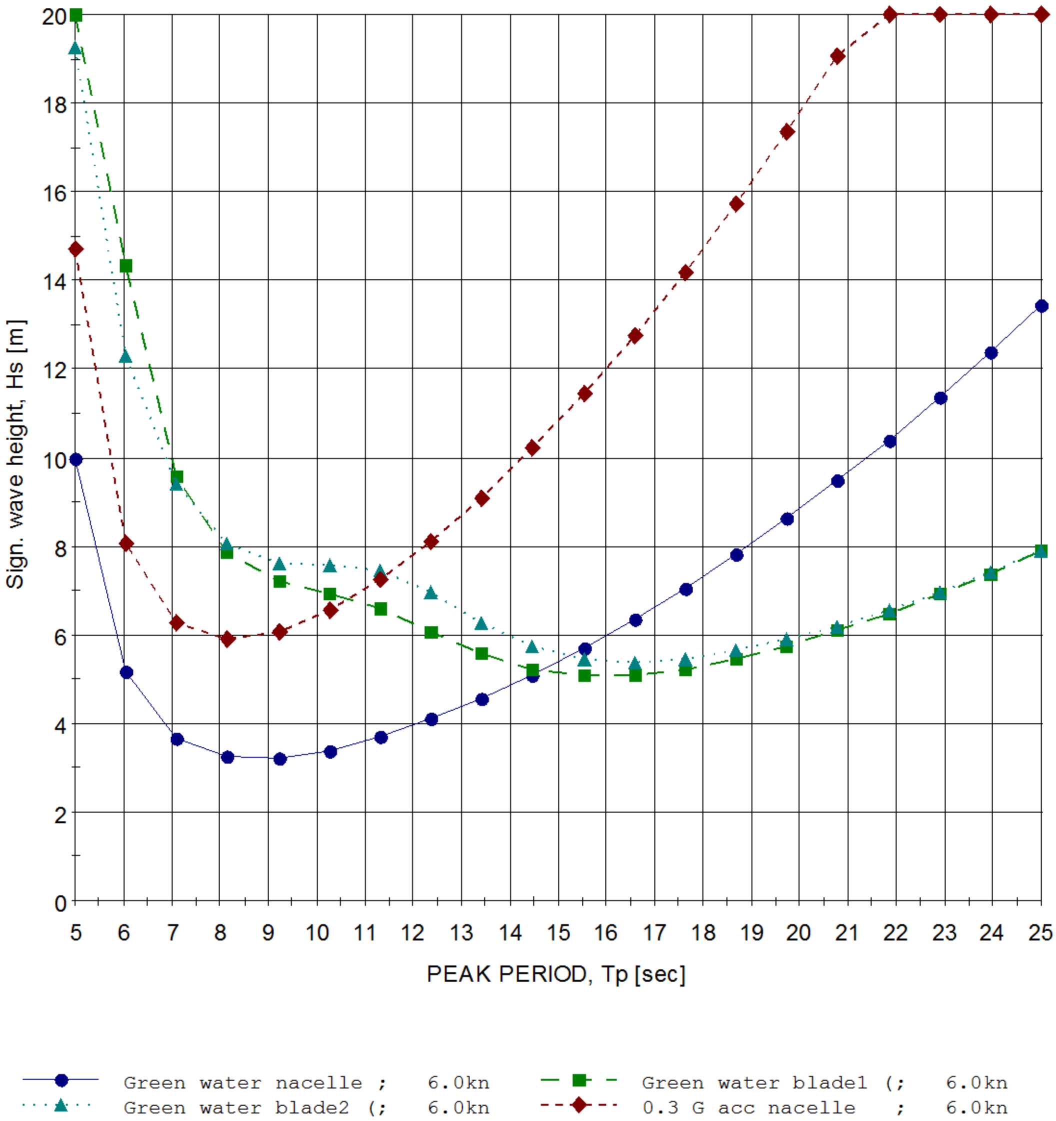
PEAK PERIOD, Tp [sec]
Green water nacelle ; 6.0kn
Green water blade2 (; 6.0kn
Green water blade1 (; 6.0kn
0.3 G acc nacelle ; 6.0kn
Project: 1/100
Wave spectrum Pierson-Moskowitz
Long-crested seas

Copy of Transit, With Payload, - Heading: 30.0°



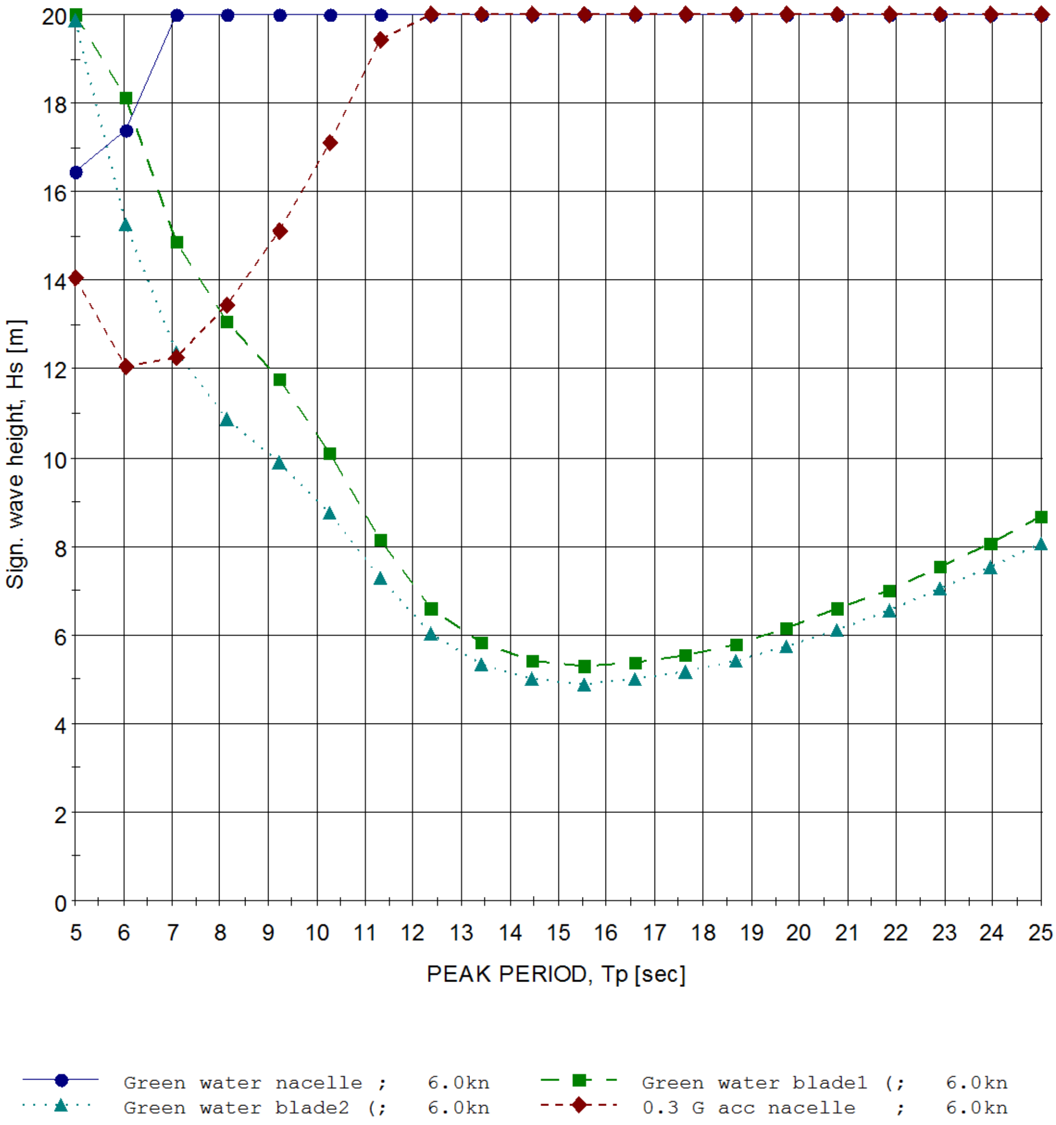
Project: 1/100
Wave spectrum Pierson-Moskowitz
Long-crested seas

Copy of Transit, With Payload, - Heading: 60.0°



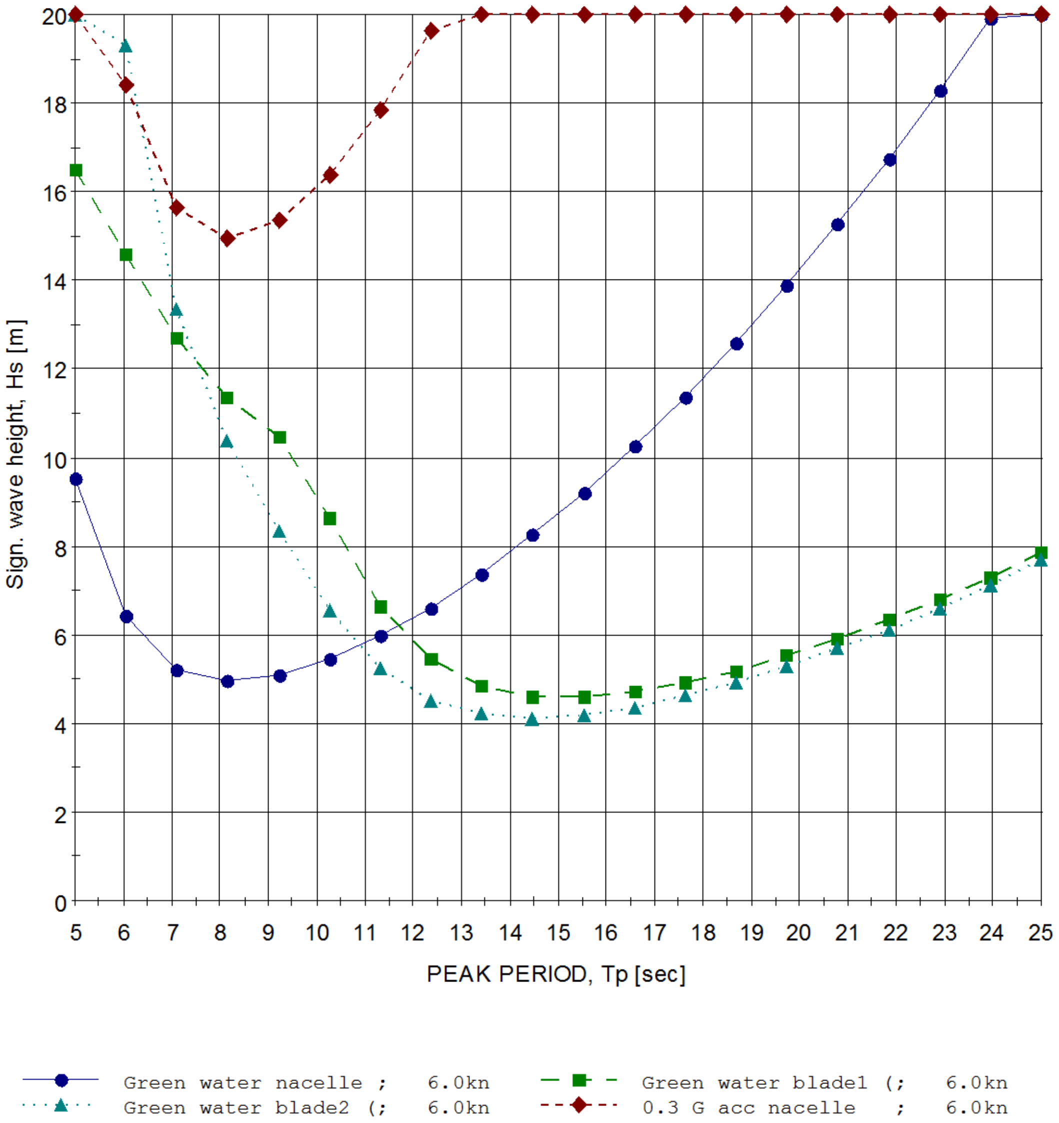
Project: 1/100
Wave spectrum Pierson-Moskowitz
Long-crested seas

Copy of Transit, With Payload, - Heading: 90.0°



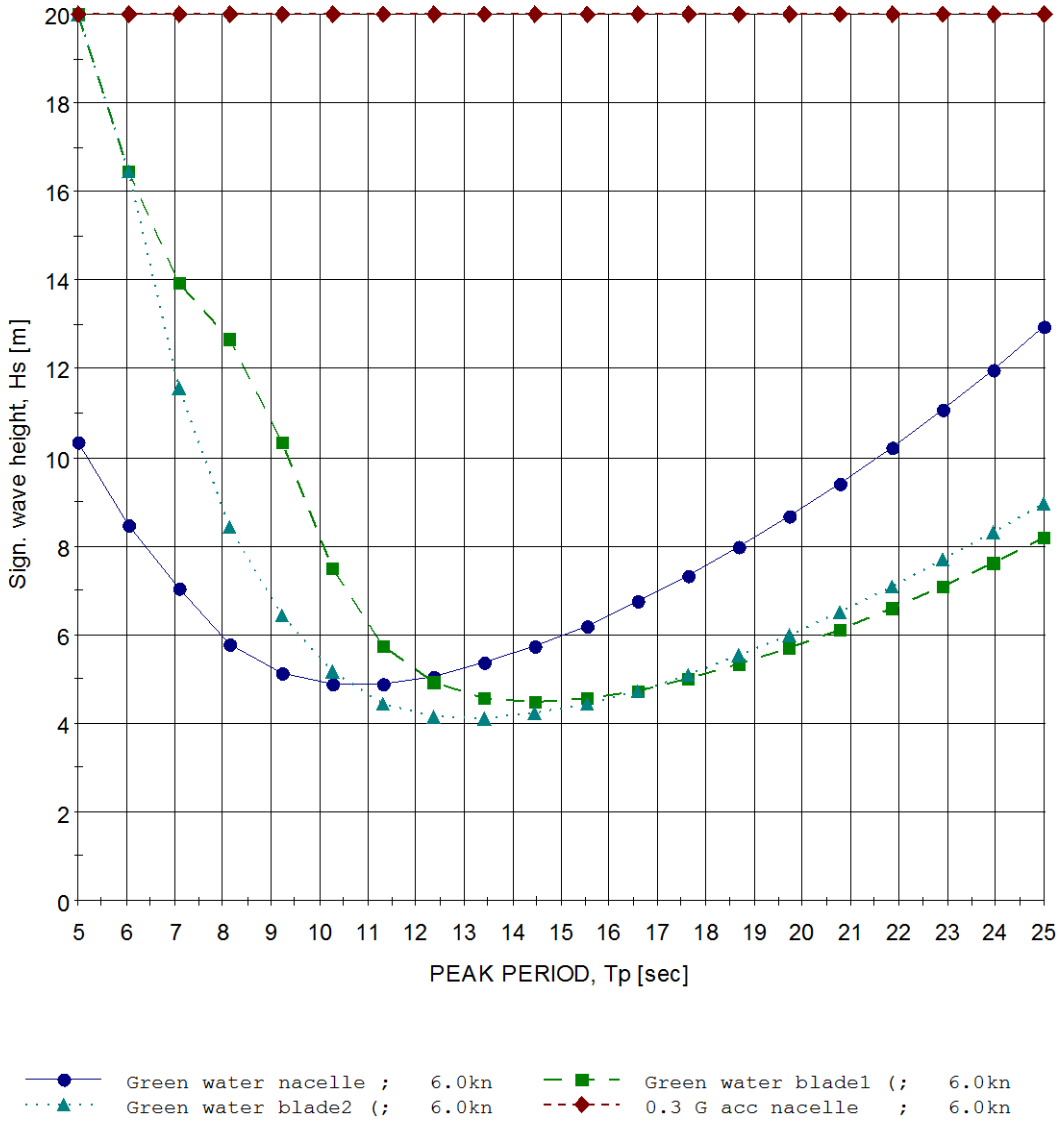
Project: 1/100
Wave spectrum Pierson-Moskowitz
Long-crested seas

