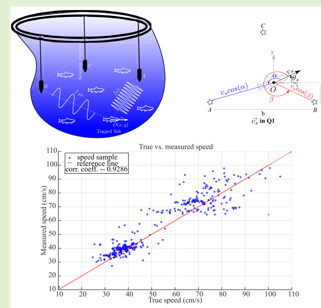
A New Method for Measuring Free-Ranging Fish Swimming Speed in Commercial Marine Farms Using Doppler Principle

Waseem Hassan, Martin Føre, Magnus Oshaug Pedersen, and Jo Arve Alfredsen

***Abstract*—A novel Doppler shift based technique for measurement of free-swimming fish speed in marine farms using acoustic telemetry tags was developed and evaluated in this study. The proposed method can potentially augment current telemetry systems with a new biologically relevant measurement without significantly changing the size and energy constrained tag-side of the telemetry systems. For speeds in the range of 20cm s^{-1}-110cm s^{-1} an overall relative rms error of less than 10% in measured speed based on the proposed Doppler method was achieved in the tests conducted at a fully stocked commercial fish cage, with an rms error of 7.85cm s^{-1} (std. dev. 7.5cm s^{-1}). The study thus demonstrates the feasibility of measuring the swimming speeds of individual free-ranging fish using this method.**



Doppler based fish swimming speed measurement

***Index Terms*—Acoustic signal processing, acoustic telemetry, Doppler measurement, fast Fourier transform, marine aquaculture, sensor phenomena & characterization.**

I. Introduction

FISH swimming is a coordinated function of various body systems and is a key behavioural parameter for understanding how fish cope with the environment and respond to external factors, and how this affects their energy consumption, stress and hunger levels. Swimming speed is particularly interesting in aquaculture, as studies have shown that sustained exposure to speeds that exceed the critical swimming speeds of the fish may lead to negative welfare impacts [12], [13], [20]. This is particularly relevant in light of the present industrial trend in moving fish farming to more remote and environmentally exposed locations [2] where fish may experience higher water velocities [14]. The ability to monitor swimming speeds could thus be an important component in future farm management methods and operations that take animal welfare conditions at exposed sites into account [15]. However, unlike laboratory studies or other small scale settings, where fish swimming speeds may be manually assessed, measuring individual fish swimming speeds in marine fish farms is a challenging task that requires technological tools [8]. In addition, the large variability in swimming abilities between individuals suggest that swimming speed should first be studied on an individual level before using aggregated measures of swimming speeds as a cage management parameter in aquaculture [13].

Individual fish swimming speeds have previously been assessed using split beam sonars [17] and camera solutions coupled with machine vision techniques [19]. Such methods can provide precise estimates on swimming speeds, for individual fish that are within their observation volume (i.e. the sonar beam or visual field) at any given time. However, evaluating the ultimate welfare impacts of being exposed to sustained strong currents requires data describing the individual histories of swimming speed over time. Since neither hydroacoustic or camera-based methods can provide such data, this highlights the need for new tools for observing fish speed.

At present, bio-telemetry, where individual animals are equipped with miniature electronic devices, is the only viable option for obtaining individual data on free-ranging fish over time. Such devices, commonly known as electronic tags, often

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Waseem Hassan, Martin Føre, and Jo Arve Alfredsen are with the Department of Engineering Cybernetics, Norwegian University of Science and Technology (ITK-NTNU), 7491 Trondheim, Norway (e-mail: waseem.hassan@ntnu.no; martin.fore@ntnu.no; jo.arve.alfredsen@ntnu.no).

Magnus Oshaug Pedersen is with SINTEF Ocean AS, 7052 Trondheim, Norway.

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contain sensors for sensing some property in or near the fish, and may be realised as either data loggers that store data internal storage mediums or as transmitter devices that transmit data using radio or acoustic signals [23]. Since radio signals are heavily attenuated by salt water, acoustic telemetry represents the only practical option for marine applications of transmitter devices.. The tags then contain an acoustic modem for wireless underwater data transmission of the tag ID and eventual data derived from the sensor measurements. In addition to tags, a typical acoustic telemetry system includes one or more matching acoustic receivers, which are specialised hydrophone devices that receive and decode the acoustic signals emitted by acoustic tags.

Acoustic telemetry has previously been used to observe individual fish behaviour both in wild and full-scale marine aquaculture applications [7], [21] and has been proven as an effective tool to quantify various fish behaviour parameters such as variations in swimming depth and activity [6], muscle activity via Electromyography (EMG) [4] and 3D position [10]. However, there exist no acoustic telemetry solutions able to directly measure instantaneous swimming speeds of individual fish. Indirect methods where speed is derived from consecutive position measurements tend to yield conservative estimates, and are strongly biased to the sampling rate and precision of the positioning system [4].

The first step in developing tools for measuring new parameters is to identify sensor principles able to measure the value of interest, in this case movement speed. Movement speed of objects in water is often measured using either impeller/turbine-based or acoustic methods. Although impellers have previously been applied to marine mammals [9], such solutions need to be mounted externally on the fish which could impair swimming ability and cause welfare issues due to skin abrasion.It is thus more likely that a viable solution can be found by applying acoustic principles.

Most acoustic methods exploit the Doppler effect, i.e. that the frequency of an acoustic signal received by a receiver will differ from the frequency of the signal emitted by the transmitter if there is relative movement between these. This Doppler Shifted Frequency (DSF) will be lower than the transmitted frequency when source and transmitter are moving away from each other, and conversely, higher if they are approaching. Examples of previous studies using this principle includes measuring aeroplane speed using the DSF of the acoustic tone generated by the propeller [5], and the calculation of fish tail beat rate using the DSF in a continuous acoustic signal [22]. Existing solutions using the Doppler effect for speed measurement include Acoustic Doppler Current Profilers (ADCPs) and Acoustic Doppler Velocimeters (ADVs) that could be used to measure current speeds in fish farms [16]. However, these devices are typically designed for stationary placement at the seabed or structural components, or to be mounted at vehicles, and are thus not suited to be mounted on or inside fish.

Although it might be possible to make an ADCP-like sensor small enough to fit inside an acoustic tag, this could prove difficult as the signal processing required to find the DSF might be beyond the capacity of the tag, both in terms of computation and power. Moreover, such a sensor would need to emit a dedicated acoustic signal to sense the DSF caused by the relative movement between the fish and the surrounding water, further increasing both power consumption and technical complexity. Using the DSF induced by tag movement upon the already existing carrier wave used to transfer data may therefore pose a more elegant and practical solution. This would move the effort of computing the Doppler shift to the receiver side, and not consume acoustic bandwidth, enabling the tag to simultaneously transmit other data types. Essentially, this means that movement speed would "piggyback" on other sensor data, enabling the collection of more diversified data-sets without increasing the number of fish tagged. A similar approach has previously been explored in laboratory experiments, where Doppler shift was employed to calculate fish tail beat frequency by using a continuous wave acoustic signal [22]. However, many present day solutions for acoustic telemetry use energy saving pulse interval modulation schemes rather than continuous signals to encode data from acoustic tags, with both encoding and processing being done in the time domain. A burst of pulses is then transmitted from the tag with the time interval between consecutive pulses being varied or kept constant to encode ID and sensor data [18]. Although this prohibits the possibility of obtaining continuous Doppler shift measurements, it is conceivable that modern signal processing methods can be used to obtain enough data from such pulses.