Copy of Transit, With Payload, - Heading: 120.0°

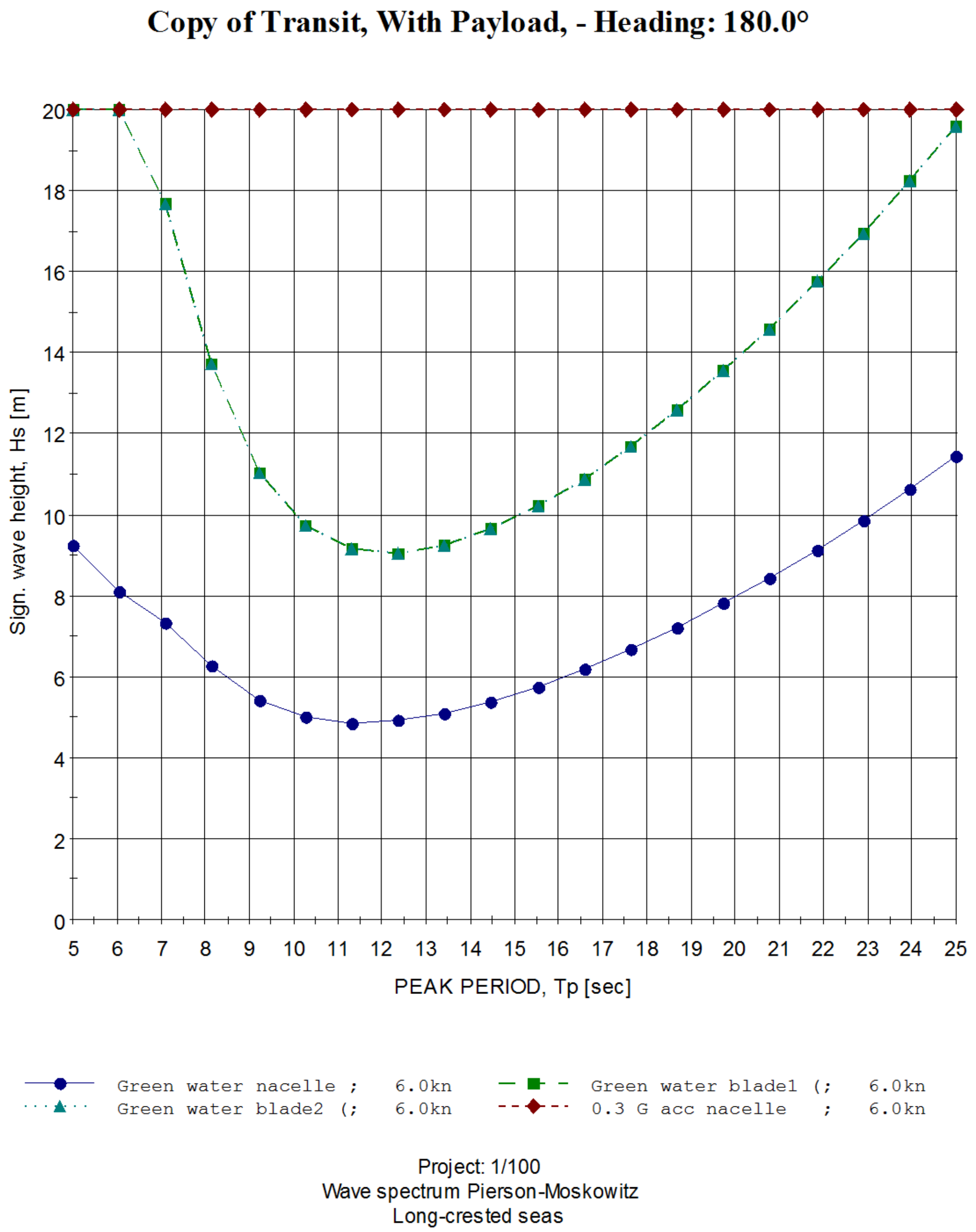


Project: 1/100
Wave spectrum Pierson-Moskowitz
Long-crested seas

Copy of Transit, With Payload, - Heading: 150.0°



Project: 1/100
Wave spectrum Pierson-Moskowitz
Long-crested seas


Copy of Transit, With Payload, - Heading: 180.0°
Sign. wave height, Hs [m]
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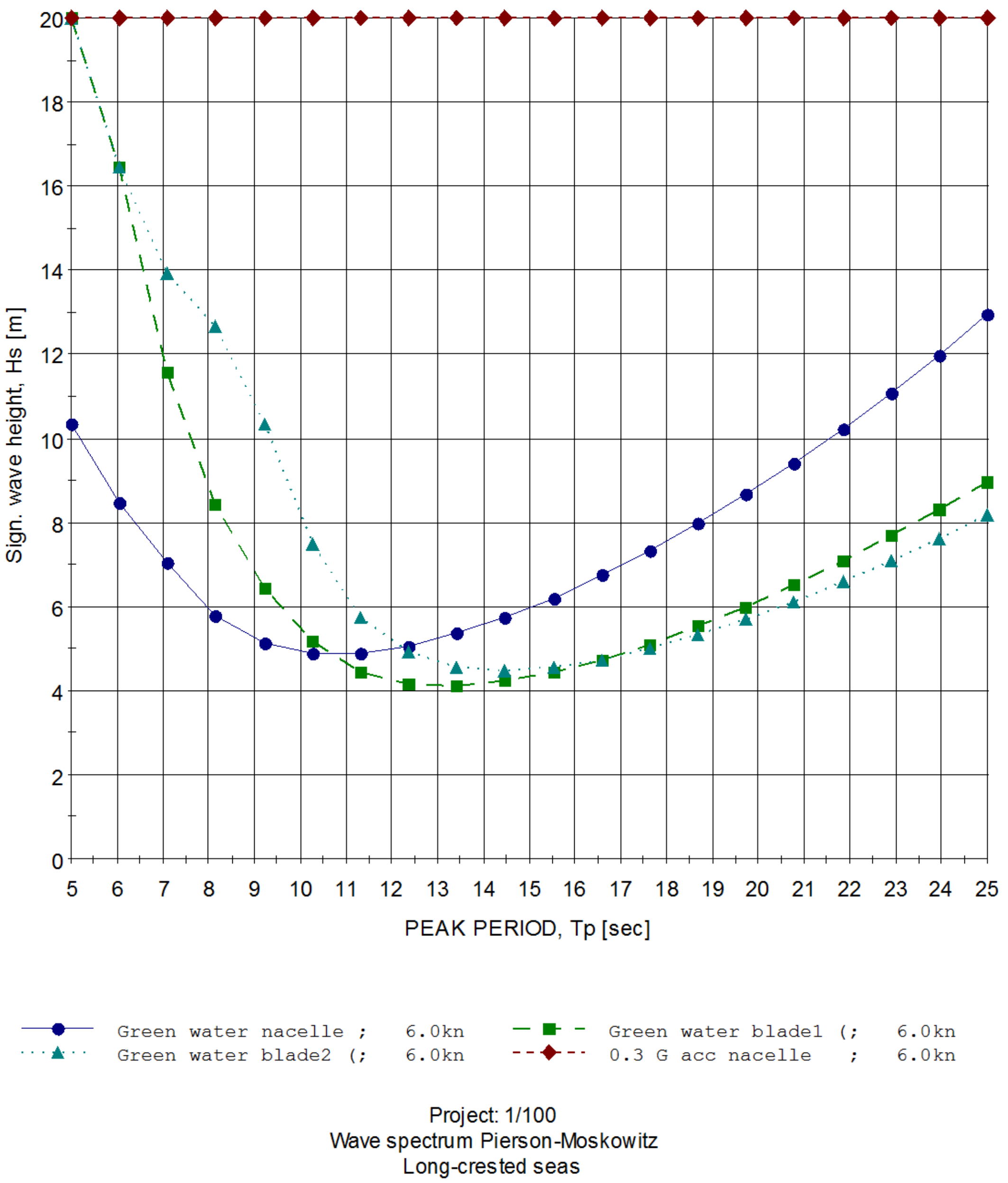
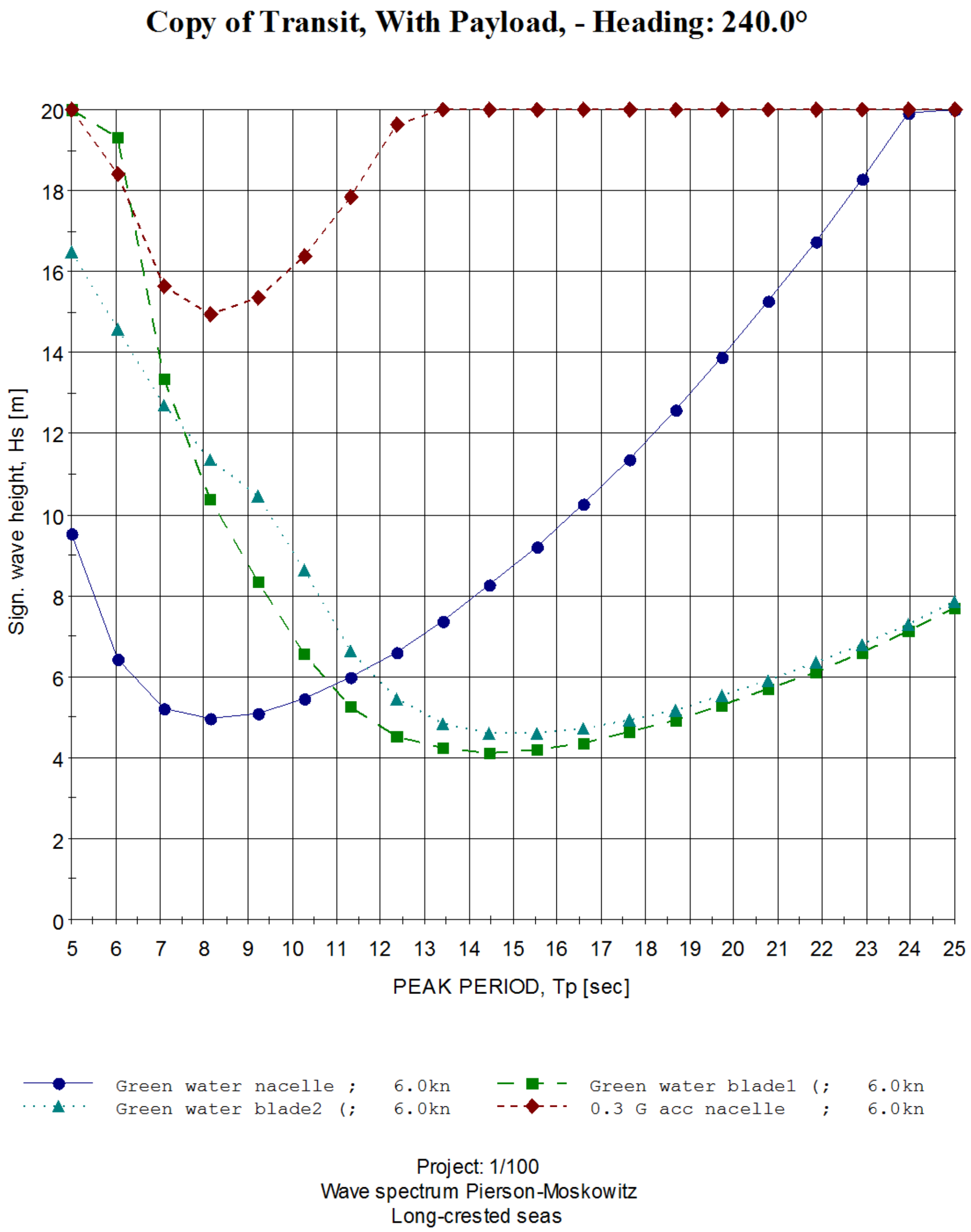
PEAK PERIOD, Tp [sec]
Green water nacelle ; 6.0kn
Green water blade1 (; 6.0kn
Green water blade2 (; 6.0kn
0.3 G acc nacelle ; 6.0kn
Project: 1/100
Wave spectrum Pierson-Moskowitz
Long-crested seas

Copy of Transit, With Payload, - Heading: 210.0°




Copy of Transit, With Payload, - Heading: 240.0°
Sign. wave height, Hs [m]
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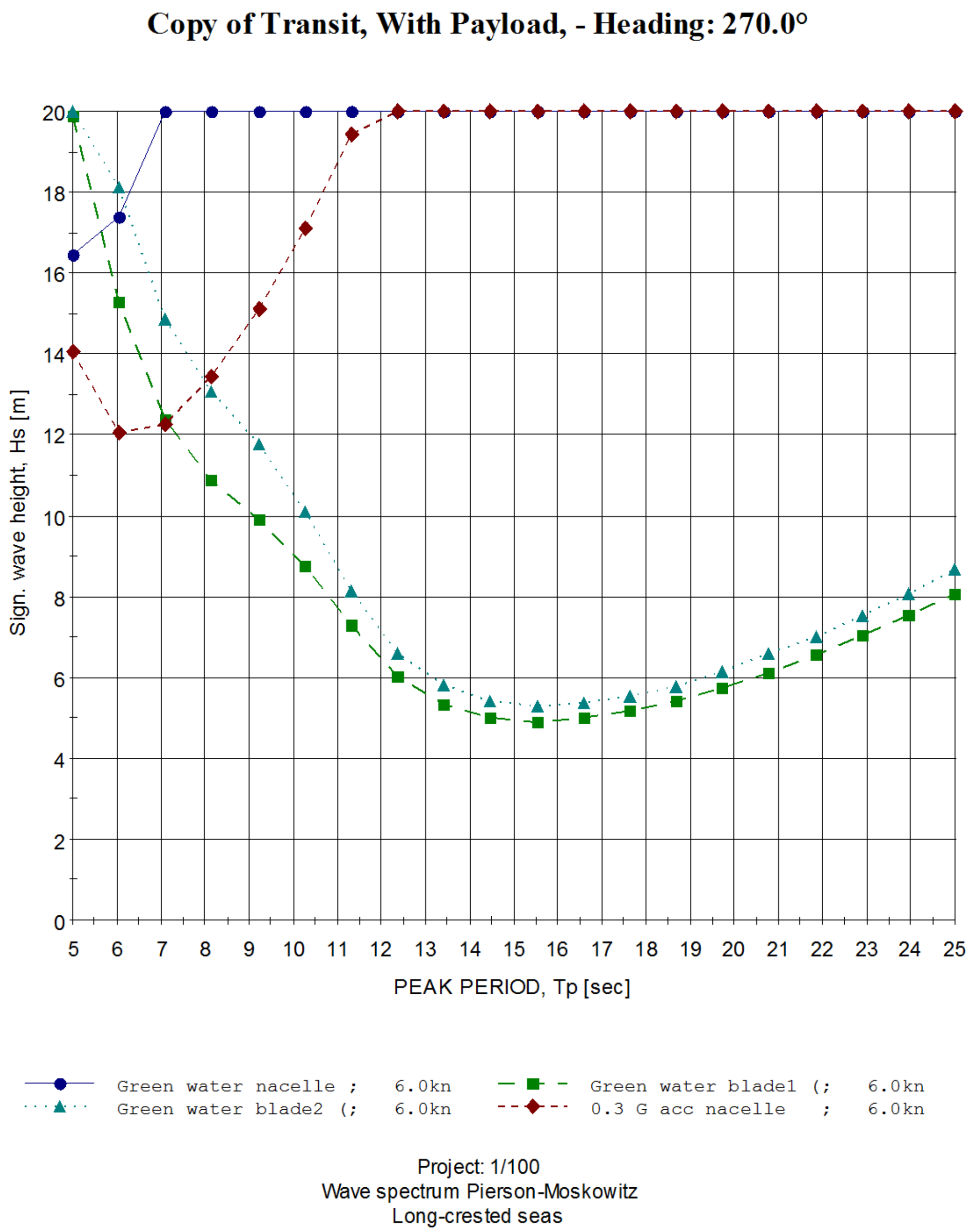
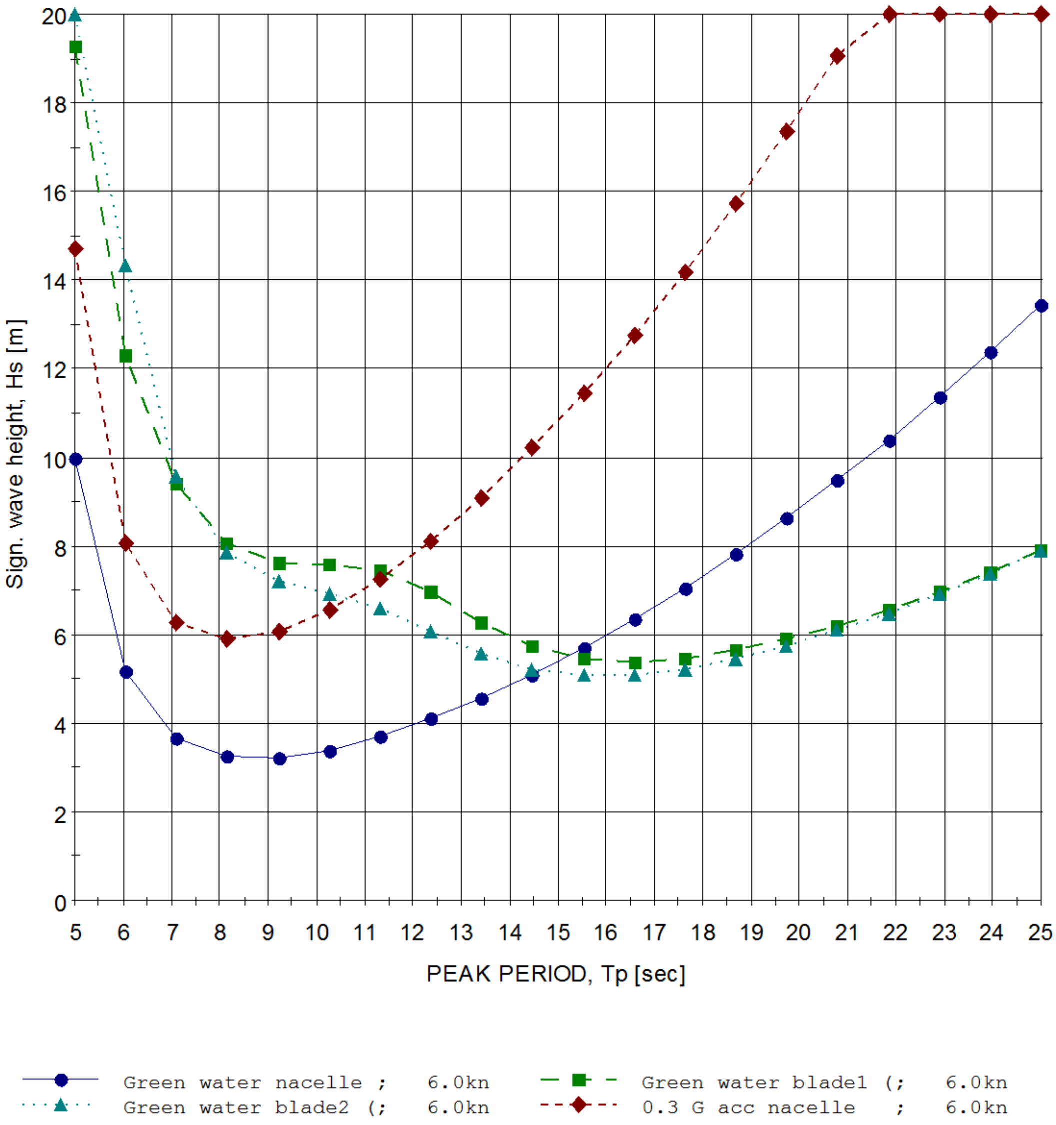
PEAK PERIOD, Tp [sec]
Green water nacelle ; 6.0kn
Green water blade1 (; 6.0kn
Green water blade2 (; 6.0kn
0.3 G acc nacelle ; 6.0kn
Project: 1/100
Wave spectrum Pierson-Moskowitz
Long-crested seas

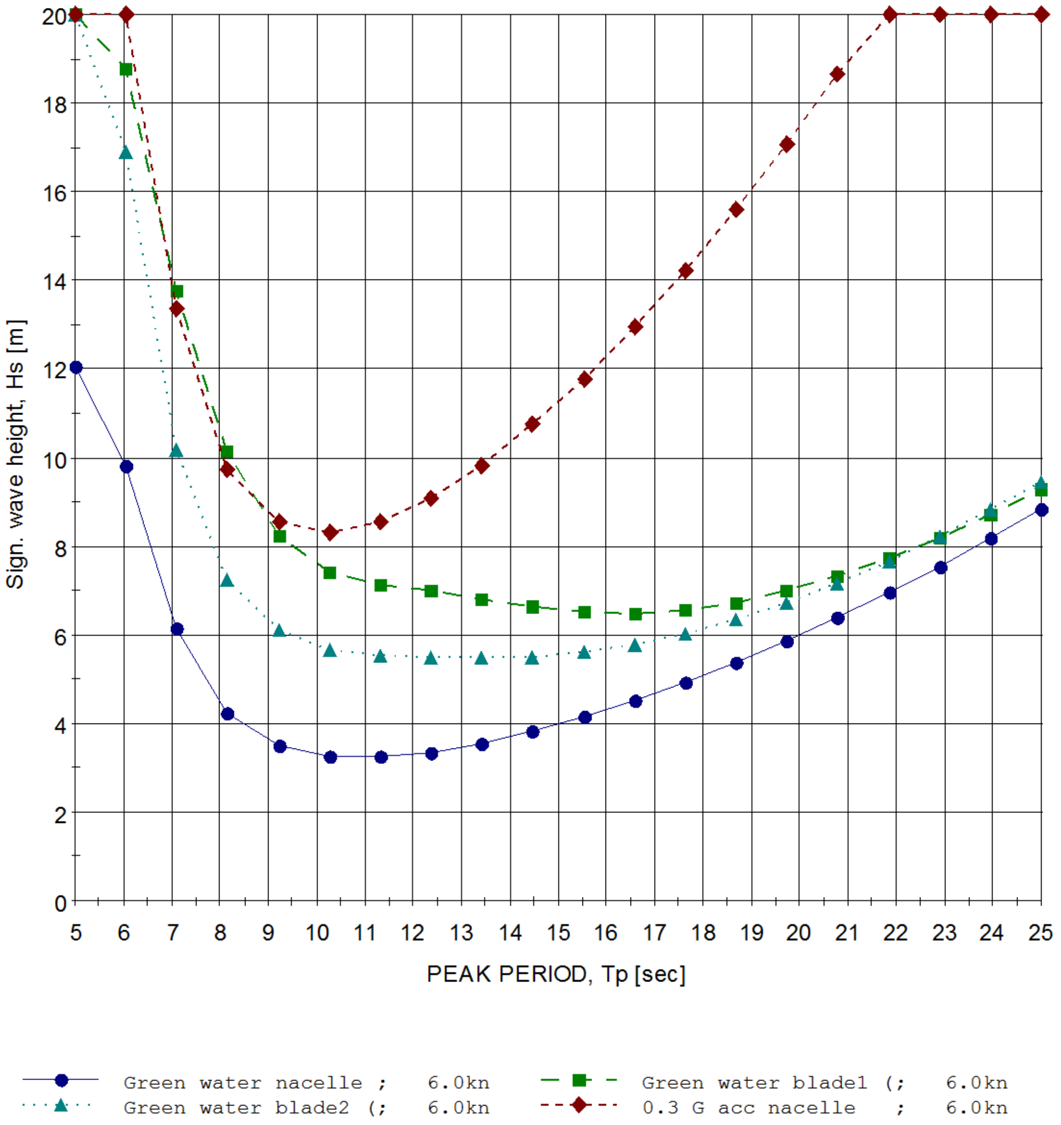

Copy of Transit, With Payload, - Heading: 270.0°
Sign. wave height, Hs [m]
0
2
4
6
8
10
12
14
16
18
20
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
PEAK PERIOD, Tp [sec]
Green water nacelle ; 6.0kn
Green water blade2 (; 6.0kn
Green water blade1 (; 6.0kn
0.3 G acc nacelle ; 6.0kn
Project: 1/100
Wave spectrum Pierson-Moskowitz
Long-crested seas

Copy of Transit, With Payload, - Heading: 300.0°



Project: 1/100
Wave spectrum Pierson-Moskowitz
Long-crested seas

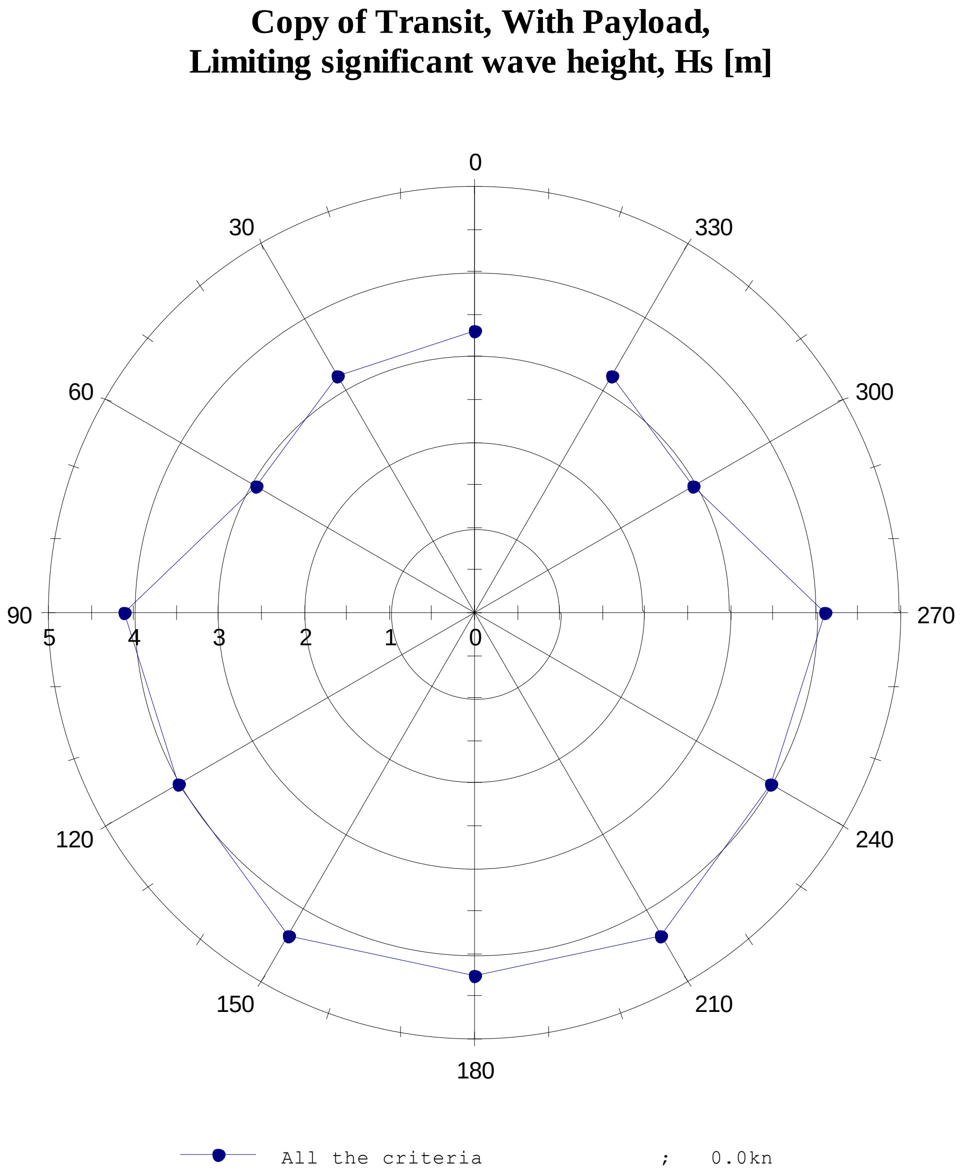
Copy of Transit, With Payload, - Heading: 330.0°