In this study, we developed and tested a fish swimming speed measurement technique based on the Doppler shift observed in the acoustic carrier wave transmitted by a telemetry tag. The technique is based on a commercially available acoustic telemetry system and extends the capabilities of this system by additional signal processing done in the acoustic receivers. The measurement technique was tested in a series of experiments ranging from speed extraction in a simple 1D laboratory setup, through a meso-scale experiment to evaluate 2D effects, to a full scale setup with multiple acoustic receivers in a commercial fish cage. The technique was evaluated for accuracy bounds and resolution of the measured speed using a signal frequency of 69 kHz, which is within the frequency range typically used in marine acoustic telemetry applications, and for speed ranges relevant for farmed Atlantic salmon. The sensitivity of the method towards inaccurate positioning was explored through a theoretical computer simulation study.

II. Materials and Methods

A. Theory and Method of Approach

Fig. 1 illustrates the proposed method. The DSF of a signal (f_d) represents a frequency shift in the received frequency (f_r) relative to the frequency transmitted by the source (f_s) and is found as:

$$f_d = f_s - f_r \tag{1}$$

A positive value of f_d means that the transmitter is moving towards the receiver, whereas a negative value implies that the transmitter is moving away from a receiver. The speed of transmitter υ is related to f_d as:

$$\upsilon = \frac{c f_d}{f_s} \tag{2}$$

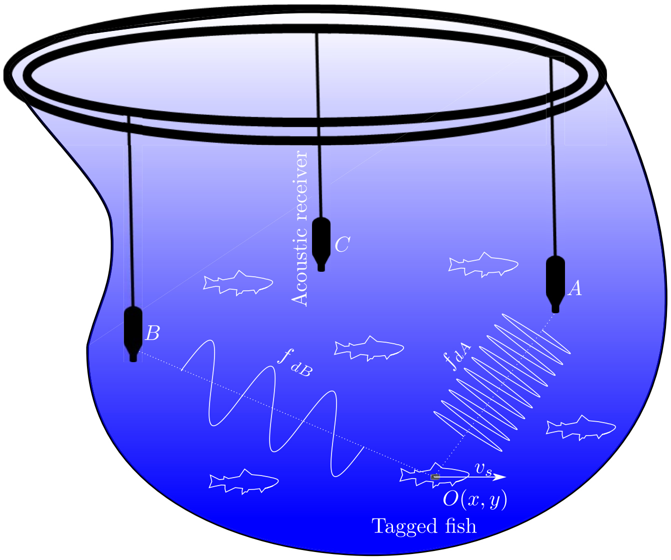


Fig. 1. Conceptual illustration of a tagged fish swimming inside a fish cage at a position O with swimming velocity $\vec{v_S}$ in the horizontal plane. The acoustic wave is compressed or stretched when received by receiver A, B and C depending on whether the fish movement is towards or away from the receivers.

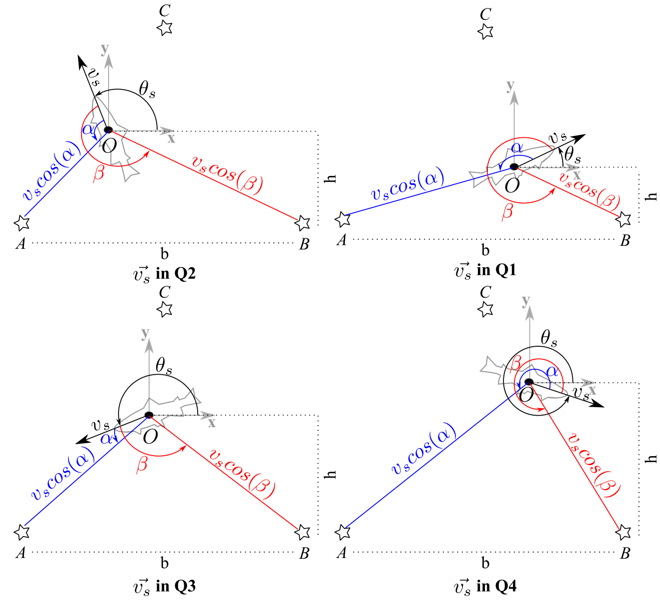


Fig. 2. Orientation of transmitter tag located at O moving with a velocity $\vec{v_S}$ in the four quadrants Q1-Q4 (horizontal plane). The Doppler shift measured at receiver locations A and B will be proportional to the components of the transmitter speed v_S along the lines AO and BO, respectively, defined by the angles α and β. A third receiver at location C enables TDoA based transmitter localisation.

where c is the speed of the acoustic signal in the propagation medium. The Doppler effect only applies to the velocity component along the axis between the receiver and transmitter, hence the angle θ between the velocity vector ($\vec{v}$) and this axis needs to be considered. This component is found as the cosine speed component of the transmitter's speed:

$$v = \frac{cf_d}{f_s cos\theta} \tag{3}$$

Reference [3] explained the use of the Doppler effect to determine the position and speed of a moving source in 3D using multiple sensor nodes, and highlighted the challenges using the method in that no closed-form solution exists and that non-linear equations are involved in the calculations. However, the authors also pointed out that by knowing the transmitted signal's frequency (f_s) and the position of a transmitter it is possible to achieve an exact solution. Most commercially available telemetry systems for marine applications use fixed known frequencies (f_s) ranging between 10 kHz and 100 kHz. Moreover, Time Difference of Arrival (TDoA) based positioning systems have been successfully used to position acoustic transmitter tags in marine aquaculture [10]. In TDoA based acoustic telemetry positioning, position in 3D (x, y, z) coordinates can be obtained directly using the difference in arrival times of an acoustic signal from a transmitter tag on four different acoustic receivers placed at known positions. A setup using three hydrophones can also be sufficient when using depth-sensing tags as TDoA then only needs to to locate the tag in the horizontal plane (xy-coordinates). When using TDoA, all receivers used in the calculations need to be synchronised to a common clock source, usually by using Global Navigation Satellite Systems (GNSS) [18].

This means that exact speed solutions are possible to achieve by extending existing acoustic telemetry systems with additional signal processing methods and frequency analysis at the receiver end. The likelihood of the proposed method functioning under the farm relevant conditions increases by employing the existing acoustic systems that have been extensively tested in the marine environment since the proposed method does not introduce significant modifications.

B. Speed Computation Algorithm

The algorithm for computing movement speed was based on combining (3) with a geometric setup that would be reasonable to apply in a fish cage. A 2D (xy-plane) example of such a setup with three acoustic receivers A, B and C is shown in Fig. 2. The movement velocity vector $\vec{v_s}$ of an acoustic tag placed at O with coordinates (x_O, y_O) would then make an angle θ_s with respect to the x-axis.

For all values of θ_s, the DSFs observed at receivers A (f_{dA}) and B (f_{dB}) are given by:

$$f_{dA} = \frac{f_s v_s cos\alpha}{c} \tag{4}$$

$$f_{dB} = \frac{f_s v_s cos\beta}{c} \tag{5}$$

where α and β are the angles between $\vec{v_s}$ and the axes between O and receivers A and B respectively, and $v_s cos\alpha$ and $v_s cos\beta$ are the velocity components along these lines. Dividing (4) by (5) yields:

$$\frac{cos\alpha}{cos\beta} = \frac{f_{dA}}{f_{dB}} \tag{6}$$

Estimating f_{dA} and f_{dB} through Fast Fourier Transform (FFT) or similar frequency analysis enables finding the two unknown angles (i.e. α and β) using TDoA positioning methods and system geometry.