Project: 1/100
Wave spectrum Pierson-Moskowitz
Long-crested seas

Results for velocity 0 knots, failure at one of thousand wind turbines

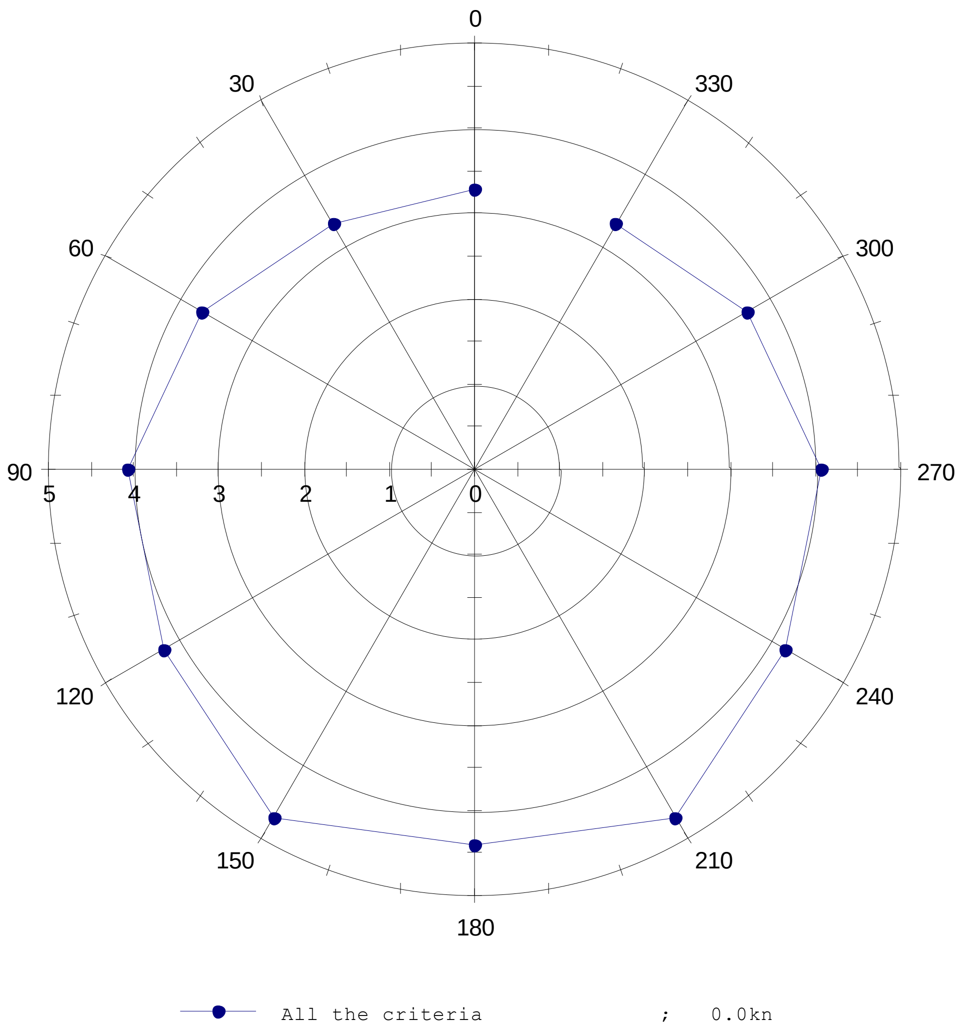
Polarplot long-crested seas



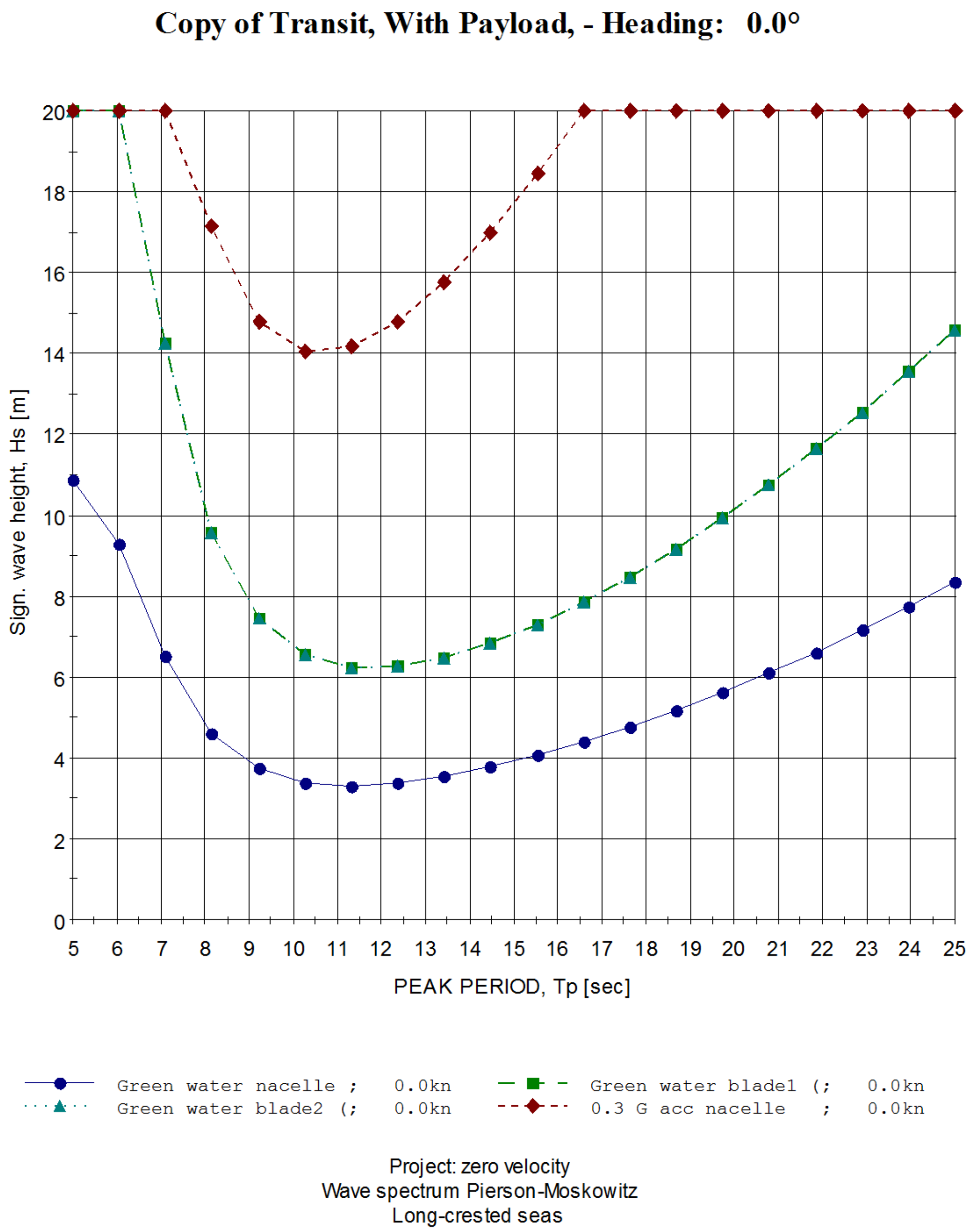
Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas
Limiting values selected within Tp = 5.0 to 25.0 s and breaking waves limit
Zero degrees heading is head seas

Polarplot short-crested seas

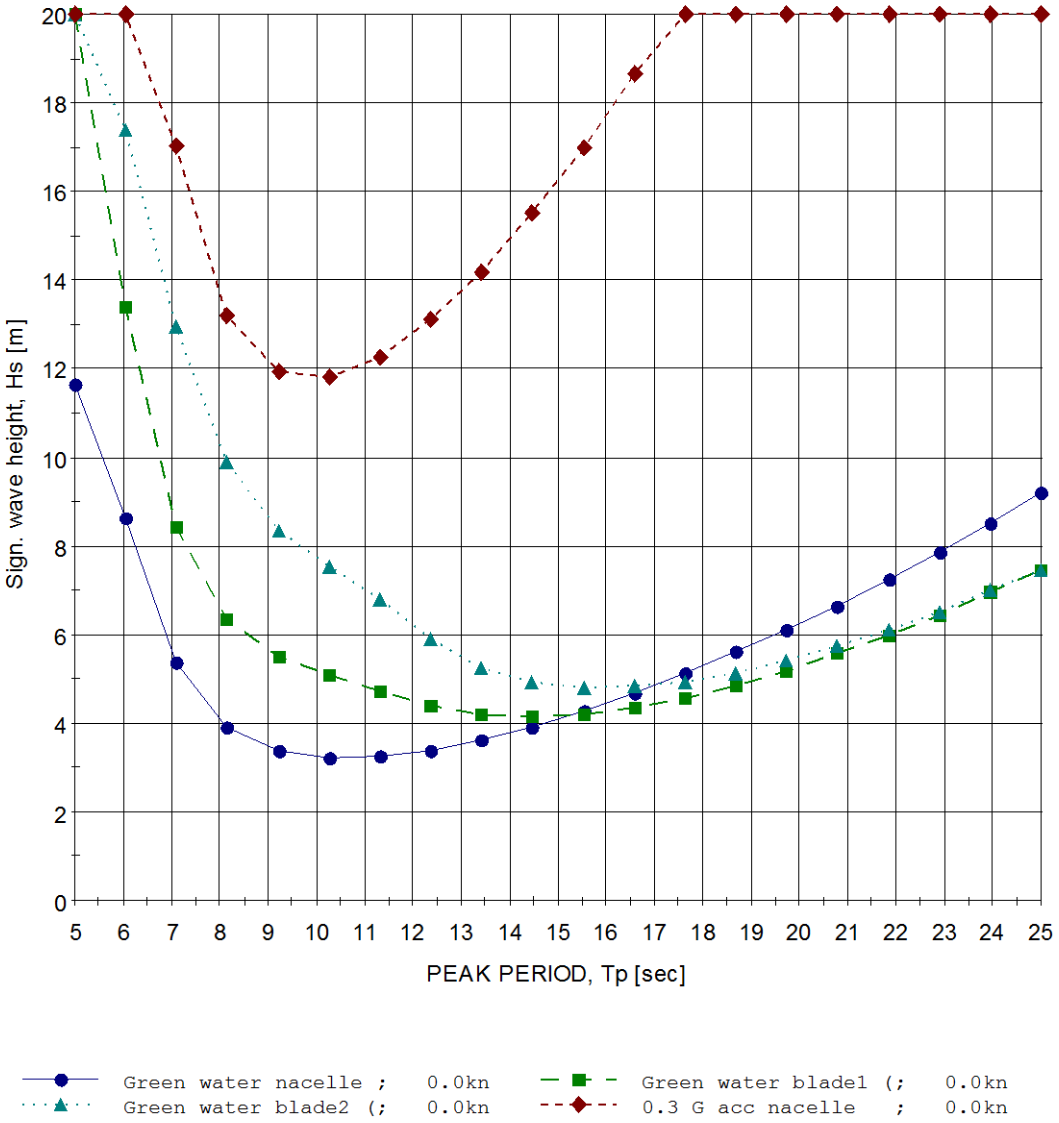
Copy of Transit, With Payload,
Limiting significant wave height, Hs [m]



Project: zero velocity
Wave spectrum Pierson-Moskowitz
Short-crested seas (Power of cosine = 4, wave spreading angle = ±90.0°)
Limiting values selected within Tp = 5.0 to 25.0 s and breaking waves limit
Zero degrees heading is head seas

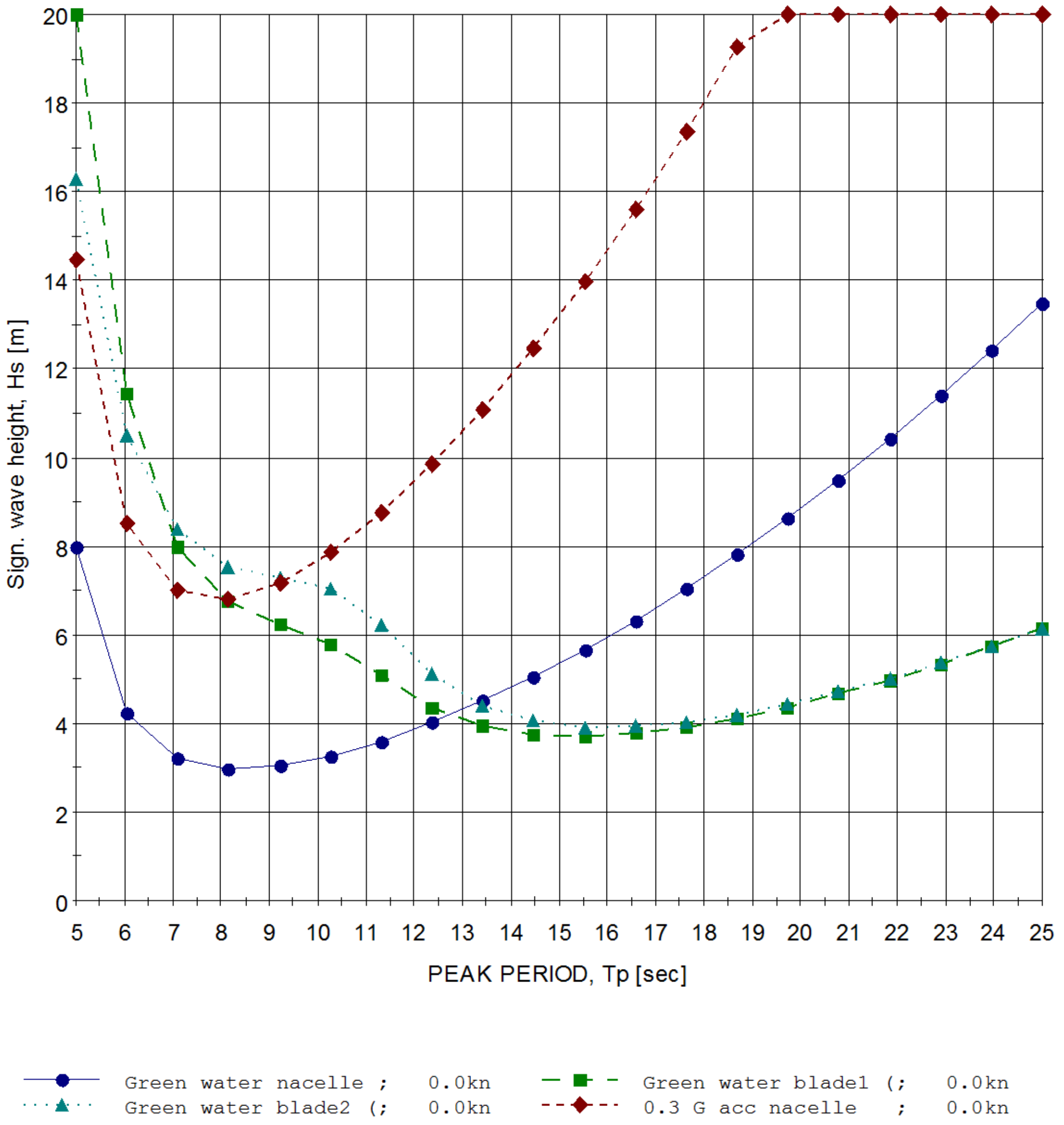

Copy of Transit, With Payload, - Heading: 0.0°
Sign. wave height, Hs [m]
0
2
4
6
8
10
12
14
16
18
20
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
PEAK PERIOD, Tp [sec]
Green water nacelle ; 0.0kn
Green water blade1 (; 0.0kn
Green water blade2 (; 0.0kn
0.3 G acc nacelle ; 0.0kn
Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas

Copy of Transit, With Payload, - Heading: 30.0°

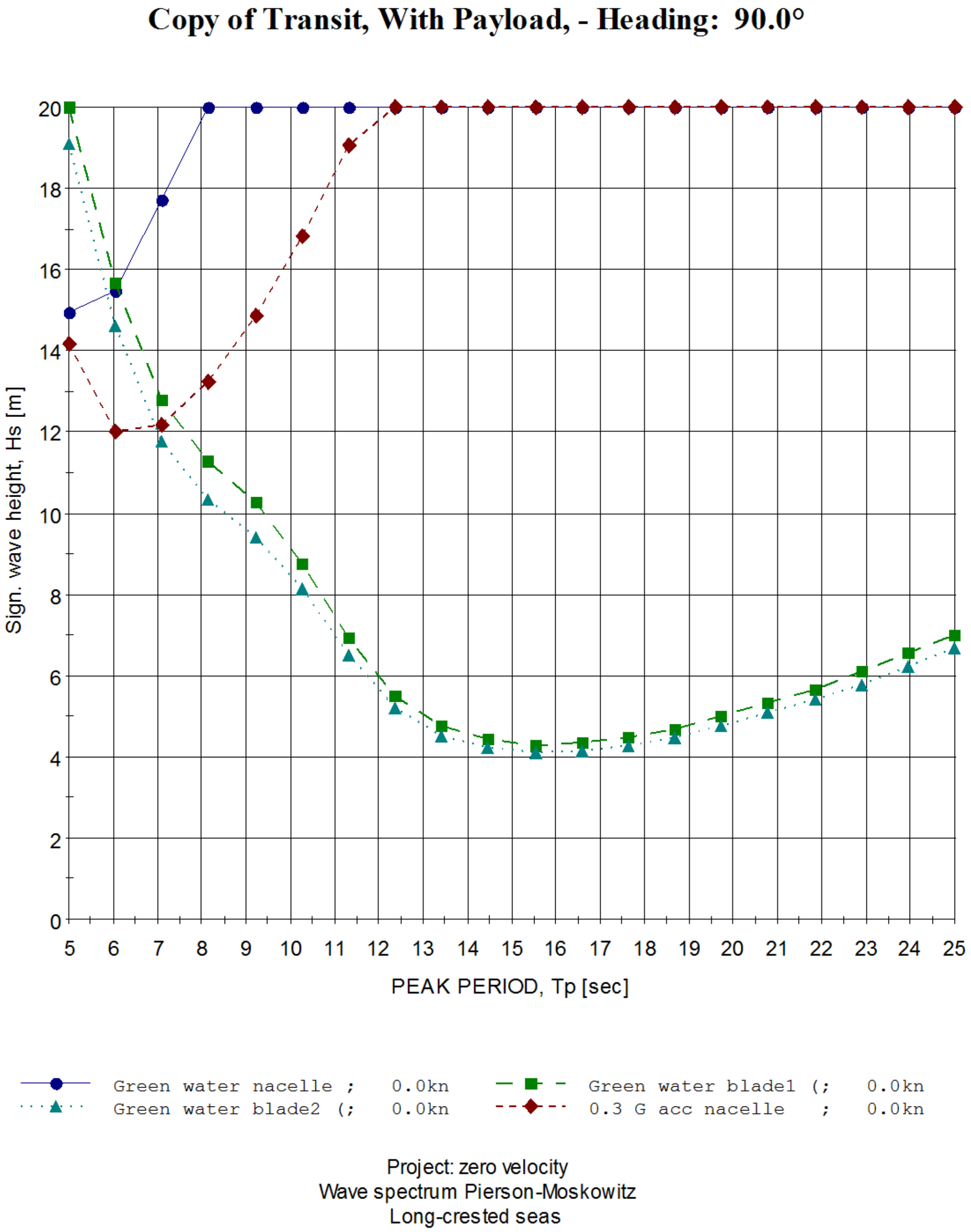


Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas

Copy of Transit, With Payload, - Heading: 60.0°



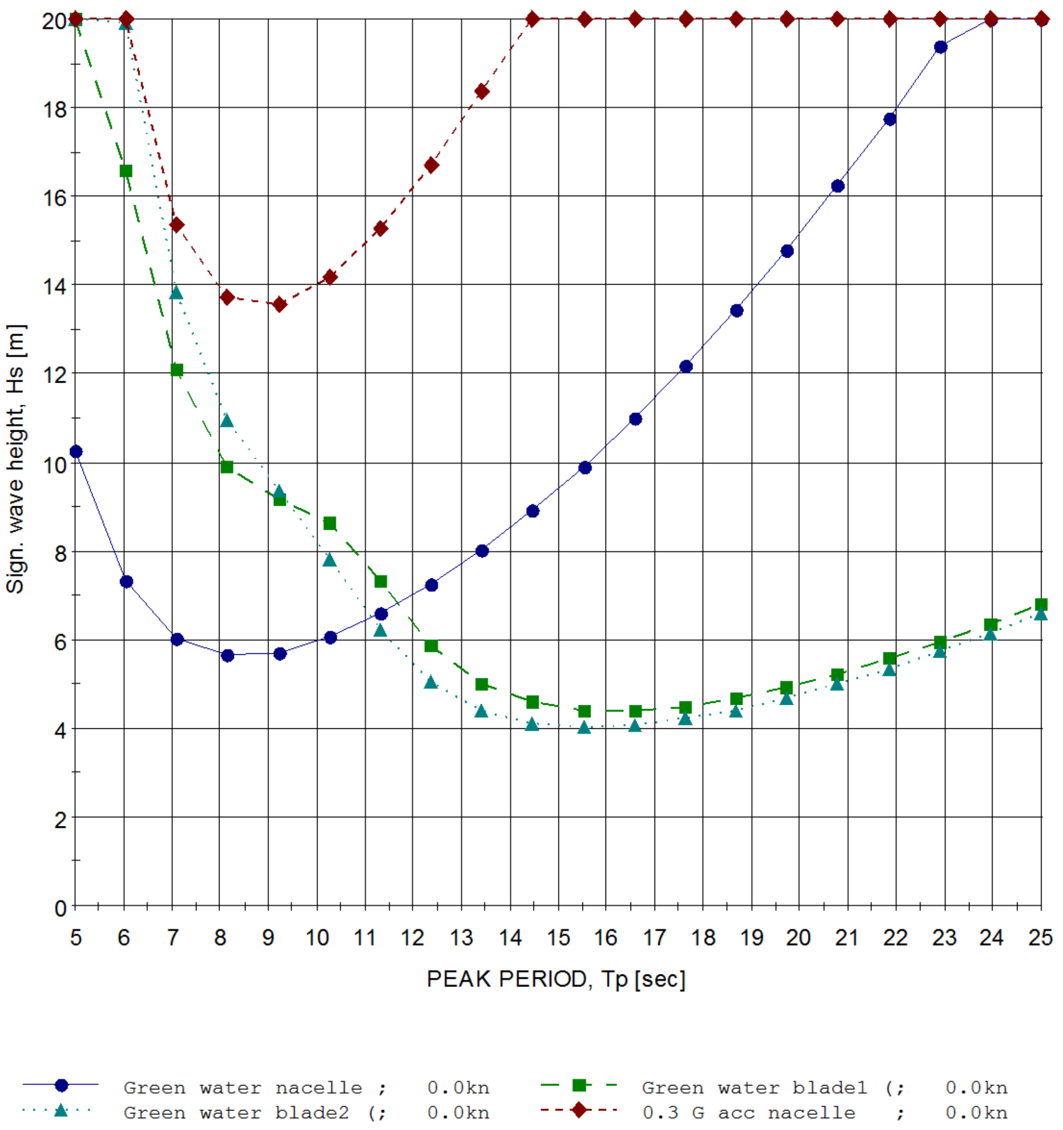
Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas



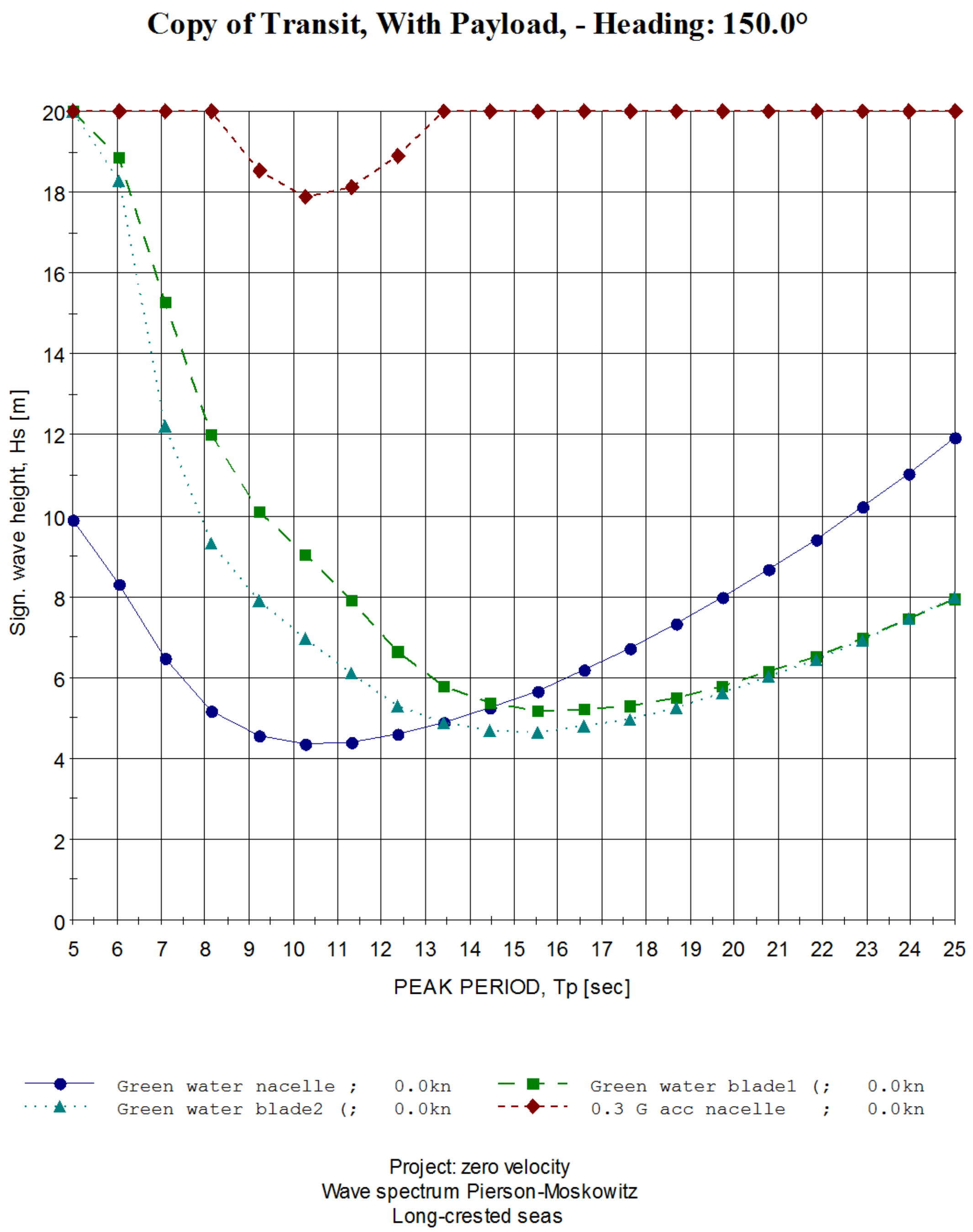
Copy of Transit, With Payload, - Heading: 90.0°