Assuming that the coordinates (x_O, y_O) of the tag and receivers A and B are known, the angle $\angle AOB$ can be calculated from $\triangle AOB$ since all three sides of the triangle are then known. $\angle AOB$ relates to the two unknown angles as:

$$\angle AOB = \beta - \alpha \quad (7)$$

Deriving β from (7) and inserting it into (6) then yields:

$$\frac{cos\alpha}{cos(\angle AOB + \alpha)} = \frac{f_{dA}}{f_{dB}} \quad (8)$$

Inverting and solving (8) for α yields:

$$\frac{cos(\angle AOB + \alpha)}{cos\alpha} = \frac{f_{dB}}{f_{dA}} \quad (9)$$

$$\frac{cos(\angle AOB)cos\alpha - sin(\angle AOB)sin\alpha}{cos\alpha} = \frac{f_{dB}}{f_{dA}} \quad (10)$$

$$cos(\angle AOB) - \frac{sin(\angle AOB)sin\alpha}{cos\alpha} = \frac{f_{dB}}{f_{dA}} \quad (11)$$

$$cos(\angle AOB) - sin(\angle AOB)tan\alpha = \frac{f_{dB}}{f_{dA}} \quad (12)$$

$$tan\alpha = \frac{cos(\angle AOB) - \frac{f_{dB}}{f_{dA}}}{sin(\angle AOB)} \quad (13)$$

$$\alpha = atan(\frac{cos(\angle AOB) - \frac{f_{dB}}{f_{dA}}}{sin(\angle AOB)}) \quad (14)$$

Equations (6) and (7) can be written similarly in terms of angle β:

$$\frac{cos(\beta - \angle AOB)}{cos\beta} = \frac{f_{dA}}{f_{dB}} \quad (15)$$

or

$$\beta = atan(\frac{\frac{f_{dA}}{f_{dB}} - cos(\angle AOB)}{sin(\angle AOB)}) \quad (16)$$

Once angles α and β are found using either (14) and (7) or (16) and (7), the unknown speed v_s of the acoustic transmitter can be calculated using (3) in terms of α:

$$v_s = \frac{f_{dA}c}{f_s cos\alpha} \quad (17)$$

or in terms of β:

$$v_s = \frac{f_{dB}c}{f_s cos\beta} \quad (18)$$

To relate v_s to the $xy-$plane defined in Fig. 2, a right angle triangle $\triangle BOX$ can be defined using the $y-$component of O, y_O, as the height h of the triangle. The base of this triangle can then be calculated by subtracting x_O from the known distance b between A and B. The angle $\angle BOX$ can then be calculated and used to derive an expression for the angle between $\vec{v_s}$ and the $x-$axis, θ_s:

$$\theta_s = 360^\circ - \beta - \angle BOX \quad (19)$$

Equations to calculate angles θ_s, α and β when the velocity vector lies in one of the four different quadrants are shown in Fig. 2. When defining all angles in anticlockwise direction with respect to the x-axis, this yields the same set of equations for all quadrants except the 4th quadrant (Q4) where θ_s is calculated as a negative value. The present quadrant can easily be determined using the sign of the DSF (f_d) value on both receivers. Equations (4)-(19) can be applied to any pair of receivers (i.e. A and B, B and C or A and C).

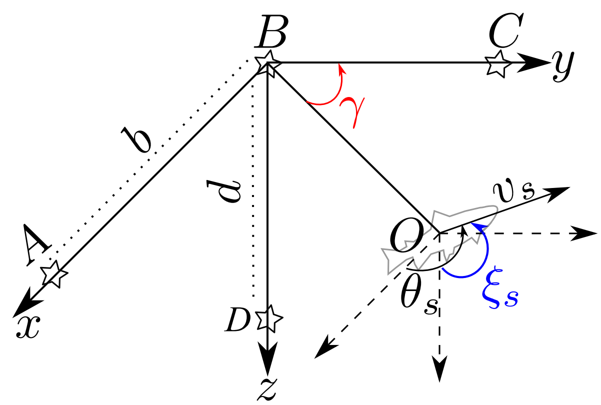


Fig. 3. Conceptual description of determining 3D fish velocities using three acoustic receivers. Receivers A and B are used to derive the direction of v_s in the plane spanned between them and O (θ_s), while receivers B and D are used to derive the angle in the plane BDO (ξ_s). The fourth receiver C is present to enable TDoA based localisation of the tag's position O. Angle γ accounts for scaling of the velocity vector $\vec{v_s}$ with tag's depth variation.

For simplicity, the above mentioned equations are derived in a 2D (x, y) plane assuming a fixed depth. However, since (4)-(19) can be applied to any geometric plane defined between a pair of receivers and O, it is possible to find 3D-velocities by using three hydrophones. The 3D velocity vector would then be projected onto two 2D planes e.g. $xy-$ and $yz-$planes, which could be solved independently. The equations would then be used to find the angles between the velocity vector and the $x-$ (θ_s) and $z-$axes (ξ_s). To accommodate this, (17) and (18) would be expanded to account for depth variation as:

$$v_s = \frac{f_{dA}c}{f_s cos\alpha sin\xi_s cos\gamma} \quad (20)$$

$$v_s = \frac{f_{dB}c}{f_s cos\beta sin\xi_s cos\gamma} \quad (21)$$

where γ is the angle between the receivers A, B and C and tag's depth planes. For 3D speed measurement, using only two acoustic receivers in $xy-$plane and accounting for the tag's depth variation, i.e. the angle γ, will result in measurement of $v_s sin\xi_s$ which is the cosine $z-$component of the original speed. An additional receiver at z-axis along with the receiver at y-axis then can be used in the $yz-$plane to measure ξ_s, hence speed in 3D.

C. System Requirements

Calculating speeds using (4)-(21) requires the acoustic receivers to perform FFT frequency analysis to determine the DFS. In addition, the source frequency (f_s) used by the acoustic tag and its position must be known. If TDoA algorithms are used to acquire position, at least three (if the tags measure depth) or four synchronised acoustic receivers are required. Three acoustic receivers are required to execute FFT frequency analysis for 3D speed measurement, whereas two acoustic receivers are required for speed measurement in 2D.

D. Experimental Testing, Verification and Validation

A series of experiments were executed to verify and validate the method and to assess the error bounds on the resulting speed values. Experiments were conducted in three different environments: controlled lab, meso-scale in nearshore waters and a full scale fish farm. A custom made acoustic tag with a centre frequency of 68.968 kHz was used as the transmitter in the setup, while up to three broad spectrum hydrophones (Ocean Sonics Ltd., Nova Scotia, Canada) were used to collect acoustic data. The acoustic signal emitted by the tag was generated by a microcontroller based embedded system and designed to resemble the signal used in typical acoustic telemetry systems (i. e. a burst of pulses similar to those used in pulse interval encoding approaches). Eight pulses were used in a single burst and each pulse was set up with a longer duration (128 ms) than that typically used by commercial Pulse Position Modulation (PPM) protocols (10 ms) to improve the velocity resolution of the system [11]. The pulse bursts were spaced by a longer time interval (seconds) than the pulses in each burst (150 ms) to distinguish the separate bursts.

The basic principle in all experiments was to move the acoustic tag in a predefined motion pattern while monitoring the positions and speeds accurately using auxiliary positioning and speed measurement systems. Measured positions were used as input to the DSF speed algorithms, while the measured speeds were used as ground truth for validation of the speed computations. The target speeds used in the experiment varied from $5\,\mathrm{cm\,s^{-1}}$ to $20\,\mathrm{cm\,s^{-1}}$ for lab experiments and from $25\,\mathrm{cm\,s^{-1}}$ to $110\,\mathrm{cm\,s^{-1}}$ for sea based experiments, covering a range of swimming speeds typical for Atlantic salmon [13]. The embedded system transmitted acoustic bursts periodically, and logged the start times of each burst and the speed and position measured by the auxiliary system at these times. This resulted in a data-set on position and speed that was fully synchronised with the emitted pulses, enabling validation of the results from the DSF computations.