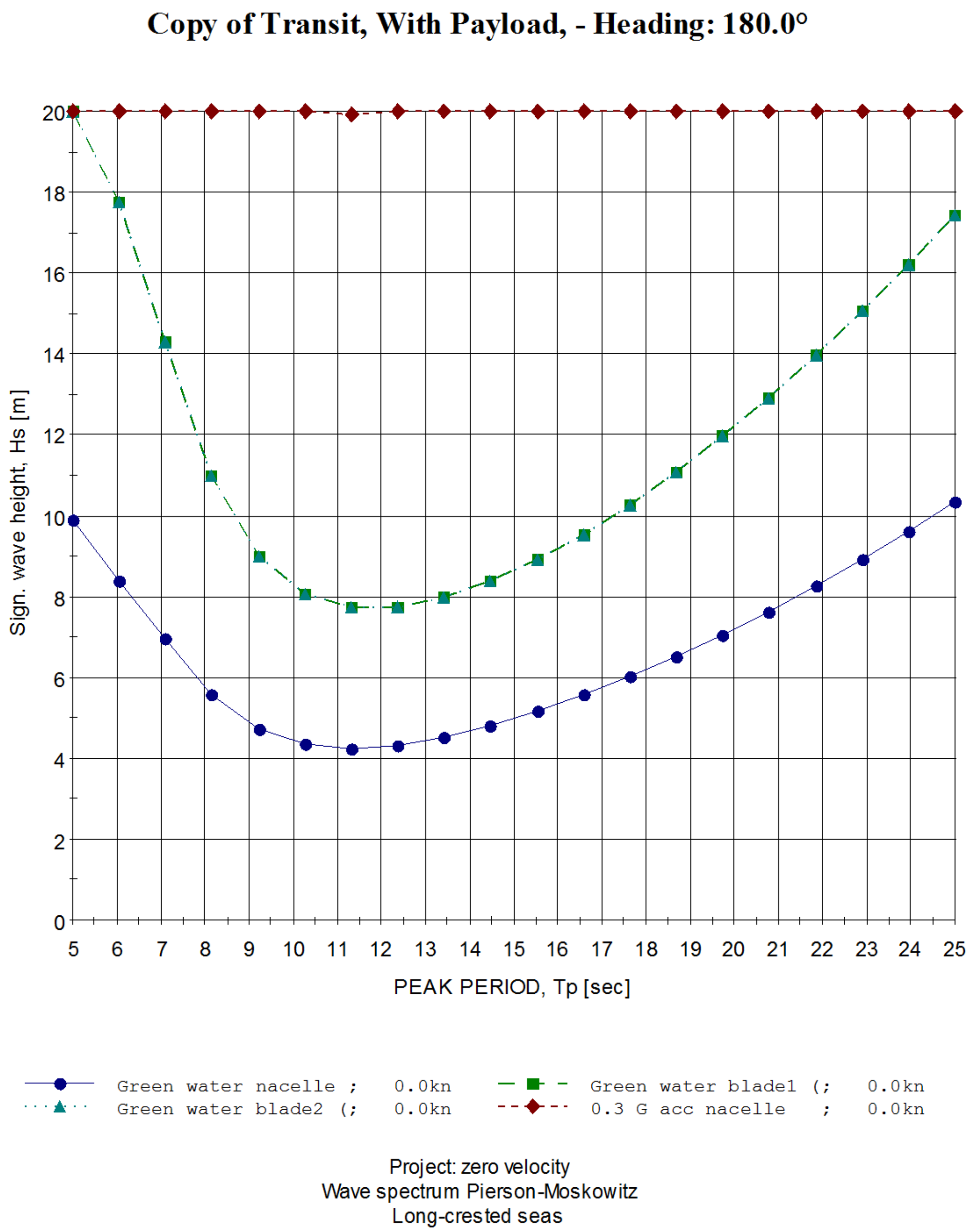
Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas

Copy of Transit, With Payload, - Heading: 120.0°

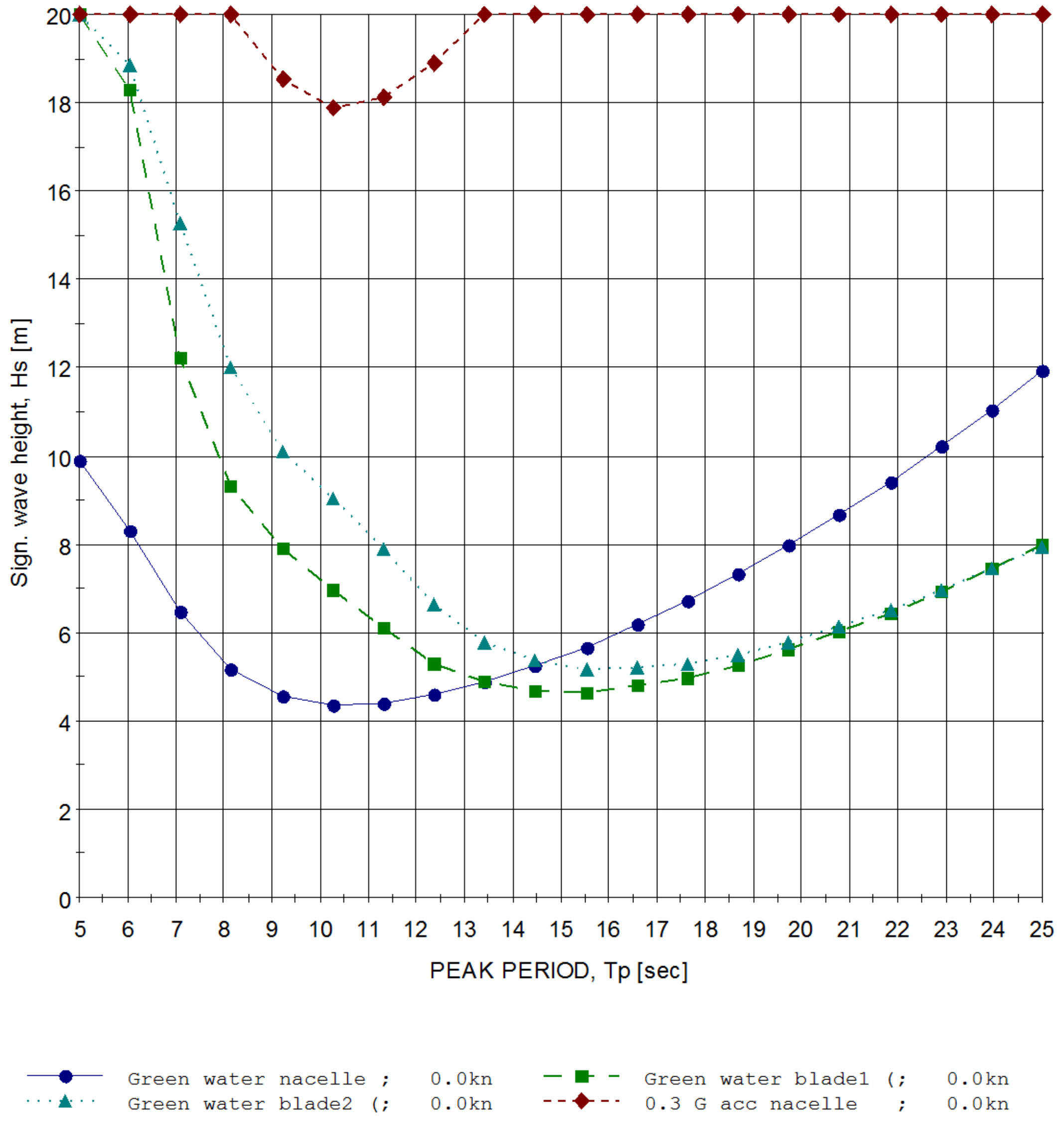


Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas


Copy of Transit, With Payload, - Heading: 150.0°
Sign. wave height, Hs [m]
0
2
4
6
8
10
12
14
16
18
20
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
PEAK PERIOD, Tp [sec]
Green water nacelle ; 0.0kn
Green water blade1 (; 0.0kn
Green water blade2 (; 0.0kn
0.3 G acc nacelle ; 0.0kn
Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas

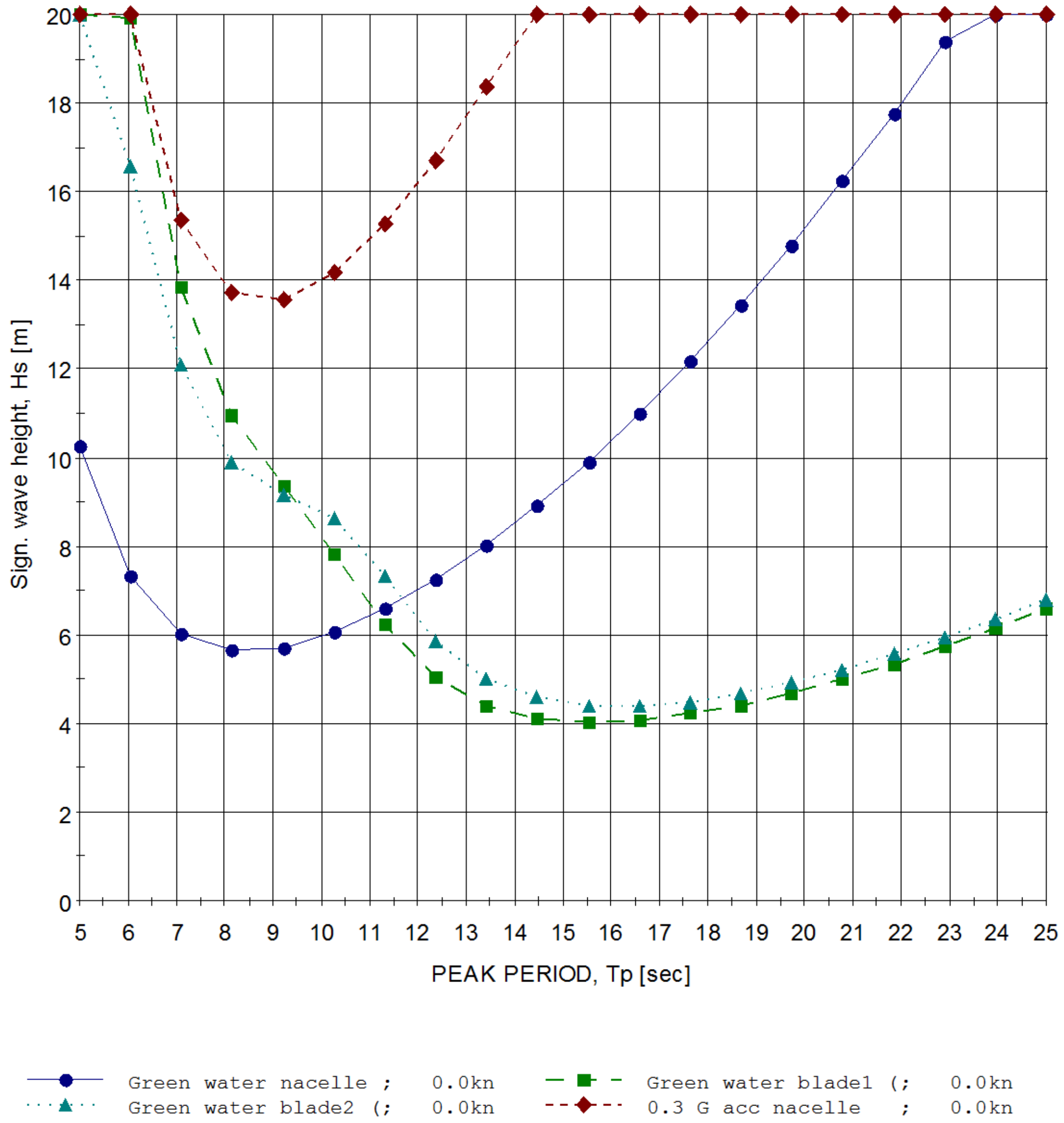

Copy of Transit, With Payload, - Heading: 180.0°
Sign. wave height, Hs [m]
0
2
4
6
8
10
12
14
16
18
20
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
PEAK PERIOD, Tp [sec]
Green water nacelle ; 0.0kn
Green water blade2 (; 0.0kn
Green water blade1 (; 0.0kn
0.3 G acc nacelle ; 0.0kn
Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas

Copy of Transit, With Payload, - Heading: 210.0°

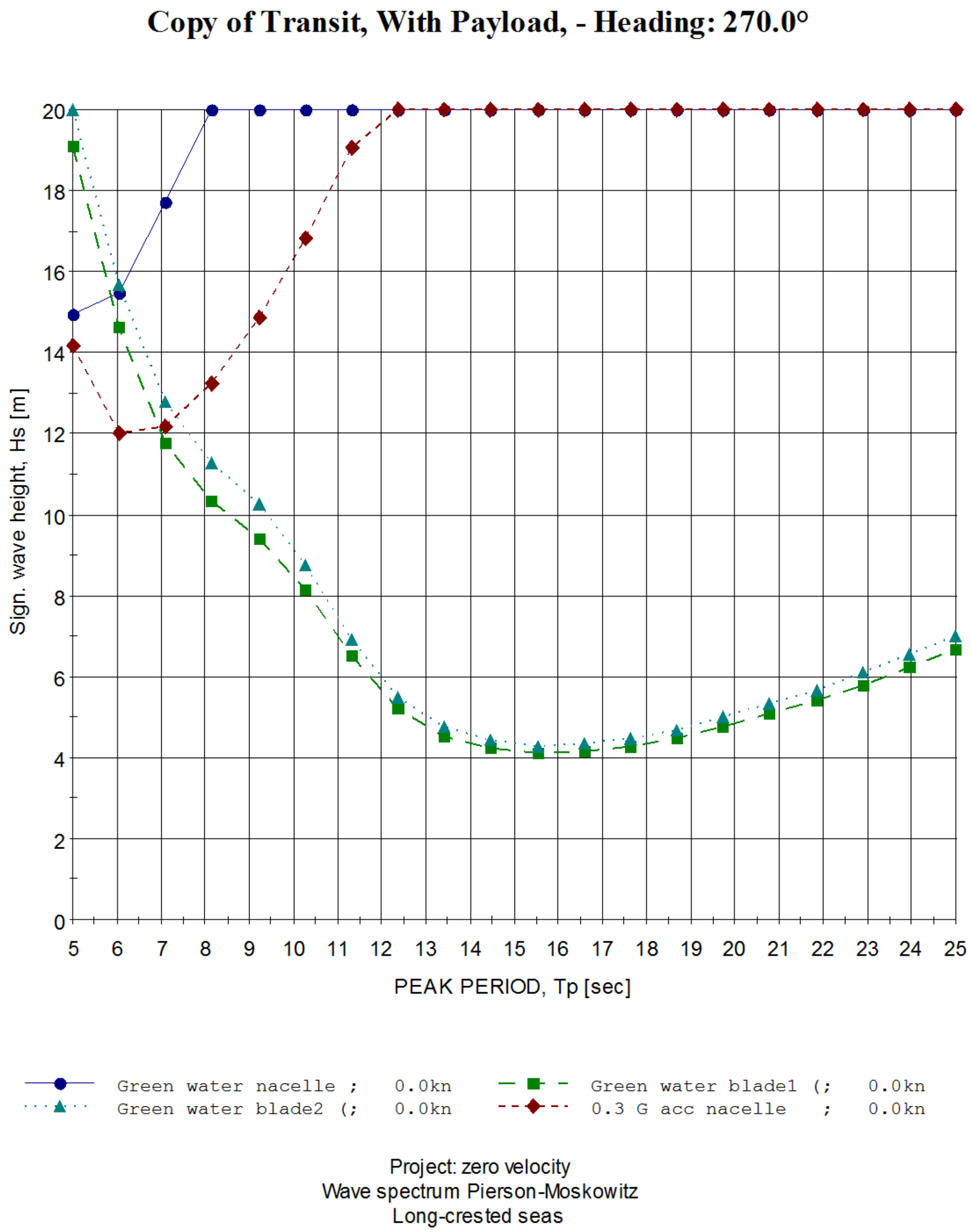


Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas

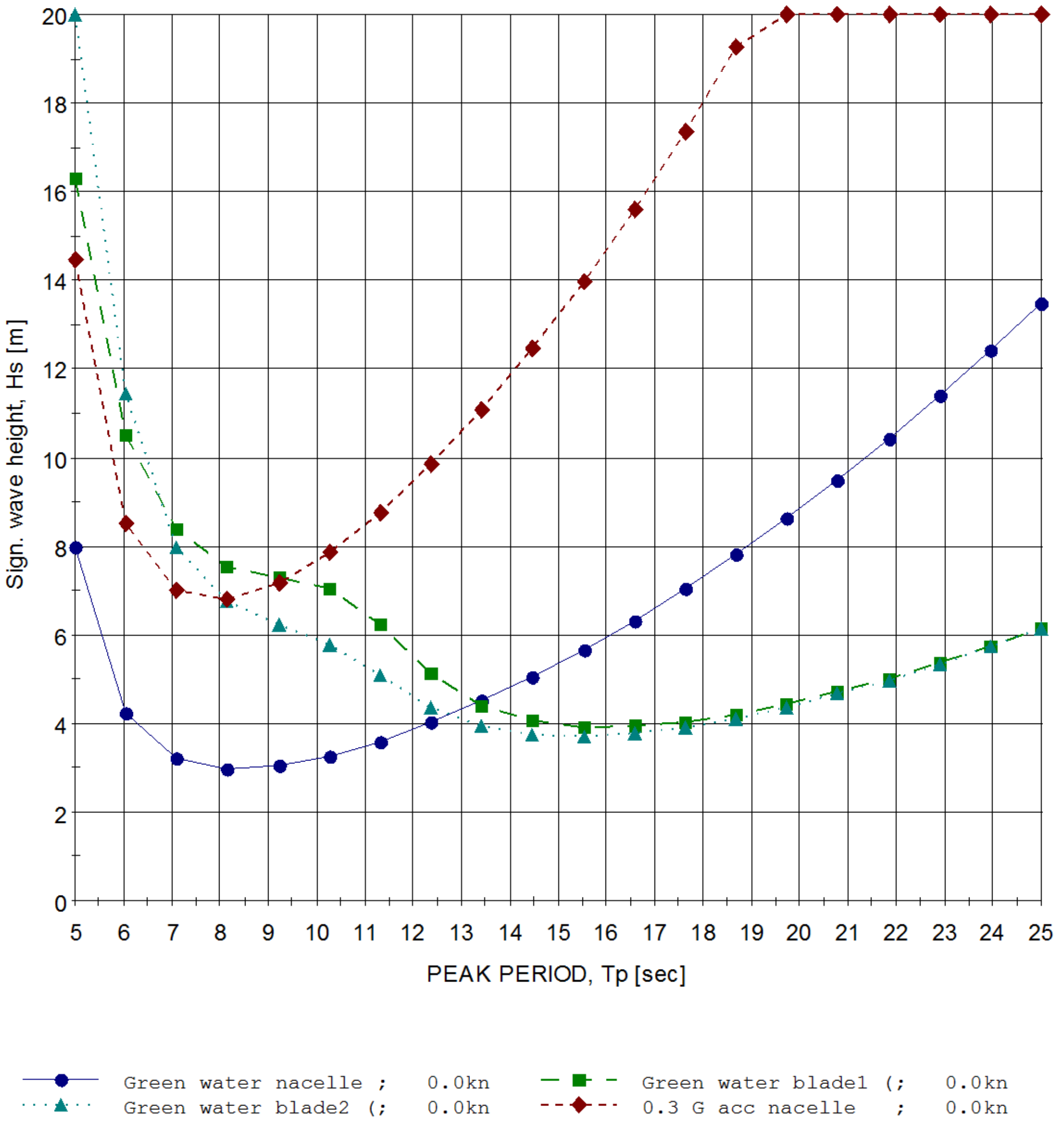
Copy of Transit, With Payload, - Heading: 240.0°



Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas

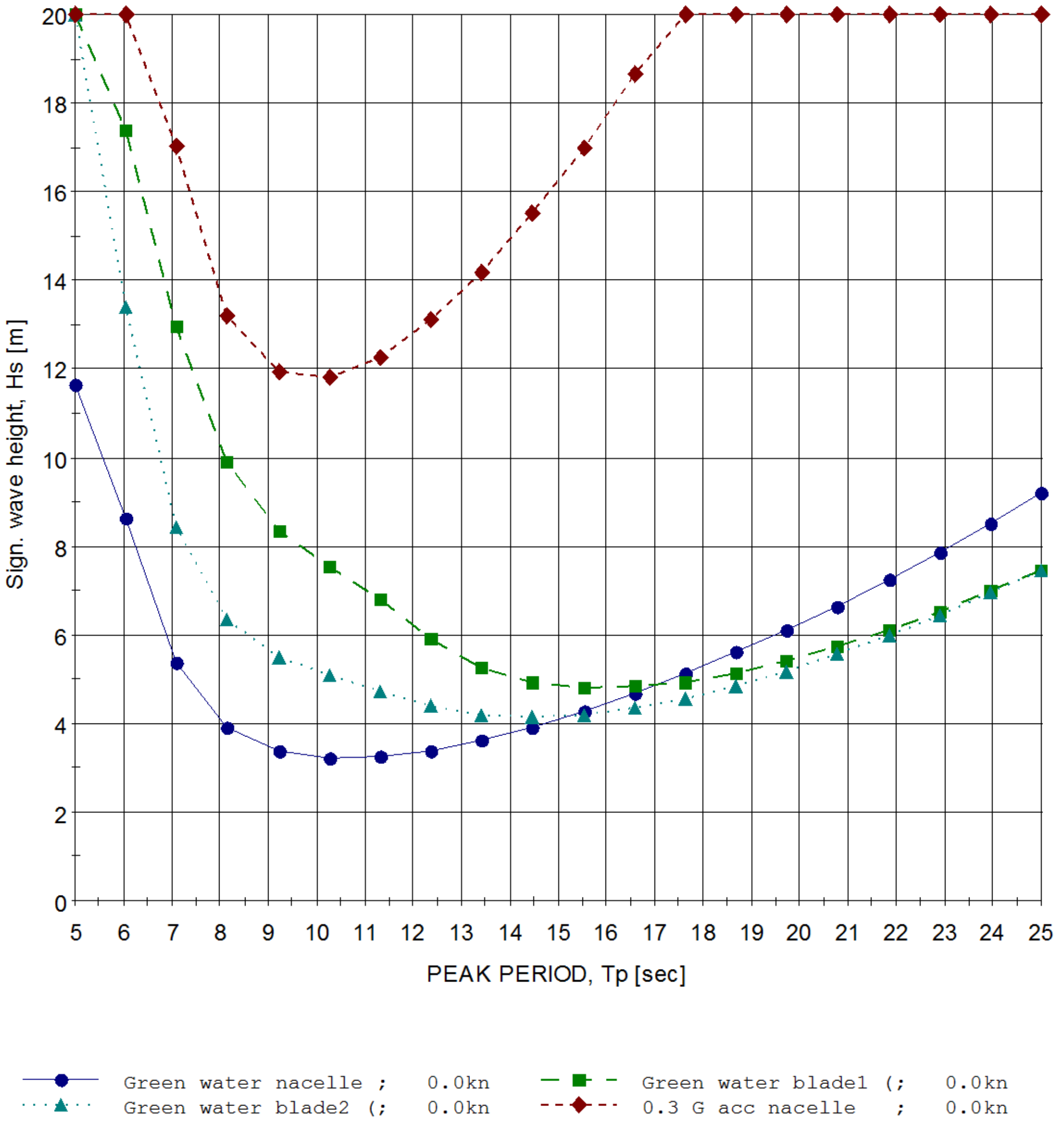

Copy of Transit, With Payload, - Heading: 270.0°
Sign. wave height, Hs [m]
0
2
4
6
8
10
12
14
16
18
20
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
PEAK PERIOD, Tp [sec]
Green water nacelle ; 0.0kn
Green water blade1 (; 0.0kn
Green water blade2 (; 0.0kn
0.3 G acc nacelle ; 0.0kn
Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas

Copy of Transit, With Payload, - Heading: 300.0°



Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas

Copy of Transit, With Payload, - Heading: 330.0°



Project: zero velocity
Wave spectrum Pierson-Moskowitz
Long-crested seas

Appendix F: MatLab scripts

Main program

```
%% Main programme
%  Originally constructed by WindFlip AS in 2009
%  Edited and expanded by Idunn Olimb in 2010
%  Last edited 29. May 2010
%
%  Reads the metocean data for all years, establish seasonal variation
%  and weather windows.

%% Clear all before start
close all
clear
clc

%% Start inputs
%  Years with metocean data from 1982 to 2008: (2000 is missing due to
%  errors in the data)
years=[1982:1:1999 2001:1:2008];

%% Loading the time-series from the metocean data
Hist=loadHist(years);

%  User can choose if the time-series should be plotted (Hs versus time)
disp(['Plots of time-series ?, ' num2str(length(years)) ' plots!'])
plotAns=input('(yes=1, no=0): ');
disp(' ')

%  Smooths the timeseries by making linear sections where there are holes
%  in the data. Plots the time-series if desired.
for i=1:length(years)
    [Hist{i}, Amount99(i)]=smoothHist(Hist{i});
    if plotAns==1
         figure(years(i))
         plot(Hist{i}(:,5), Hist{i}(:,6))
    end
end

%% Makes scatter diagrams. (Annual, monthly)
scat = makeScat(Hist);
for i=1:12
    scat_mnd{i} = makeScat_mnd(Hist,i);
end

%% Finds the variation in the average Hs and Tp per month through the year
%  Plots the results
[season_all season_Hs season_Tp] = Season(Hist);
figure(1)
plot(season_all(1,:))
xlabel('Months')
ylabel('H_s [m]')
title('Plot of average Hs for each month')

figure(2)
plot(season_all(2,:))
xlabel('Months')
ylabel('T_p [s]')
title('Plot of average Tp for each month')
```

```
%% Finding Periods with appropriate conditions, given limiting Hs of 2.5 m
%  Counting variables:
a=0;
b=0;
c=0;
%  Stating the summerseason
mnd1=5; %Summer season starts with May
mnd2=9; %Summer season ends with September

%  divh is the wanted partition of wave height when finding weather
%  windows.
divh=0.1;
%  limiting Hs set to 2.5 m.
limHs=2.5;
%  Row in data to fetch the right weather windows
row=limHs/divh;

%  Finding all weather windows for all Hs values given divh.
for i=1:length(years)
    maxH(i)=max(Hist{i}(:,6));
    [Duration{i} Nperiod{i}]=duration(divh, maxH(i), Hist{i});
    [Duration_summer{i} Nperiod_summer{i}]=duration_season(divh, ...
        maxH(i), Hist{i},mnd1,mnd2);
    [Duration_wint1{i} Nperiod_wint1{i}]=duration_season(divh, ...
        maxH(i), Hist{i},1,(mnd1-1));
    [Duration_wint2{i} Nperiod_wint2{i}]=duration_season(divh, ...
        maxH(i), Hist{i},(mnd2+1),12);

    for j=1:size(Duration{i},2)
        if Duration{i}(row,j)>0
            a=a+1;
            ww(a)=Duration{i}(row,j);
        end
    end
    for j=1:size(Duration_summer{i},2)
        if Duration_summer{i}(row,j)>0
            b=b+1;
            wwsum(b)=Duration_summer{i}(row,j);
        end
    end
    for j=1:size(Duration_wint1{i},2)
        if Duration_wint1{i}(row,j)>0
            c=c+1;
            wwwint(c)=Duration_wint1{i}(row,j);
        end
    end
    for j=1:size(Duration_wint2{i},2)
        if size(Duration_wint2{i},1)>(row-1)
            if Duration_wint2{i}(row,j)>0
                c=c+1;
                wwwint(c)=Duration_wint2{i}(row,j);
            end
        end
    end
end
%  Calculating mean and stdev of the weather windows
mean_ww = [mean(ww) mean(wwsum) mean(wwwint)];
std_ww = [std(ww) std(wwsum) std(wwwint)];
```

```
%% Finding number of weather windows by user defined max Hs and duration
maxHs=1;
quit=0;
while maxHs~=0 && quit==0

    disp(' ')
    disp('Upper limit of Weather Window, in meters and hours (0 ends prg)')

    maxHs=input('Hs [m]: ');
    if maxHs~=0
    windowL=input('T [h]: ');

    for i=1:length(years)

    Nwindow(i)=windows(divh, maxHs, windowL, Duration{i});
    Nwindow_summer(i)=windows(divh, maxHs, windowL, Duration_summer{i});
    Nwindow_wint1(i)=windows(divh, maxHs, windowL, Duration_wint1{i});
    Nwindow_wint2(i)=windows(divh, maxHs, windowL, Duration_wint2{i});
    Nwindow_winter(i)=Nwindow_wint1(i)+Nwindow_wint2(i);

    end

    end

    disp(' ')
    disp(['From ' num2str(length(years)) ...
        ' years of data (# Weather Windows/Year)'])
    disp(['Average # Weather Windows/Year: ' num2str(mean(Nwindow))])
    disp(['With Standard Deviation of: ' num2str(std(Nwindow))])
    disp(Nwindow)
    disp(' ')
    disp(['From ' num2str(length(years)) ...
        ' years of data (# Weather Windows/Summer)'])
    disp(['Average # WW/Summer: ' num2str(mean(Nwindow_summer))])
    disp(['With Standard Deviation of: ' num2str(std(Nwindow_summer))])
    disp(Nwindow_summer)
    disp(' ')
    disp(['From ' num2str(length(years)) ...
        ' years of data (# Weather Windows/Winter)'])
    disp(['Average # WW/Winter: ' num2str(mean(Nwindow_winter))])
    disp(['With Standard Deviation of: ' num2str(std(Nwindow_winter))])
    disp(Nwindow_winter)
    disp(' ')

    disp('Are you finished? ')
    quit=input('(yes=1, no=0): ');

end
```

Functions

loadHist

```
function Hist=loadHist(years)
%  Reads the metocean data

month=[31, 31, 28, 31, 30, 31, 30, 31, 31, 30, 31, 30];
sumdays=cumsum(month);
```

```
for i=1:length(years)
    x=0;
    x=load(['44005_' num2str(years(i)) '.php']);

    for j=1:size(x,1)
        hist(j,[1,2,3,4,6,7])=x(j,[1,2,3,4,8,9]);
        hist(j,5)=365*24*(hist(j,1)-hist(1,1))+ ...
            24*(sumdays(hist(j,2))-sumdays(hist(1,2)))+ ...
            24*(hist(j,3)-hist(1,3))+(hist(j,4)-hist(1,4));

    end

    Hist{i}=hist;
    hist=zeros(1,6);

end
```

smoothHist

```
function [hist, Amount99]=smoothHist(hist)
% Makes linear sections where there are holes in the data

no99=0;
Amount99=0;
Lhist=size(hist,1);

for i=1:Lhist
    if i>1
        if hist(i,6)>50 && no99==0
            pre(1)=hist(i-1,6);
            pre(2)=hist(i-1,5);
            no99=no99+1;
        elseif hist(i,6)>50 && no99>0 && i<Lhist
            no99=no99+1;
        elseif no99>0 && 50 > hist(i,6)
            post(1)=hist(i,6);
            post(2)=hist(i,5);
            dH=post(1)-pre(1);
            dT=post(2)-pre(2);
            for j=1:no99
               dt=hist(i-(no99+1)+j,5)-pre(2);
               hist(i-(no99+1)+j,6)=dH/dT*dt+pre(1);
            end
            no99=0;
        elseif no99>0 && hist(i,6)>50 && i==Lhist
            for j=1:no99+1
                hist(i-(no99+1)+j,6)=pre(1);
            end
            no99=0;
        end
    end
    if hist(i,6)>50
        Amount99=Amount99+1;
    end
end
```

makeScat

```
function scat = makeScat(Hist)
% Places all data in a scatter diagram based on Hs and Tp value.

years=size(Hist,2);
scat=zeros(24,14);
c=0;

for i = 1:years
    for j = 1:size(Hist{i},1)
        if Hist{i}(j,6) >30 || Hist{i}(j,7) >30 || Hist{i}(j,7) <=0
            c=c+1;
        else
            hs=Hist{i}(j,6);
            tp=Hist{i}(j,7);
            for k=1:24
                if hs<=k*0.5 && hs>(k-1)*0.5
                    x=k;
                end
            end
            for k=1:14
                if tp<=k*1.5 && tp>(k-1)*1.5
                    y=k;
                end
            end
            if x>24
                x=24;
            end
            if y>20
                y=20;
            end
            scat(x,y) = scat(x,y) + 1;
        end
    end
end
```

makeScat_mnd

```
function scat_mnd = makeScat_mnd(Hist,m)
% Places all data in monthly scatter diagram based on Hs and Tp value.

years=size(Hist,2);
scat_mnd=zeros(24,14);
c=0;

mnd = [0 31 28 31 30 31 30 31 31 30 31 30 31]*24;
mndh = [0 31 0 0 0 0 0 0 0 0 0 0 0]*24;
for i=3:length(mnd)
    mndh(i)=mndh(i-1)+mnd(i);
end

for i = 1:years
    for j = 1:size(Hist{i},1)
        if Hist{i}(j,5)<mndh(m+1) && Hist{i}(j,5)>=mndh(m)
            if Hist{i}(j,6) >30 || Hist{i}(j,7) >30 || Hist{i}(j,7) <=0
                c=c+1;
            else
                hs=Hist{i}(j,6);
```

```
                tp=Hist{i}(j,7);
                for k=1:24
                    if hs<=k*0.5 && hs>(k-1)*0.5
                        x=k;
                    end
                end
                for z=1:14
                    if tp<=z*1.5 && tp>(z-1)*1.5
                        y=z;
                    end
                end
                if x>24
                    x=24;
                end
                if y>14
                    y=14;
                end
                scat_mnd(x,y) = scat_mnd(x,y) + 1;
            end
        end
    end
end
```

Season

```
function [season_all season_Hs season_Tp] = Season(Hist)
% Finds average Hs and Tp for each month.

years=size(Hist,2);
c=0;

mnd = [31 28 31 30 31 30 31 31 30 31 30 31]*24;
mndh = [31 0 0 0 0 0 0 0 0 0 0 0]*24;
for i=2:length(mnd)
    mndh(i)=mndh(i-1)+mnd(i);
end
sumhs=zeros(1,12);
sumtp=zeros(1,12);
count=zeros(1,12);

season_all = zeros(2,12);
season_Hs = zeros(years,12);
season_Tp = zeros(years,12);

for i = 1:years
    for j = 1:size(Hist{i},1)
        if Hist{i}(j,6) > 50 || Hist{i}(j,7) > 50
            c=c+1;
        else
            if Hist{i}(j,5)<=31
                sumhs(1)=sumhs(1)+ Hist{i}(j,6);
                sumtp(1)=sumtp(1)+ Hist{i}(j,7);
                count(1)=count(1)+1;
            end
            for l=2:length(mndh)
                if Hist{i}(j,5)<=mndh(l) && Hist{i}(j,5)>mndh(l-1)
                    sumhs(l)=sumhs(l)+ Hist{i}(j,6);
                    sumtp(l)=sumtp(l)+ Hist{i}(j,7);
                    count(l)=count(l)+1;
```

```
                end
            end
        end
    end

    for k = 1:length(sumhs)
        season_Hs(i,k)=sumhs(k)/count(k);
        season_Tp(i,k)=sumtp(k)/count(k);
    end
end

for i=1:length(season_all)
    season_all(1,i)=mean(season_Hs(:,i));
    season_all(2,i)=mean(season_Tp(:,i));
end
```

duration

```
function [Duration Nperiod]=duration(divh, maxH, hist)
% Finding number of calm periods for different limits and duration
% of those periods.

Nperiod(ceil(maxH/divh))=0;
on(ceil(maxH/divh))=0;

for j=1:ceil(maxH/divh);%going through different parameters for Hs cutoffs
    a=divh*j;
    for i=1:size(hist,1)
        %Running through all the different entries in the data

        %Start Counting Calm Period
        if i<size(hist,1)
        if (i==1 && a>=hist(i,6) && a>=hist(i+1,6))
            %If first value is limit, start counting calm period
            time(1,j)=hist(i,5);
            on(j)=1;
        elseif i>1 && a>=hist(i,6) && a>=hist(i+1,6) && hist(i-1,6)>a
            %If Hs falls past limit
            time(1,j)=hist(i,5);
            on(j)=1;
        elseif i>1 && a>=hist(i,6) && a>=hist(i+1,6) && ...
                (hist(i,5)-hist(i-1,5))>24
            %If Hs is under limit after starting up after timegap
            time(1,j)=hist(i,5);
            on(j)=1;
        end
        end

        %Stop Counting And Save data
        if i>1 && i~=size(hist,1)
            if hist(i,6)>a && a>=hist(i-1,6) && on(j)==1
                % If Hs rises past limit and time is counted(on==1)
                Nperiod(j)=Nperiod(j)+1;
                time(2,j)=hist(i,5);
                Duration(j,Nperiod(j))=time(2,j)-time(1,j);
                on(j)=0;
            elseif a>=hist(i-1,6) && on(j)==1 && hist(i+1,5)-hist(i,5)>24
                %If last value before a TimeGap is under limit and time
                %was counted
```

```
                Nperiod(j)=Nperiod(j)+1;
                time(2,j)=hist(i,5);
                Duration(j,Nperiod(j))=time(2,j)-time(1,j);
                on(j)=0;
            end
        elseif a>=hist(i,6) && on(j)==1 && i==size(hist,1)
            %Last value in data is under limit and time is counting
            Nperiod(j)=Nperiod(j)+1;
            time(2,j)=hist(i,5);
            Duration(j,Nperiod(j))=time(2,j)-time(1,j);
            on(j)=0;
        end
    end
end
```

duration_season

```
function [Duration Nperiod]=duration_season(divh, maxH, hist,m1,m2)
% Finding number of calm periods for different limits and duration
% of those periods. Seasonal, with given start and end month.

mnd = [31 28 31 30 31 30 31 31 30 31 30 31]*24;
mndh = [31 0 0 0 0 0 0 0 0 0 0 0]*24;
for i=2:length(mnd)
    mndh(i)=mndh(i-1)+mnd(i);
end

Duration(ceil(maxH/divh))=0;
Nperiod(ceil(maxH/divh))=0;
on(ceil(maxH/divh))=0;

for j=1:ceil(maxH/divh);%going through different parameters for Hs cutoffs
    a=divh*j;
    for i=1:size(hist,1)
        %Start Counting Calm Period
        if hist(i,5)<=mndh(m2) && hist(i,5)>(mndh(m1)-mnd(m1))
            if i<mndh(m2) && i<size(hist,1)
                if (i==(mndh(m1)-mnd(m1)+1) && a>=hist(i,6) && ...
                        a>=hist(i+1,6))
                    %If first value is limit, start counting calm period
                    time(1,j)=hist(i,5);
                    on(j)=1;
                elseif i>(mndh(m1)-mnd(m1)+1) && a>=hist(i,6) && ...
                        a>=hist(i+1,6) && hist(i-1,6)>a
                    %If Hs falls past limit
                    time(1,j)=hist(i,5);
                    on(j)=1;
                elseif i>(mndh(m1)-mnd(m1)+1) && a>=hist(i,6) && ...
                        a>=hist(i+1,6) && (hist(i,5)-hist(i-1,5))>24
                    %If Hs is under limit after starting up after timegap
                    time(1,j)=hist(i,5);
                    on(j)=1;
                end
            end
            %Stop Counting And Save data
            if i>(mndh(m1)-mnd(m1)+1) && i~=mndh(m2) && i~=size(hist,1)
            if hist(i,6)>a && a>=hist(i-1,6) && on(j)==1
                % If Hs rises past limit and time is counted(on==1)
                Nperiod(j)=Nperiod(j)+1;
```

```
                time(2,j)=hist(i,5);
                Duration(j,Nperiod(j))=time(2,j)-time(1,j);
                on(j)=0;
            elseif a>=hist(i-1,6) && on(j)==1 && hist(i+1,5)-hist(i,5)>24
                %If last value before a TimeGap is under limit and time
                %was counted
                Nperiod(j)=Nperiod(j)+1;
                time(2,j)=hist(i,5);
                Duration(j,Nperiod(j))=time(2,j)-time(1,j);
                on(j)=0;
            end
            elseif a>=hist(i,6) && on(j)==1 && i==mndh(m2)
                %Last value in data is under limit and time is counting
                Nperiod(j)=Nperiod(j)+1;
                time(2,j)=hist(i,5);
                Duration(j,Nperiod(j))=time(2,j)-time(1,j);
                on(j)=0;
            end
        end
    end
end
```

windows

```
function Nwindow=windows(divh, maxHs, windowL, Duration)
% Finding what data that is needed

row=floor(maxHs/divh);
Nwindow=0;

if row<1
    disp(['failure, maxHs to small, ' num2str(divh) ' <= maxHs']);
    Nwindow=0;
elseif size(Duration,1)>24
    Nwindow=periods(windowL, Duration(row, :));
end
```

periods

```
function Nwindow=periods(windowL, Duration)
% Collecting Data For Each Year for periods of different length for
% different Hs limits

maxDur=max(Duration);
Ndur=floor(maxDur/windowL);
Nwindow=0;

for i=1:size(Duration,2)
    for j=1:Ndur
        a=windowL*j;
        b=windowL*(j+1);
        if a <= Duration(i) && Duration(i) < b
            Nwindow=Nwindow+j;
        end
    end
end
```