The goal of the initial 1D lab trials was to verify that the DSF speed extraction technique was feasible to apply for systems of this scale, and to evaluate the accuracy of the method. The experiment was conducted in a tank filled with water (4.3 m × 1.5 m × 2.0 m). A cart-on-rail mechanical setup driven by a geared DC motor (maxon RE 35) was used to move an acoustic tag mounted on an adjustable rod protruding down into the water. The embedded system controlled the speed of the DC motor and logged the reference speed measured by an encoder. The system was programmed to move back and forth in line with a hydrophone, meaning that the tag was either moving directly towards or away from the receiver (Fig. 4a). Position logging was therefore not required in this experiment.

The next step towards enabling 2D speed calculations was to evaluate if the method could estimate movements that are not in line with a hydrophone. This was done in an experiment in a fjord very close to shore. The acoustic tag was then attached to a rod fastened to a remotely controlled catamaran (Fig. 4b) placing the tag at a depth of 1 m. Burst start time, speed and position of the vehicle were measured using an on-board Real Time Kinematics (RTK) GPS, while the catamaran was driven in a straight line. Two hydrophones were placed such that one was in line with the tag/vehicle movement (i.e. with the tag moving directly from or toward it as in the 1D trials), while the other hydrophone was placed such that the angle between the tag movement direction and the line between the tag and the receiver varied between −45° and 60°.

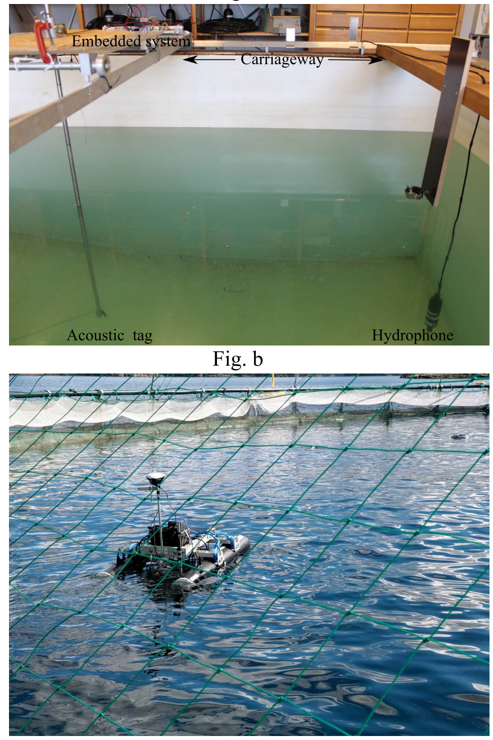
Fig. a


Fig. b

Fig. 4. (**Fig. a**) Electromechanical setup used for in lab experiments. Acoustic tag, hydrophone and direction of motion are highlighted with text. (**Fig. b**) Catamaran used to move the acoustic tag in the sea based experiments.

The final experiment aimed to test the ability of the method to measure 2D movement speeds in a relevant acoustic environment, and was thus conducted in a commercial sea-cage stocked with fish (approximately 200,000 animals). The catamaran was then driven in a circular path, meaning that the angles between the tag movement direction and the line from the hydrophones to the tag position varied continuously. This also served to demonstrate and test the algorithm for a more realistic range of speeds and angles (α and β in Fig. 2).

E. Collection and Processing of Acoustic Data

Through all experiments, the hydrophones stored acoustic data in waveform audio format (.wav) using a sampling frequency of $256\,\mathrm{kS\,s^{-1}}$ and a recording time of 10 min for each data-set. The data-set were analysed using Matlab (The MathWorks, Inc., Natick, Massachusetts, USA), finding peak frequency and DSF values for individual pulses by employing FFT. Average and modal values for eight DSF peaks (i.e. a single burst) were used for speed calculations (hereafter referred to as the averaging method and modal method, respectively). Since the trial in the sea cage was closest to a real world application, the data from this experiment was used in subsequent analyses to assess the error levels of the method.