Additional scripts for verification of data

verification

```
%% Verification programme
%  Made by Idunn Olimb in 2010
%  Last edited 1st June 2010


%% Clear all before start
close all
clear
clc

%% Start inputs
%  Years with continous metocean data
years=1987; % or 1985
%% Loading the time-series from the metocean data
Hist=loadHist(years);

for i=1:length(years)

%  Smooths the timeseries by making linear sections where there are holes
%  in the data. Plots the time-series if desired.
    [Hist{i}, Amount99(i)]=smoothHist(Hist{i});
    [Hist{i}, Amount99Tp(i)]=smoothHistTp(Hist{i});

% Plots the Hs and Tp data for the relevant year
    figure(years(i))
    plot(Hist{i}(:,5), Hist{i}(:,6))
    figure(2)
    plot(Hist{i}(:,5), Hist{i}(:,7))

% Define the period of interest during the chosen year
    periodCheck=3000:1:5000;
% Calculates average Hs and Tp during the chosen period
    avHs1=mean(Hist{i}(periodCheck,6));
    avTp1=mean(Hist{i}(periodCheck,7));

% Plots the data and the mean, for both Hs and Tp, for the period
    figure(3)
    plot(Hist{i}(periodCheck,5), Hist{i}(periodCheck,6))
    hold on
    plot(Hist{i}(periodCheck,5),avHs1)

    figure(4)
    plot(Hist{i}(periodCheck,5), Hist{i}(periodCheck,7))
    hold on
    plot(Hist{i}(periodCheck,5),avTp1)

% Finds the mean upcrossing period for both Hs and Tp in the period
    s=0;
    t=0;
    for j=1001:1:2000
        if Hist{i}(j-1,6)<=avHs1 && Hist{i}(j,6)>avHs1
            s=s+1;
            MeancrossHs(s)=Hist{i}(j-1,5);
        end
        if Hist{i}(j-1,7)<=avTp1 && Hist{i}(j,7)>avTp1
```

```
            t=t+1;
            MeancrossTp(t)=Hist{i}(j-1,5);
        end
    end
    TzHs=(MeancrossHs(length(MeancrossHs))-MeancrossHs(1)) ...
        /(length(MeancrossHs)-1);
    TzTp=(MeancrossTp(length(MeancrossTp))-MeancrossTp(1)) ...
        /(length(MeancrossTp)-1);
end
```

smoothHistTp

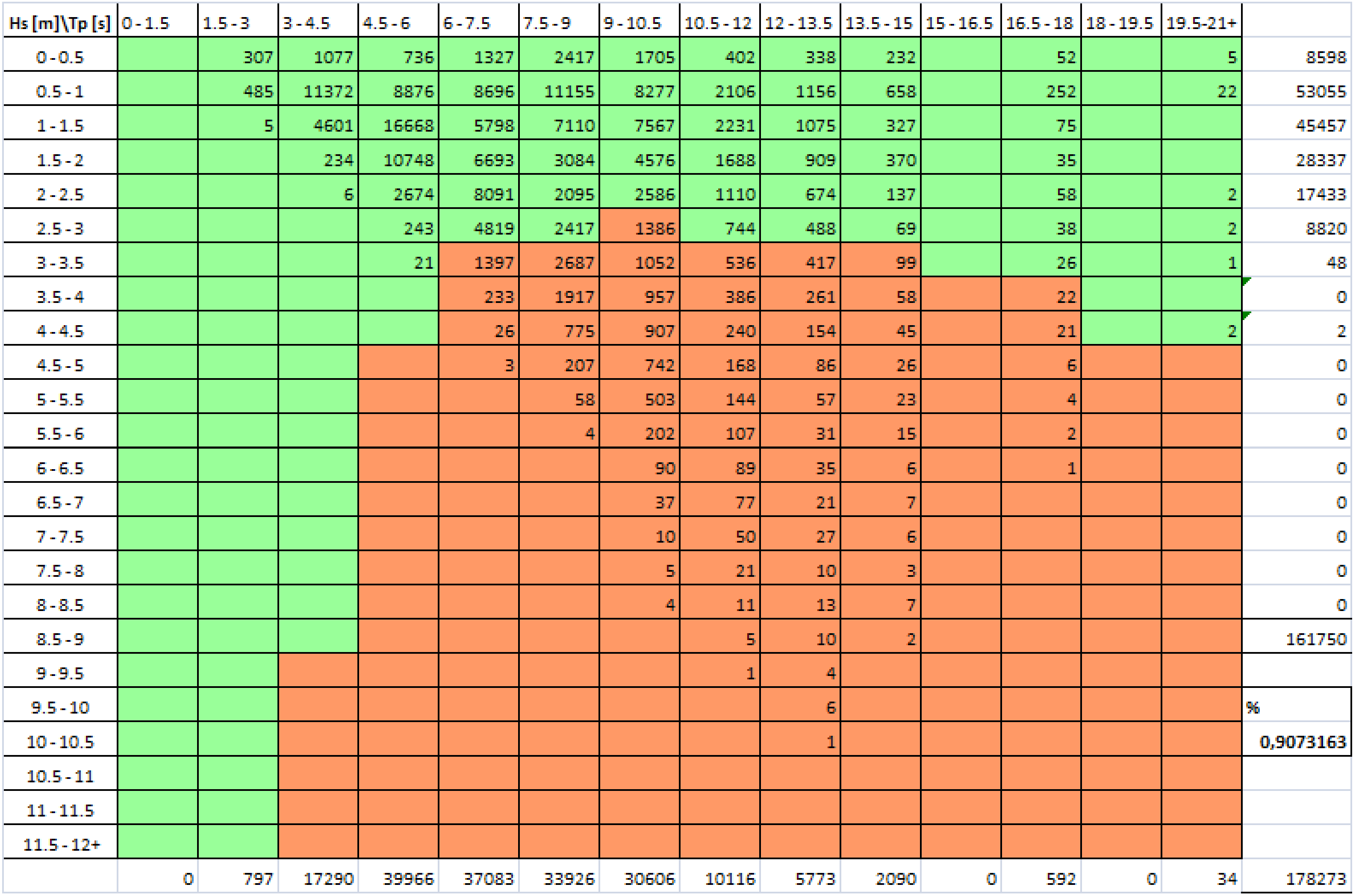
```
function [hist, Amount99]=smoothHistTp(hist)
% Makes linear sections where there are holes in the data

no99=0;
Amount99=0;
Lhist=size(hist,1);

for i=1:Lhist
    if i>1
        if hist(i,7)>50 && no99==0
            pre(1)=hist(i-1,7);
            pre(2)=hist(i-1,5);
            no99=no99+1;
        elseif hist(i,7)>50 && no99>0 && i<Lhist
            no99=no99+1;
        elseif no99>0 && 50 > hist(i,7)
            post(1)=hist(i,7);
            post(2)=hist(i,5);
            dH=post(1)-pre(1);
            dT=post(2)-pre(2);
            for j=1:no99
               dt=hist(i-(no99+1)+j,5)-pre(2);
               hist(i-(no99+1)+j,7)=dH/dT*dt+pre(1);
            end
            no99=0;
        elseif no99>0 && hist(i,7)>50 && i==Lhist
            for j=1:no99+1
                hist(i-(no99+1)+j,7)=pre(1);
            end
            no99=0;
        end
    end
    if hist(i,7)>50
        Amount99=Amount99+1;
    end
end
```

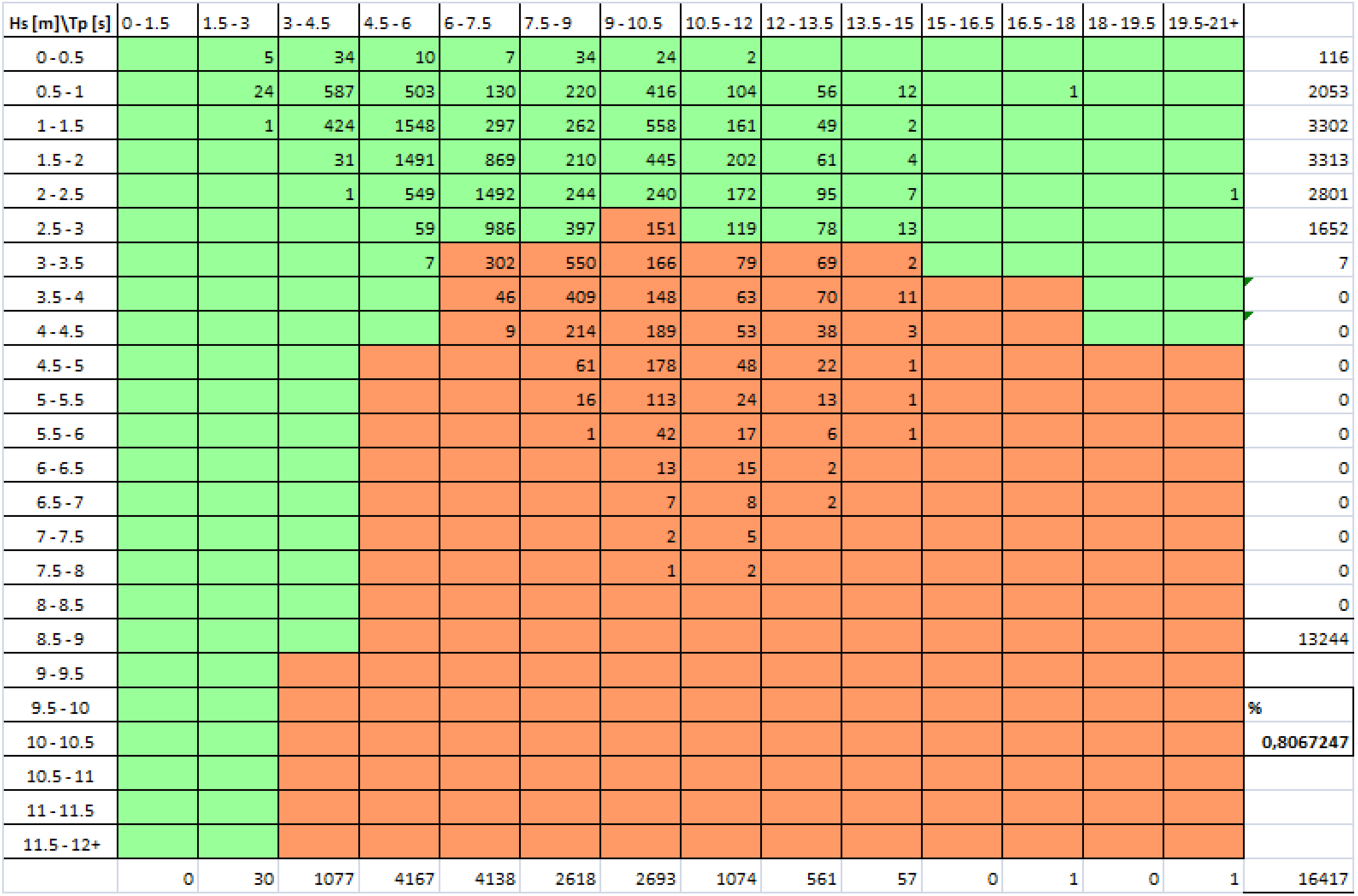
Appendix G: Scatter diagrams

Annual



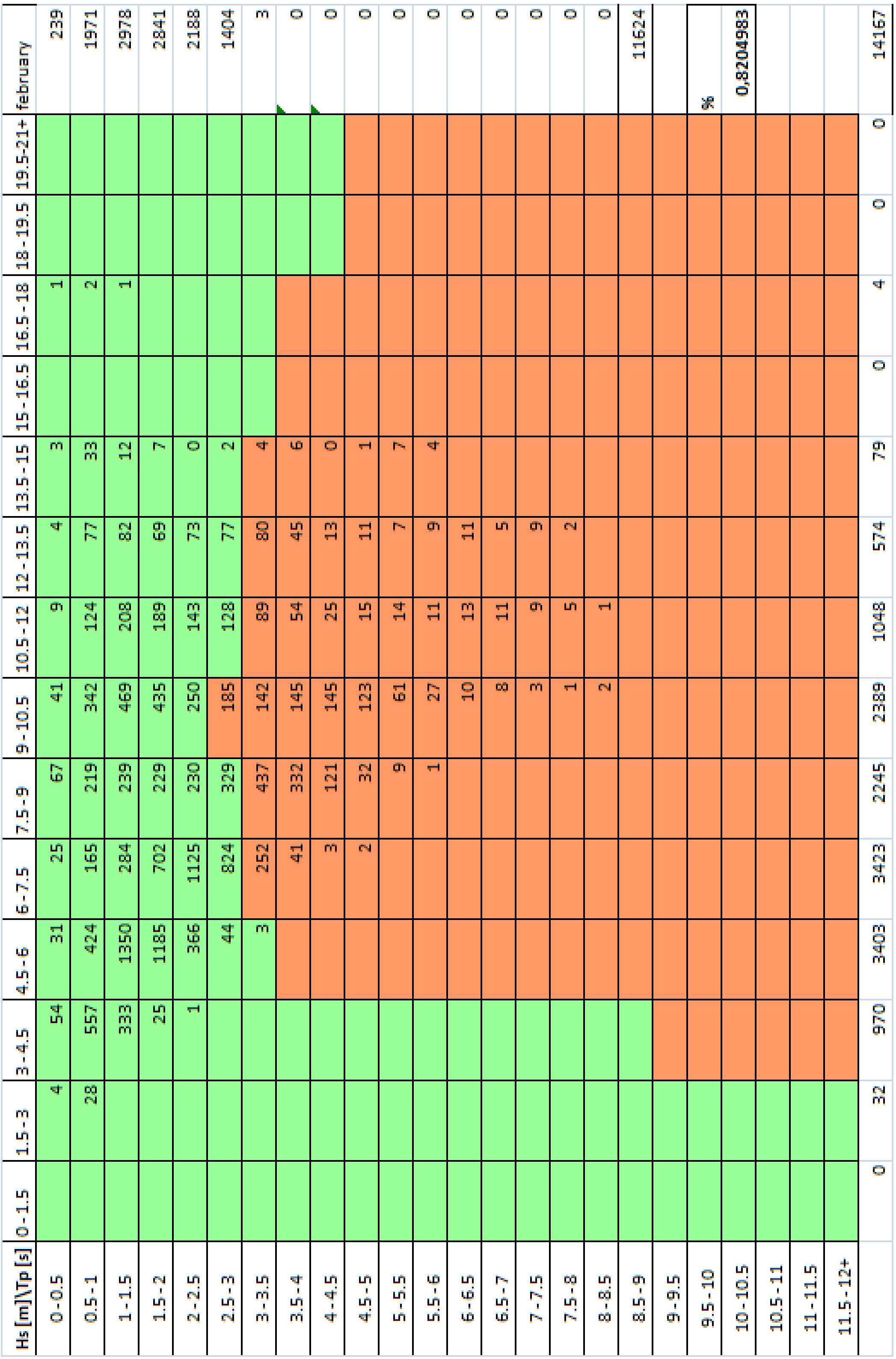
Hs [m]\Tp [s]	0 - 1.5	1.5 - 3	3 - 4.5	4.5 - 6	6 - 7.5	7.5 - 9	9 - 10.5	10.5 - 12	12 - 13.5	13.5 - 15	15 - 16.5	16.5 - 18	18 - 19.5	19.5-21+	
0 - 0.5		307	1077	736	1327	2417	1705	402	338	232		52		5	8598
0.5 - 1		485	11372	8876	8696	11155	8277	2106	1156	658		252		22	53055
1 - 1.5		5	4601	16668	5798	7110	7567	2231	1075	327		75			45457
1.5 - 2			234	10748	6693	3084	4576	1688	909	370		35			28337
2 - 2.5			6	2674	8091	2095	2586	1110	674	137		58		2	17433
2.5 - 3				243	4819	2417	1386	744	488	69		38		2	8820
3 - 3.5				21	1397	2687	1052	536	417	99		26		1	48
3.5 - 4					233	1917	957	386	261	58		22			0
4 - 4.5					26	775	907	240	154	45		21		2	2
4.5 - 5					3	207	742	168	86	26		6			0
5 - 5.5						58	503	144	57	23		4			0
5.5 - 6						4	202	107	31	15		2			0
6 - 6.5							90	89	35	6		1			0
6.5 - 7							37	77	21	7					0
7 - 7.5							10	50	27	6					0
7.5 - 8							5	21	10	3					0
8 - 8.5							4	11	13	7					0
8.5 - 9								5	10	2					161750
9 - 9.5								1	4						
9.5 - 10									6						%
10 - 10.5									1						0,9073163
10.5 - 11															
11 - 11.5															
11.5 - 12+															
	0	797	17290	39966	37083	33926	30606	10116	5773	2090	0	592	0	34	178273

January



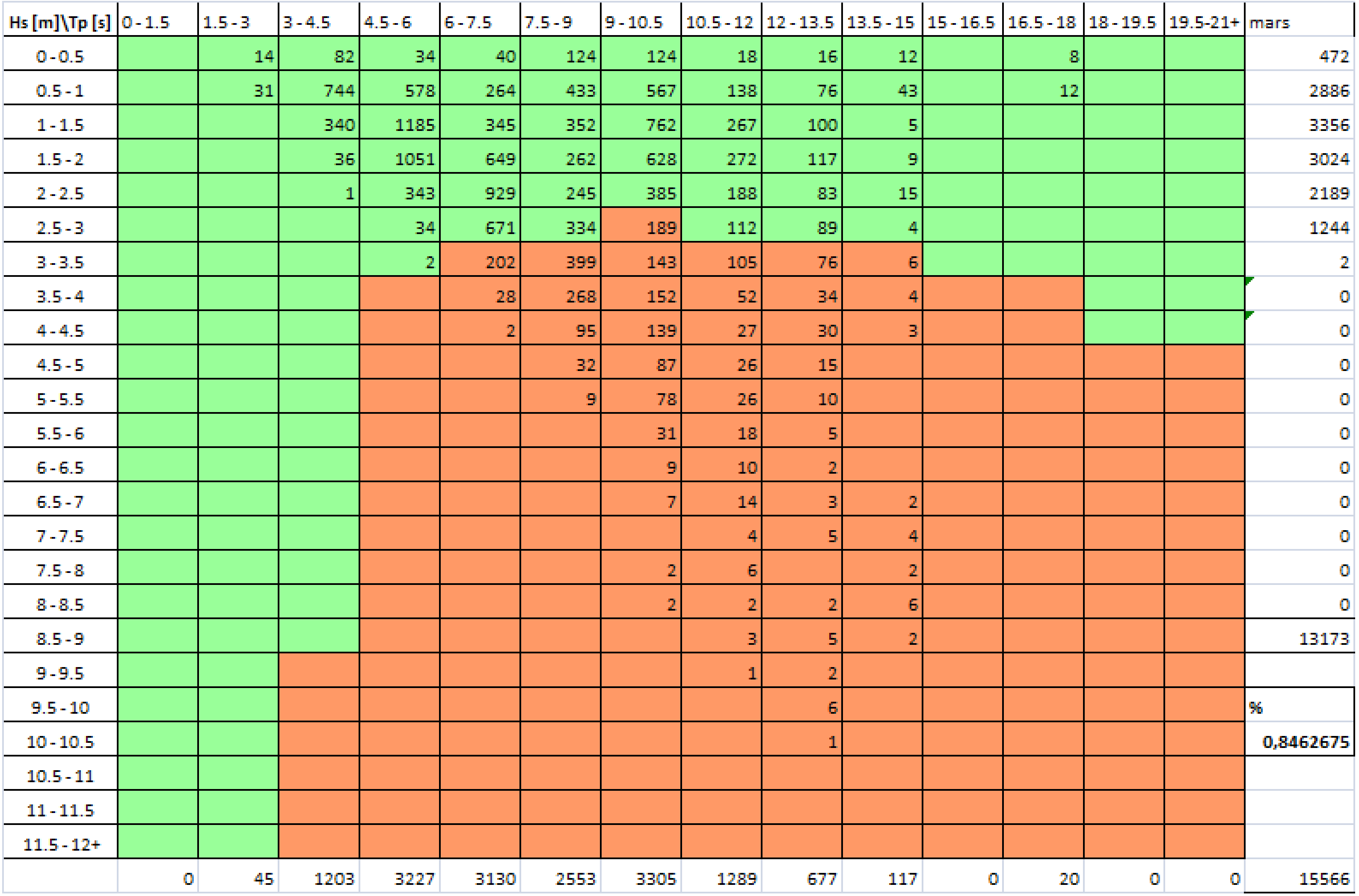
Hs [m]\Tp [s]	0 - 1.5	1.5 - 3	3 - 4.5	4.5 - 6	6 - 7.5	7.5 - 9	9 - 10.5	10.5 - 12	12 - 13.5	13.5 - 15	15 - 16.5	16.5 - 18	18 - 19.5	19.5-21+	
0 - 0.5		5	34	10	7	34	24	2							116
0.5 - 1		24	587	503	130	220	416	104	56	12		1			2053
1 - 1.5		1	424	1548	297	262	558	161	49	2					3302
1.5 - 2			31	1491	869	210	445	202	61	4					3313
2 - 2.5			1	549	1492	244	240	172	95	7				1	2801
2.5 - 3				59	986	397	151	119	78	13					1652
3 - 3.5				7	302	550	166	79	69	2					7
3.5 - 4					46	409	148	63	70	11					0
4 - 4.5					9	214	189	53	38	3					0
4.5 - 5						61	178	48	22	1					0
5 - 5.5						16	113	24	13	1					0
5.5 - 6						1	42	17	6	1					0
6 - 6.5							13	15	2						0
6.5 - 7							7	8	2						0
7 - 7.5							2	5							0
7.5 - 8							1	2							0
8 - 8.5															0
8.5 - 9															13244
9 - 9.5															
9.5 - 10															%
10 - 10.5															**0,8067247**
10.5 - 11															
11 - 11.5															
11.5 - 12+															
	0	30	1077	4167	4138	2618	2693	1074	561	57	0	1	0	1	16417

February



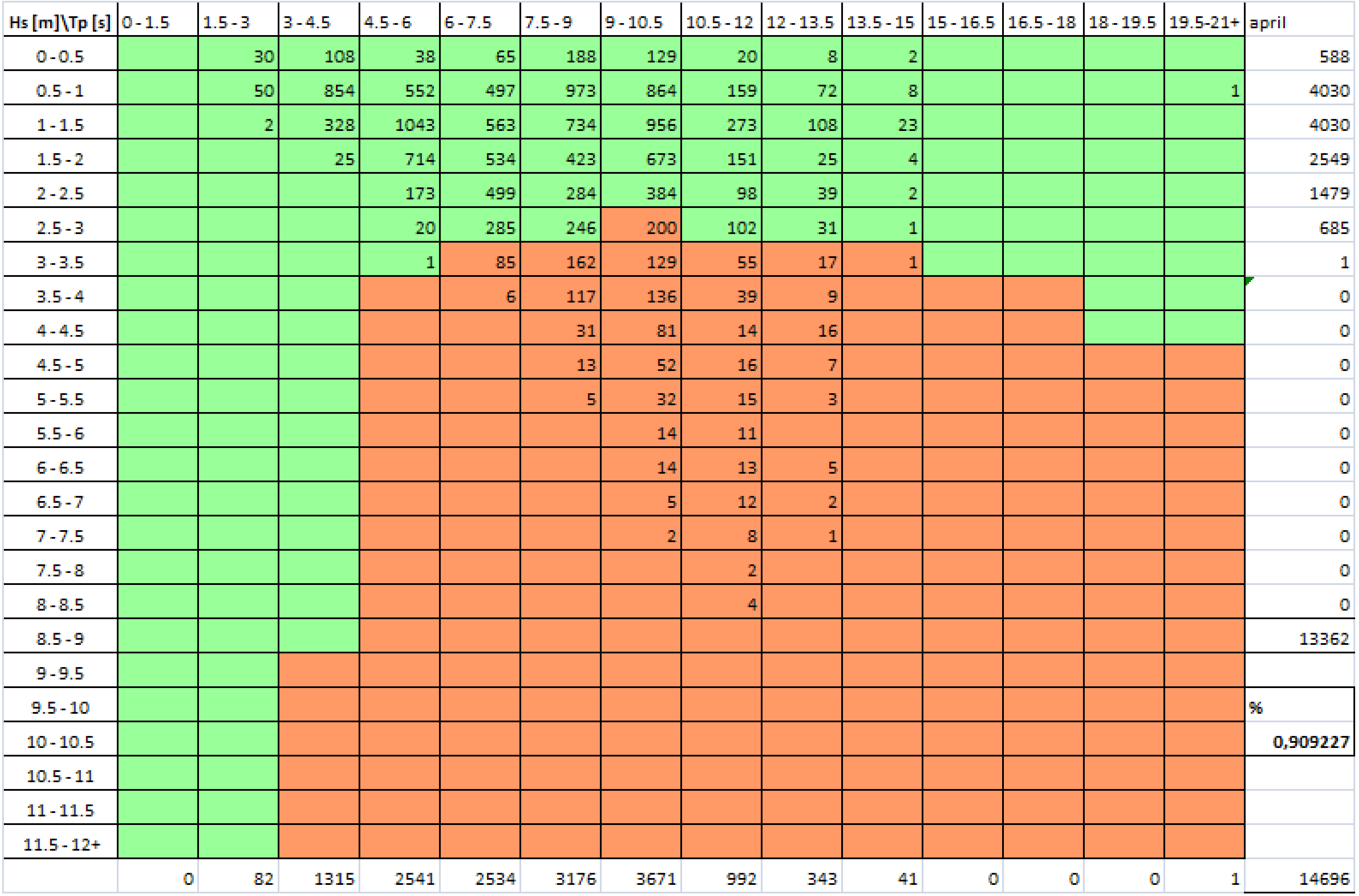
Hs [m]\Tp [s]	0 - 1.5	1.5 - 3	3 - 4.5	4.5 - 6	6 - 7.5	7.5 - 9	9 - 10.5	10.5 - 12	12 - 13.5	13.5 - 15	15 - 16.5	16.5 - 18	18 - 19.5	19.5 - 21+	february
0 - 0.5		4	54	31	25	67	41	9	4	3		1			239
0.5 - 1		28	557	424	165	219	342	124	77	33		2			1971
1 - 1.5			333	1350	284	239	469	208	82	12		1			2978
1.5 - 2			25	1185	702	229	435	189	69	7					2841
2 - 2.5			1	366	1125	230	250	143	73	0					2188
2.5 - 3				44	824	329	185	128	77	2					1404
3 - 3.5				3	252	437	142	89	80	4					3
3.5 - 4					41	332	145	54	45	6					0
4 - 4.5					3	121	145	25	13	0					0
4.5 - 5					2	32	123	15	11	1					0
5 - 5.5						9	61	14	7	7					0
5.5 - 6						1	27	11	9	4					0
6 - 6.5							10	13	11						0
6.5 - 7							8	11	5						0
7 - 7.5							3	9	9						0
7.5 - 8							1	5	2						0
8 - 8.5							2	1							0
8.5 - 9															11624
9 - 9.5															
9.5 - 10															%
10 - 10.5															0,8204983
10.5 - 11															
11 - 11.5															
11.5 - 12+															
	0	32	970	3403	3423	2245	2389	1048	574	79	0	4	0	0	14167

Mars



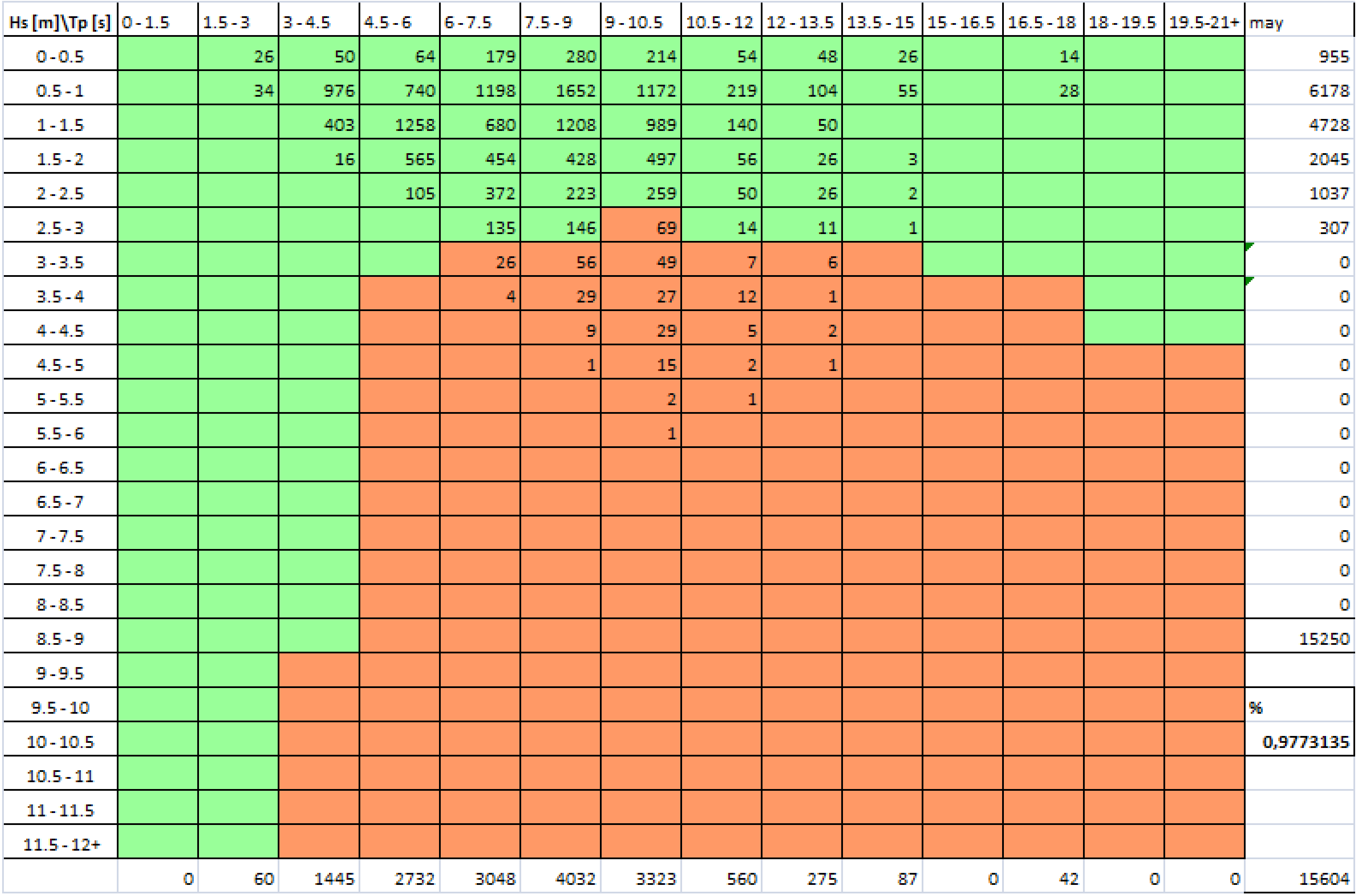
Hs [m]\Tp [s]	0 - 1.5	1.5 - 3	3 - 4.5	4.5 - 6	6 - 7.5	7.5 - 9	9 - 10.5	10.5 - 12	12 - 13.5	13.5 - 15	15 - 16.5	16.5 - 18	18 - 19.5	19.5-21+	mars
0 - 0.5		14	82	34	40	124	124	18	16	12		8			472
0.5 - 1		31	744	578	264	433	567	138	76	43		12			2886
1 - 1.5			340	1185	345	352	762	267	100	5					3356
1.5 - 2			36	1051	649	262	628	272	117	9					3024
2 - 2.5			1	343	929	245	385	188	83	15					2189
2.5 - 3				34	671	334	189	112	89	4					1244
3 - 3.5				2	202	399	143	105	76	6					2
3.5 - 4					28	268	152	52	34	4					0
4 - 4.5					2	95	139	27	30	3					0
4.5 - 5						32	87	26	15						0
5 - 5.5						9	78	26	10						0
5.5 - 6							31	18	5						0
6 - 6.5							9	10	2						0
6.5 - 7							7	14	3	2					0
7 - 7.5								4	5	4					0
7.5 - 8							2	6		2					0
8 - 8.5							2	2	2	6					0
8.5 - 9								3	5	2					13173
9 - 9.5								1	2						
9.5 - 10									6						%
10 - 10.5									1						0,8462675
10.5 - 11															
11 - 11.5															
11.5 - 12+															
	0	45	1203	3227	3130	2553	3305	1289	677	117	0	20	0	0	15566

April



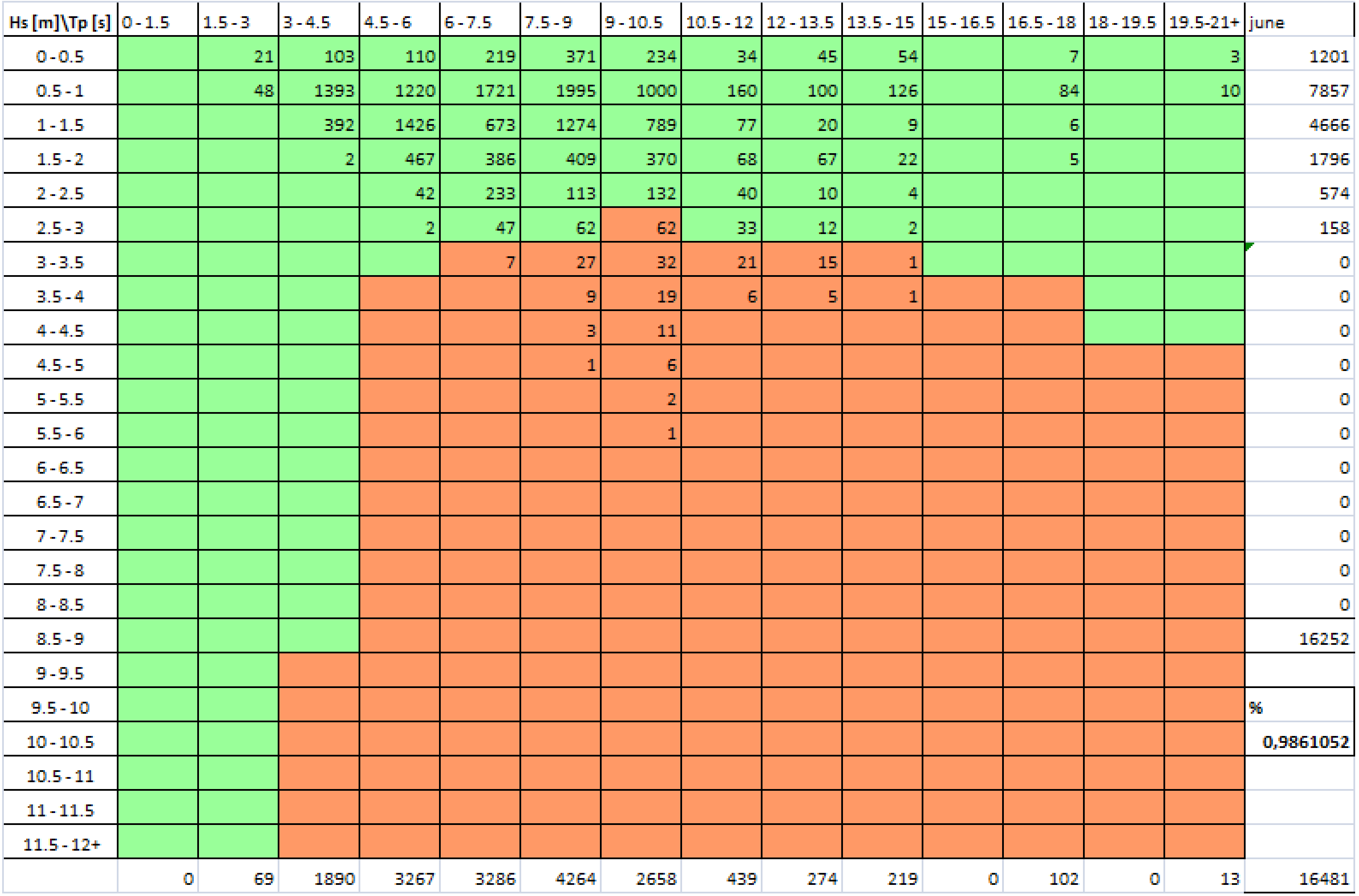
Hs [m]\Tp [s]	0 - 1.5	1.5 - 3	3 - 4.5	4.5 - 6	6 - 7.5	7.5 - 9	9 - 10.5	10.5 - 12	12 - 13.5	13.5 - 15	15 - 16.5	16.5 - 18	18 - 19.5	19.5-21+	april
0 - 0.5		30	108	38	65	188	129	20	8	2					588
0.5 - 1		50	854	552	497	973	864	159	72	8				1	4030
1 - 1.5		2	328	1043	563	734	956	273	108	23					4030
1.5 - 2			25	714	534	423	673	151	25	4					2549
2 - 2.5				173	499	284	384	98	39	2					1479
2.5 - 3				20	285	246	200	102	31	1					685
3 - 3.5				1	85	162	129	55	17	1					1
3.5 - 4					6	117	136	39	9						0
4 - 4.5						31	81	14	16						0
4.5 - 5						13	52	16	7						0
5 - 5.5						5	32	15	3						0
5.5 - 6							14	11							0
6 - 6.5							14	13	5						0
6.5 - 7							5	12	2						0
7 - 7.5							2	8	1						0
7.5 - 8								2							0
8 - 8.5								4							0
8.5 - 9															13362
9 - 9.5															
9.5 - 10															%
10 - 10.5															0,909227
10.5 - 11															
11 - 11.5															
11.5 - 12+															
	0	82	1315	2541	2534	3176	3671	992	343	41	0	0	0	1	14696

May



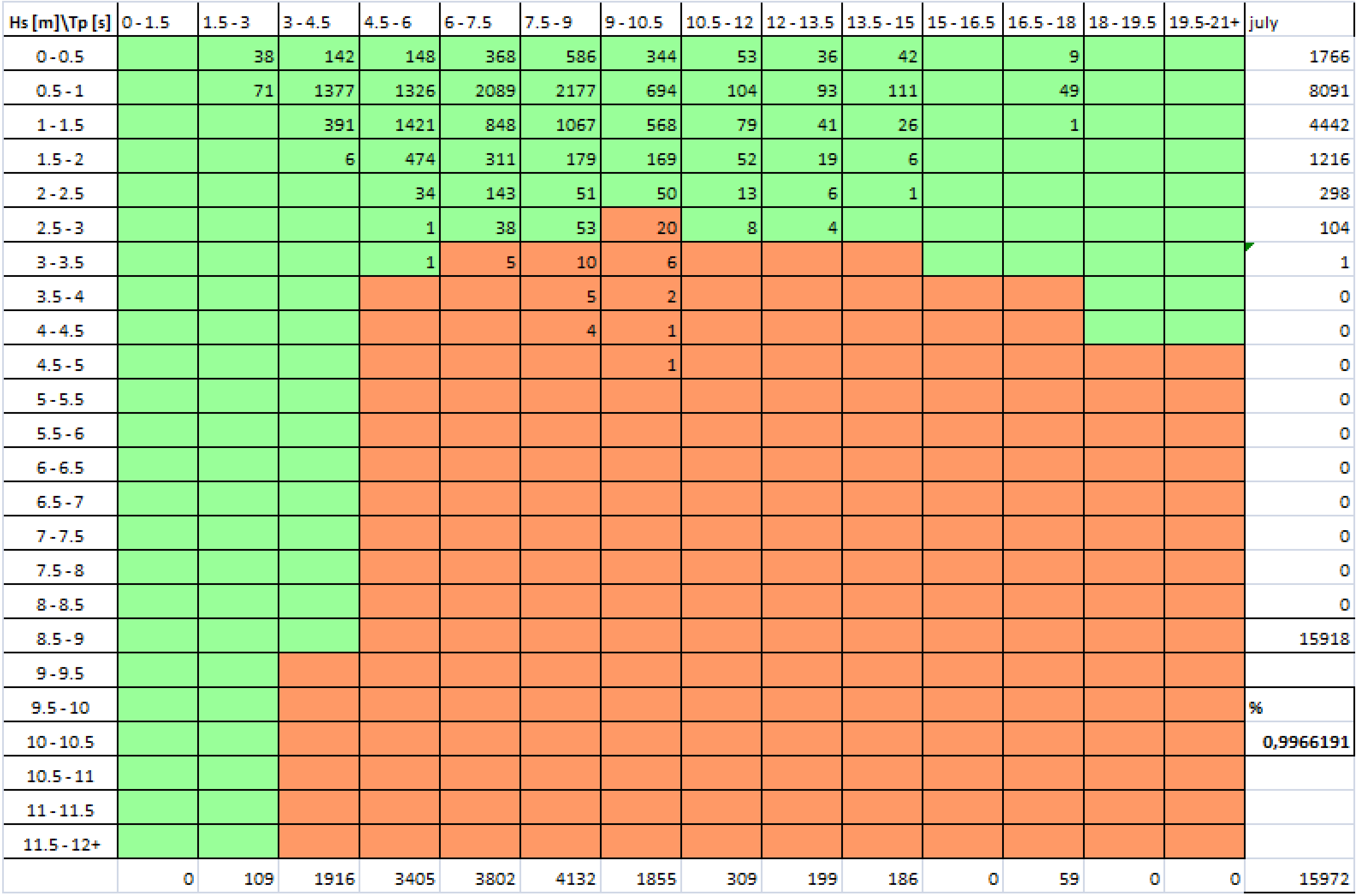
Hs [m]\Tp [s]	0 - 1.5	1.5 - 3	3 - 4.5	4.5 - 6	6 - 7.5	7.5 - 9	9 - 10.5	10.5 - 12	12 - 13.5	13.5 - 15	15 - 16.5	16.5 - 18	18 - 19.5	19.5-21+	may
0 - 0.5		26	50	64	179	280	214	54	48	26		14			955
0.5 - 1		34	976	740	1198	1652	1172	219	104	55		28			6178
1 - 1.5			403	1258	680	1208	989	140	50						4728
1.5 - 2			16	565	454	428	497	56	26	3					2045
2 - 2.5				105	372	223	259	50	26	2					1037
2.5 - 3					135	146	69	14	11	1					307
3 - 3.5					26	56	49	7	6						0
3.5 - 4					4	29	27	12	1						0
4 - 4.5						9	29	5	2						0
4.5 - 5						1	15	2	1						0
5 - 5.5							2	1							0
5.5 - 6							1								0
6 - 6.5															0
6.5 - 7															0
7 - 7.5															0
7.5 - 8															0
8 - 8.5															0
8.5 - 9															15250
9 - 9.5															
9.5 - 10															%
10 - 10.5															0,9773135
10.5 - 11															
11 - 11.5															
11.5 - 12+															
	0	60	1445	2732	3048	4032	3323	560	275	87	0	42	0	0	15604

June



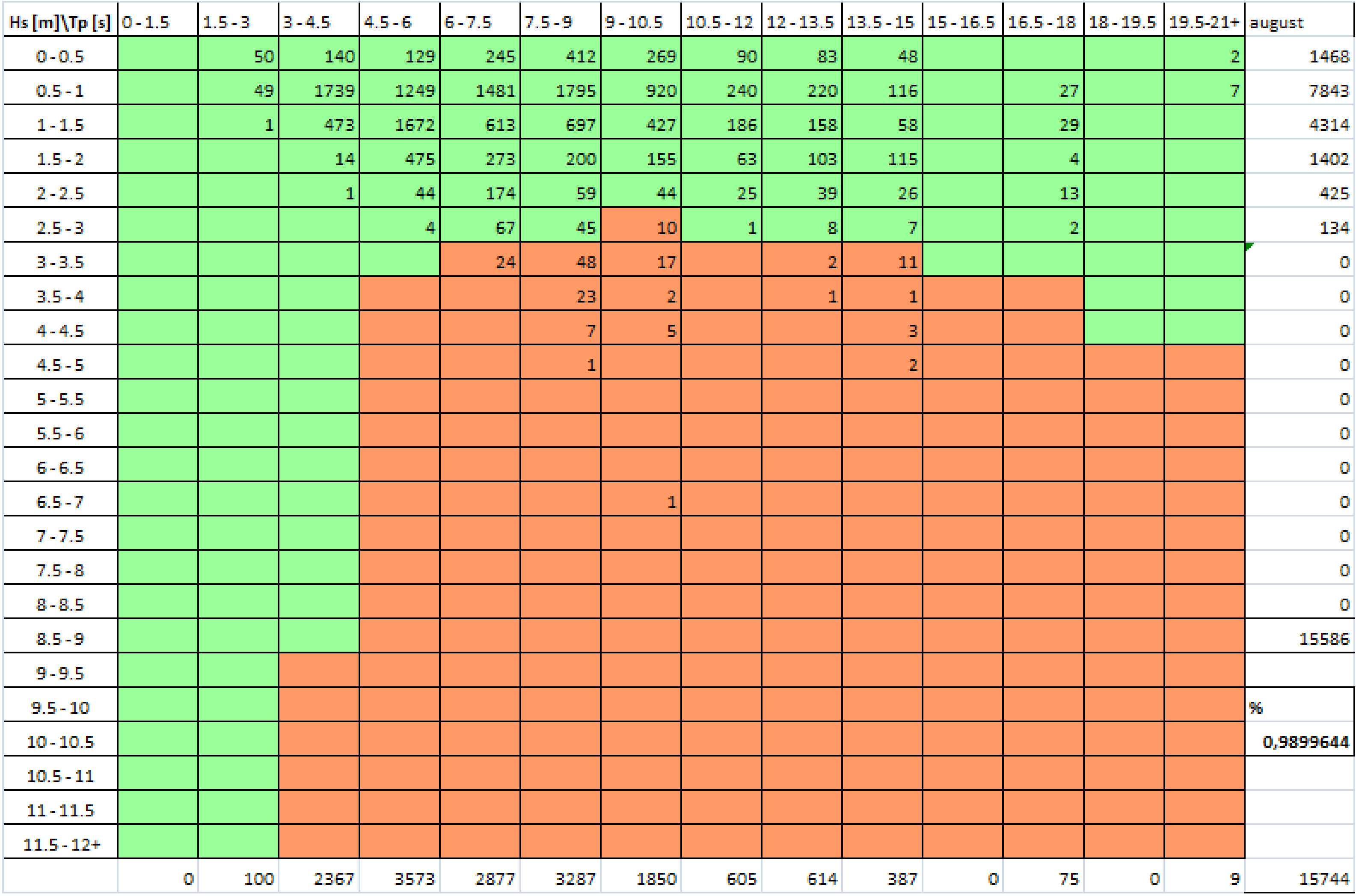
Hs [m]\Tp [s]	0 - 1.5	1.5 - 3	3 - 4.5	4.5 - 6	6 - 7.5	7.5 - 9	9 - 10.5	10.5 - 12	12 - 13.5	13.5 - 15	15 - 16.5	16.5 - 18	18 - 19.5	19.5-21+	june
0 - 0.5		21	103	110	219	371	234	34	45	54		7		3	1201
0.5 - 1		48	1393	1220	1721	1995	1000	160	100	126		84		10	7857
1 - 1.5			392	1426	673	1274	789	77	20	9		6			4666
1.5 - 2			2	467	386	409	370	68	67	22		5			1796
2 - 2.5				42	233	113	132	40	10	4					574
2.5 - 3				2	47	62	62	33	12	2					158
3 - 3.5					7	27	32	21	15	1					0
3.5 - 4						9	19	6	5	1					0
4 - 4.5						3	11								0
4.5 - 5						1	6								0
5 - 5.5							2								0
5.5 - 6							1								0
6 - 6.5															0
6.5 - 7															0
7 - 7.5															0
7.5 - 8															0
8 - 8.5															0
8.5 - 9															16252
9 - 9.5															
9.5 - 10															%
10 - 10.5															**0,9861052**
10.5 - 11															
11 - 11.5															
11.5 - 12+															
	0	69	1890	3267	3286	4264	2658	439	274	219	0	102	0	13	16481

July



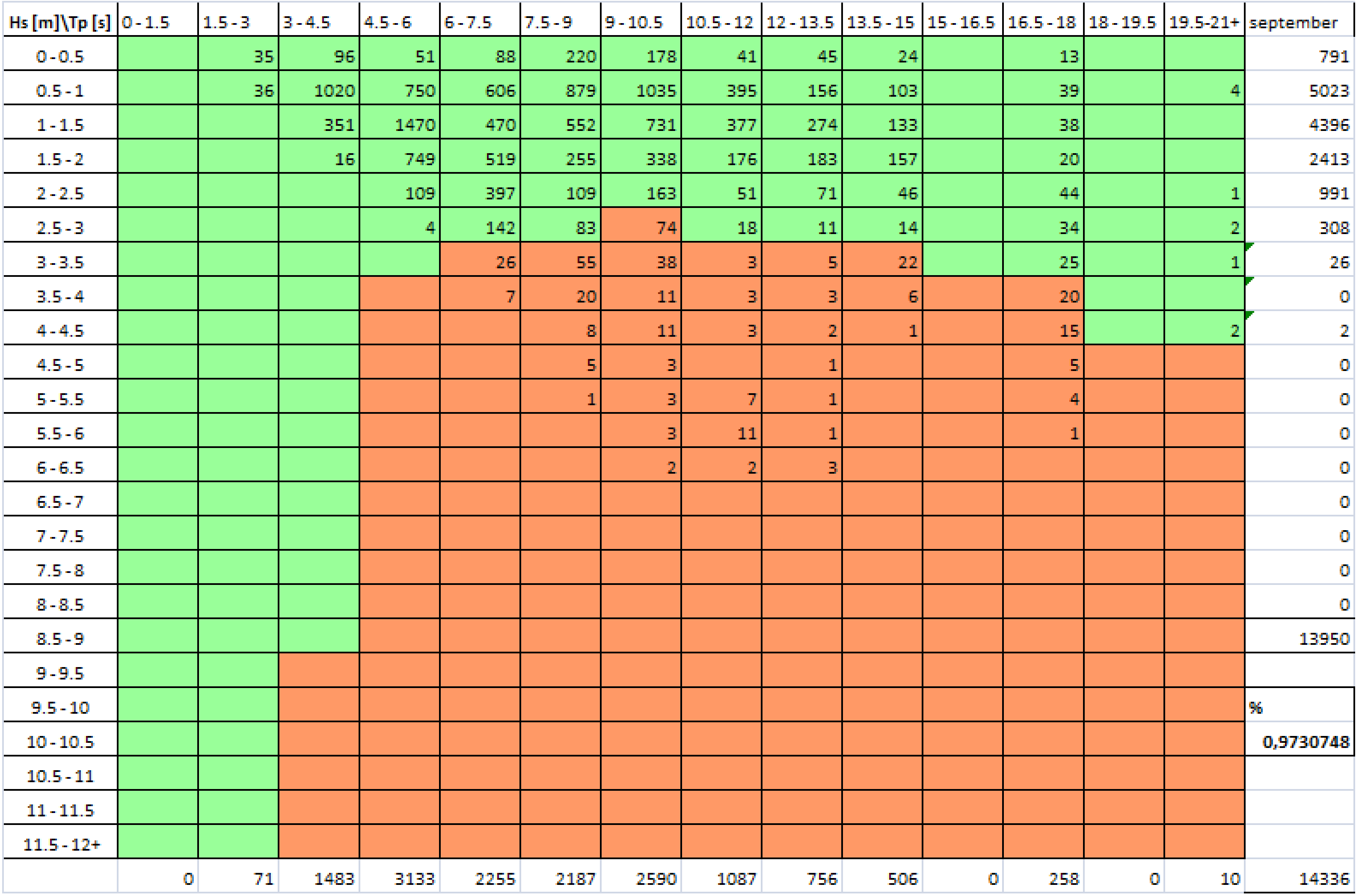
Hs [m]\Tp [s]	0 - 1.5	1.5 - 3	3 - 4.5	4.5 - 6	6 - 7.5	7.5 - 9	9 - 10.5	10.5 - 12	12 - 13.5	13.5 - 15	15 - 16.5	16.5 - 18	18 - 19.5	19.5-21+	july
0 - 0.5		38	142	148	368	586	344	53	36	42		9			1766
0.5 - 1		71	1377	1326	2089	2177	694	104	93	111		49			8091
1 - 1.5			391	1421	848	1067	568	79	41	26		1			4442
1.5 - 2			6	474	311	179	169	52	19	6					1216
2 - 2.5				34	143	51	50	13	6	1					298
2.5 - 3				1	38	53	20	8	4						104
3 - 3.5				1	5	10	6								1
3.5 - 4						5	2								0
4 - 4.5						4	1								0
4.5 - 5							1								0
5 - 5.5															0
5.5 - 6															0
6 - 6.5															0
6.5 - 7															0
7 - 7.5															0
7.5 - 8															0
8 - 8.5															0
8.5 - 9															15918
9 - 9.5															
9.5 - 10															%
10 - 10.5															0,9966191
10.5 - 11															
11 - 11.5															
11.5 - 12+															
	0	109	1916	3405	3802	4132	1855	309	199	186	0	59	0	0	15972

August



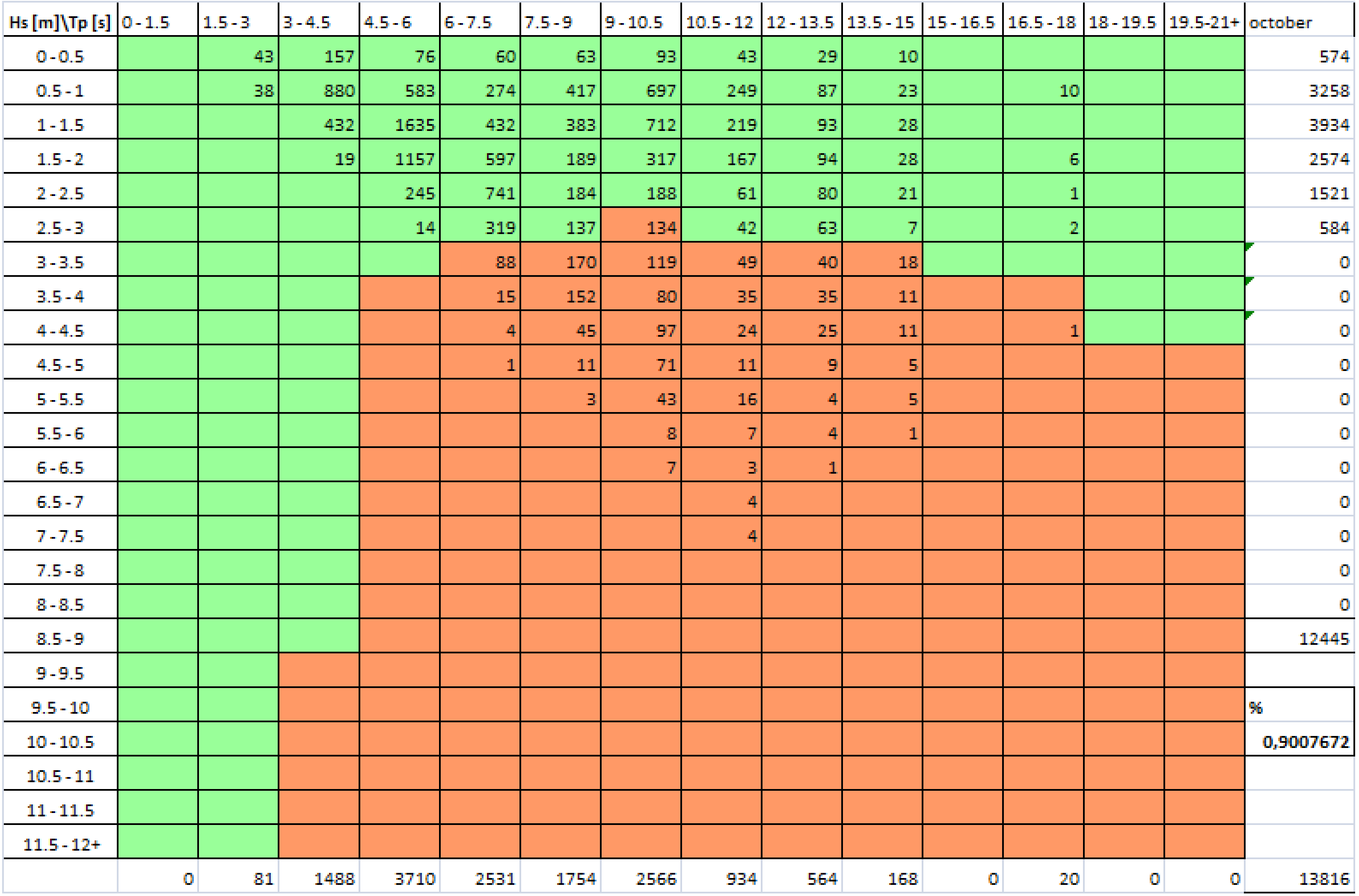
Hs [m]\Tp [s]	0 - 1.5	1.5 - 3	3 - 4.5	4.5 - 6	6 - 7.5	7.5 - 9	9 - 10.5	10.5 - 12	12 - 13.5	13.5 - 15	15 - 16.5	16.5 - 18	18 - 19.5	19.5-21+	august
0 - 0.5		50	140	129	245	412	269	90	83	48				2	1468
0.5 - 1		49	1739	1249	1481	1795	920	240	220	116		27		7	7843
1 - 1.5		1	473	1672	613	697	427	186	158	58		29			4314
1.5 - 2			14	475	273	200	155	63	103	115		4			1402
2 - 2.5			1	44	174	59	44	25	39	26		13			425
2.5 - 3				4	67	45	10	1	8	7		2			134
3 - 3.5					24	48	17		2	11					0
3.5 - 4						23	2		1	1					0
4 - 4.5						7	5			3					0
4.5 - 5						1				2					0
5 - 5.5															0
5.5 - 6															0
6 - 6.5															0
6.5 - 7							1								0
7 - 7.5															0
7.5 - 8															0
8 - 8.5															0
8.5 - 9															15586
9 - 9.5															
9.5 - 10															%
10 - 10.5															0,9899644
10.5 - 11															
11 - 11.5															
11.5 - 12+															
	0	100	2367	3573	2877	3287	1850	605	614	387	0	75	0	9	15744

September



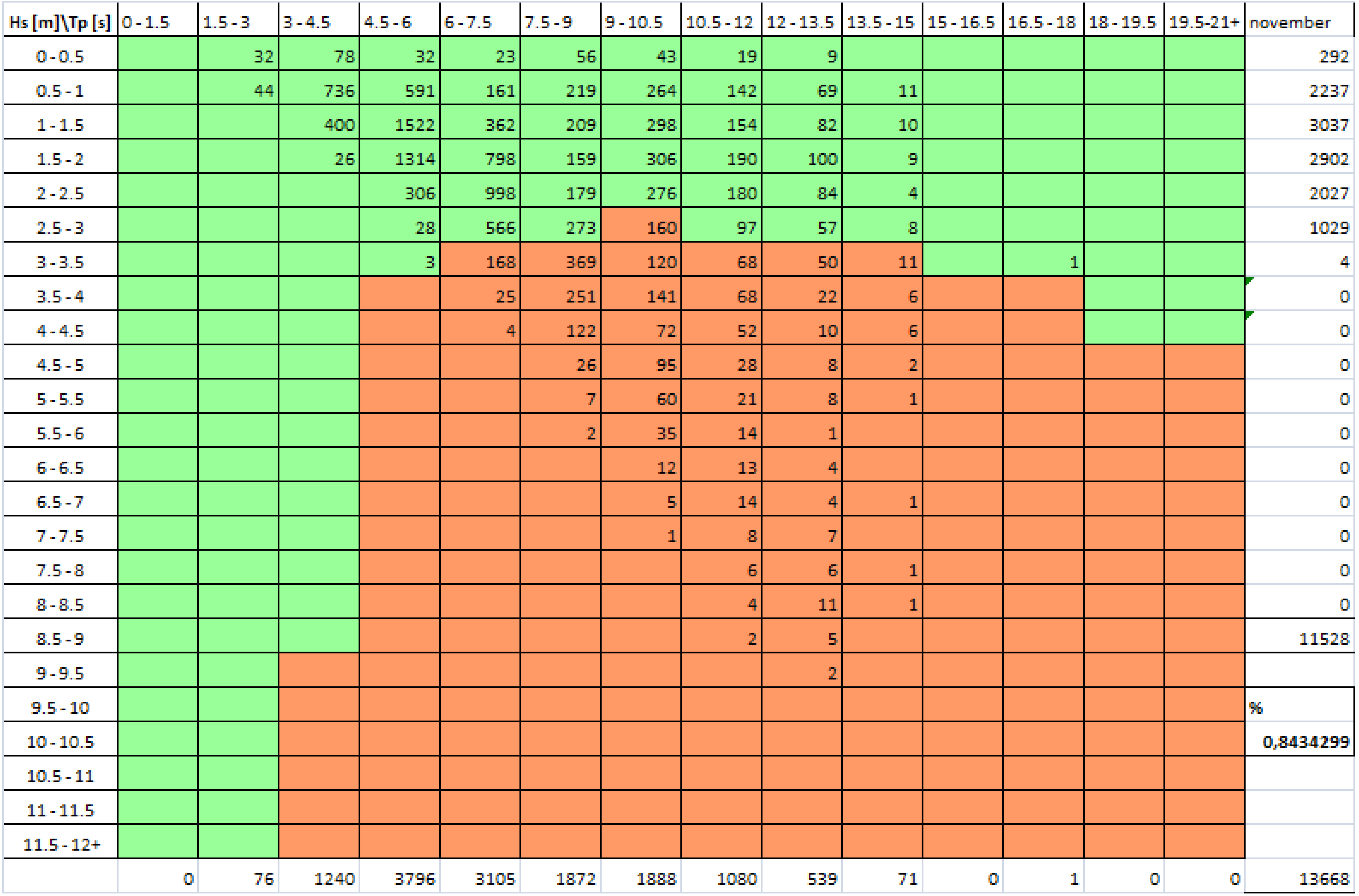
Hs [m]\Tp [s]	0 - 1.5	1.5 - 3	3 - 4.5	4.5 - 6	6 - 7.5	7.5 - 9	9 - 10.5	10.5 - 12	12 - 13.5	13.5 - 15	15 - 16.5	16.5 - 18	18 - 19.5	19.5-21+	september
0 - 0.5		35	96	51	88	220	178	41	45	24		13			791
0.5 - 1		36	1020	750	606	879	1035	395	156	103		39		4	5023
1 - 1.5			351	1470	470	552	731	377	274	133		38			4396
1.5 - 2			16	749	519	255	338	176	183	157		20			2413
2 - 2.5				109	397	109	163	51	71	46		44		1	991
2.5 - 3				4	142	83	74	18	11	14		34		2	308
3 - 3.5					26	55	38	3	5	22		25		1	26
3.5 - 4					7	20	11	3	3	6		20			0
4 - 4.5						8	11	3	2	1		15		2	2
4.5 - 5						5	3		1			5			0
5 - 5.5						1	3	7	1			4			0
5.5 - 6							3	11	1			1			0
6 - 6.5							2	2	3						0
6.5 - 7															0
7 - 7.5															0
7.5 - 8															0
8 - 8.5															0
8.5 - 9															13950
9 - 9.5															
9.5 - 10															%
10 - 10.5															0,9730748
10.5 - 11															
11 - 11.5															
11.5 - 12+															
	0	71	1483	3133	2255	2187	2590	1087	756	506	0	258	0	10	14336

October



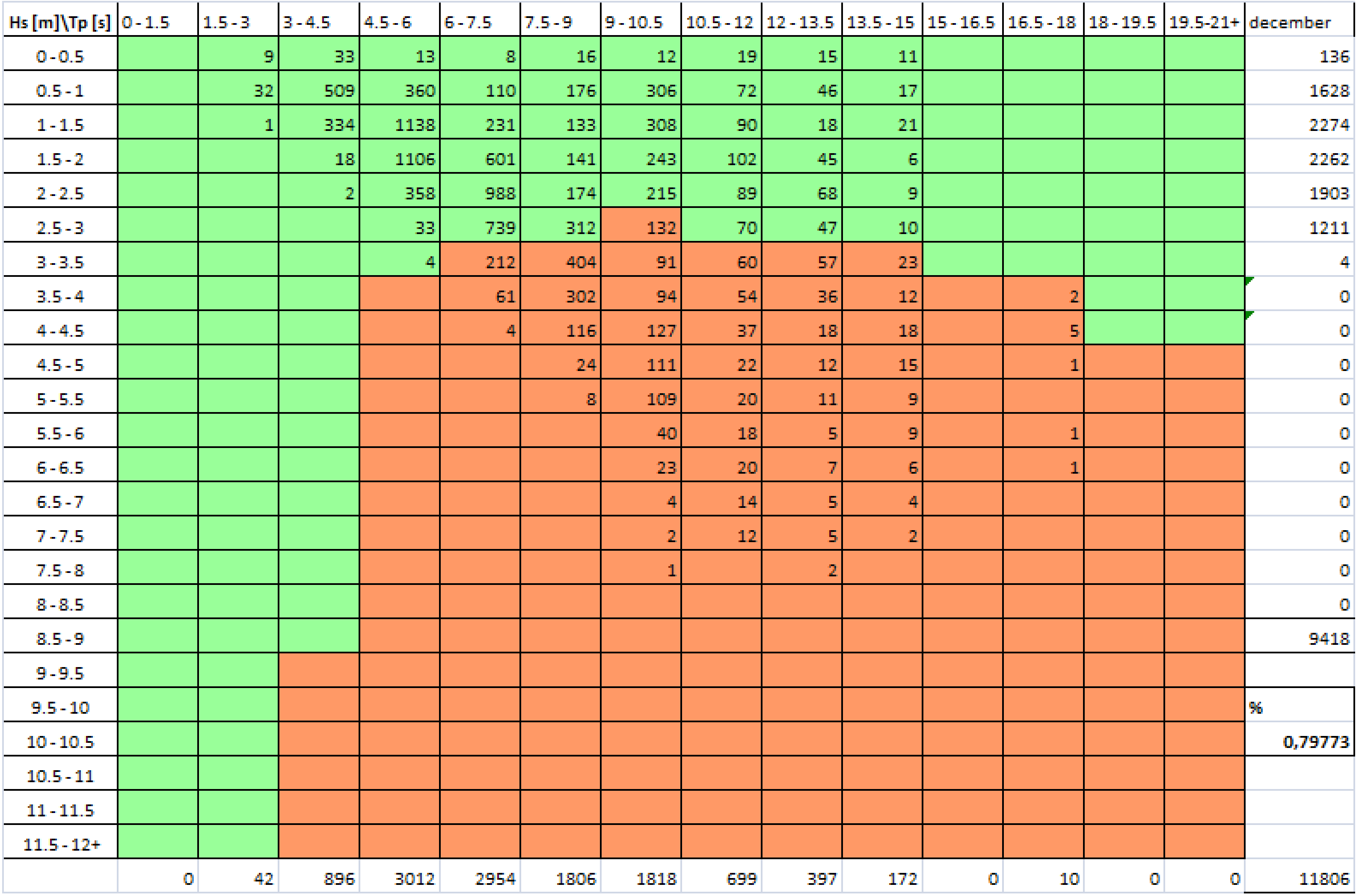
Hs [m]\Tp [s]	0 - 1.5	1.5 - 3	3 - 4.5	4.5 - 6	6 - 7.5	7.5 - 9	9 - 10.5	10.5 - 12	12 - 13.5	13.5 - 15	15 - 16.5	16.5 - 18	18 - 19.5	19.5-21+	october
0 - 0.5		43	157	76	60	63	93	43	29	10					574
0.5 - 1		38	880	583	274	417	697	249	87	23		10			3258
1 - 1.5			432	1635	432	383	712	219	93	28					3934
1.5 - 2			19	1157	597	189	317	167	94	28		6			2574
2 - 2.5				245	741	184	188	61	80	21		1			1521
2.5 - 3				14	319	137	134	42	63	7		2			584
3 - 3.5					88	170	119	49	40	18					0
3.5 - 4					15	152	80	35	35	11					0
4 - 4.5					4	45	97	24	25	11		1			0
4.5 - 5					1	11	71	11	9	5					0
5 - 5.5						3	43	16	4	5					0
5.5 - 6							8	7	4	1					0
6 - 6.5							7	3	1						0
6.5 - 7								4							0
7 - 7.5								4							0
7.5 - 8															0
8 - 8.5															0
8.5 - 9															12445
9 - 9.5															
9.5 - 10															%
10 - 10.5															0,9007672
10.5 - 11															
11 - 11.5															
11.5 - 12+															
	0	81	1488	3710	2531	1754	2566	934	564	168	0	20	0	0	13816

November



Hs [m]\Tp [s]	0 - 1.5	1.5 - 3	3 - 4.5	4.5 - 6	6 - 7.5	7.5 - 9	9 - 10.5	10.5 - 12	12 - 13.5	13.5 - 15	15 - 16.5	16.5 - 18	18 - 19.5	19.5-21+	november
0 - 0.5		32	78	32	23	56	43	19	9						292
0.5 - 1		44	736	591	161	219	264	142	69	11					2237
1 - 1.5			400	1522	362	209	298	154	82	10					3037
1.5 - 2			26	1314	798	159	306	190	100	9					2902
2 - 2.5				306	998	179	276	180	84	4					2027
2.5 - 3				28	566	273	160	97	57	8					1029
3 - 3.5				3	168	369	120	68	50	11		1			4
3.5 - 4					25	251	141	68	22	6					0
4 - 4.5					4	122	72	52	10	6					0
4.5 - 5						26	95	28	8	2					0
5 - 5.5						7	60	21	8	1					0
5.5 - 6						2	35	14	1						0
6 - 6.5							12	13	4						0
6.5 - 7							5	14	4	1					0
7 - 7.5							1	8	7						0
7.5 - 8								6	6	1					0
8 - 8.5								4	11	1					0
8.5 - 9								2	5						11528
9 - 9.5									2						
9.5 - 10															%
10 - 10.5															**0,8434299**
10.5 - 11															
11 - 11.5															
11.5 - 12+															
	0	76	1240	3796	3105	1872	1888	1080	539	71	0	1	0	0	13668

December



Hs [m]\Tp [s]	0 - 1.5	1.5 - 3	3 - 4.5	4.5 - 6	6 - 7.5	7.5 - 9	9 - 10.5	10.5 - 12	12 - 13.5	13.5 - 15	15 - 16.5	16.5 - 18	18 - 19.5	19.5-21+	december
0 - 0.5		9	33	13	8	16	12	19	15	11					136
0.5 - 1		32	509	360	110	176	306	72	46	17					1628
1 - 1.5		1	334	1138	231	133	308	90	18	21					2274
1.5 - 2			18	1106	601	141	243	102	45	6					2262
2 - 2.5			2	358	988	174	215	89	68	9					1903
2.5 - 3				33	739	312	132	70	47	10					1211
3 - 3.5				4	212	404	91	60	57	23					4
3.5 - 4					61	302	94	54	36	12		2			0
4 - 4.5					4	116	127	37	18	18		5			0
4.5 - 5						24	111	22	12	15		1			0
5 - 5.5						8	109	20	11	9					0
5.5 - 6							40	18	5	9		1			0
6 - 6.5							23	20	7	6		1			0
6.5 - 7							4	14	5	4					0
7 - 7.5							2	12	5	2					0
7.5 - 8							1		2						0
8 - 8.5															0
8.5 - 9															9418
9 - 9.5															
9.5 - 10															%
10 - 10.5															**0,79773**
10.5 - 11															
11 - 11.5															
11.5 - 12+															
	0	42	896	3012	2954	1806	1818	699	397	172	0	10	0	0	11806

Appendix H: Electronic appendices

MatLab scripts

Main program:

Electronic appendices\MatLab scripts\Program

Verification:

Electronic appendices\MatLab scripts \Verification

Report

Electronic appendices\Master thesis 2010, Idunn Olimb.pdf