F. Position Sensitivity Analysis

The sensitivity of the DSF speed calculation algorithm to errors in tag position was tested through theoretical simulations where a known error in tag position was introduced into

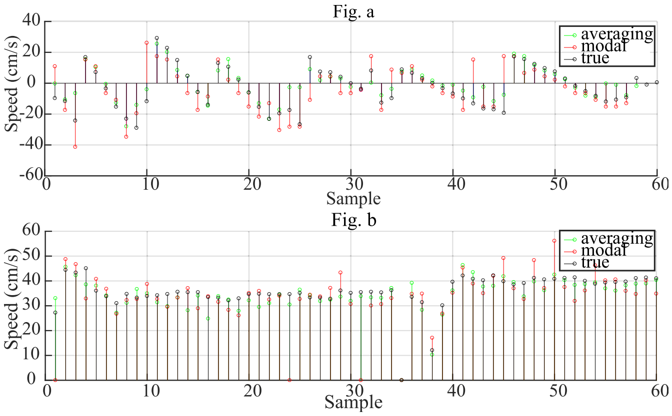


Fig. 5. (**Fig. a**) Fjord based experiments: Comparison of reference speed (true) with Doppler shift for both averaging and modal based speed measurements at hydrophone placed at angular orientation. (**Fig. b**) In fish cage experiments: Comparison of reference speed (true) with Doppler based speed measurements.

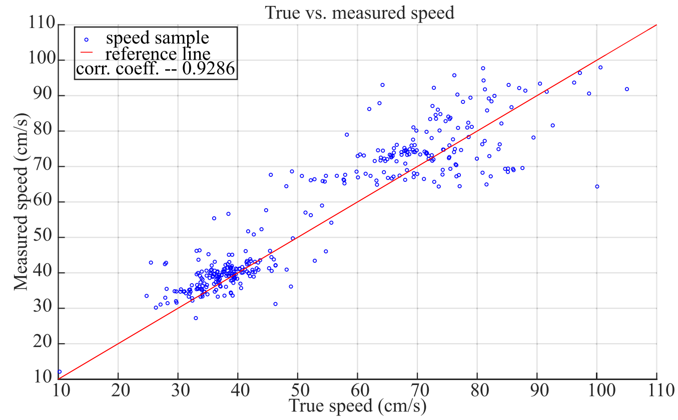


Fig. 6. Scatter plot of measured (averaging method) speed and true speed for fish cage experiments. A correlation coefficient of 0.9286 was achieved for measured and true speed with a sample count of N = 357. Reference line (1:1) is shown in red colour.

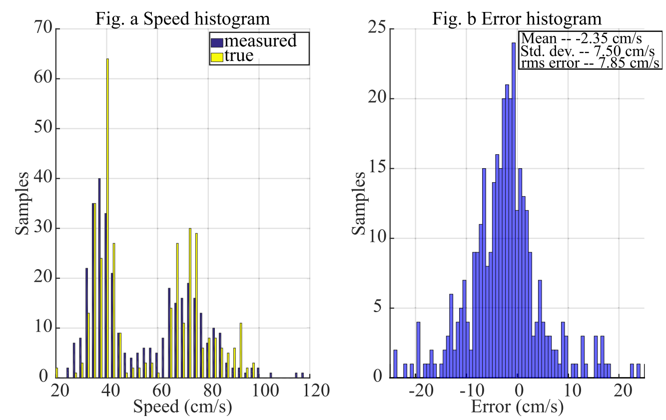


Fig. 7. (**Fig. a**) Histograms for true speed and Doppler based measured (averaging method) speed. (**Fig. b**) Histogram for error in measured (averaging method) speed. Sample count N = 357 for both plots.

the computation of the cosine value of angle $\angle AOB$. Typical Circular Error Probability (CEP) values for the TDoA based positioning methods, (i.e. an error of metres [18]) were used in the simulations.

III. Results

A. Lab Experiments

The rms error between computed and real speeds achieved in the lab experiments was found to be around $5\,\mathrm{cm\,s^{-1}}$ (std. dev. $< 2\,\mathrm{cm\,s^{-1}}$) when using the averaging method and $6\,\mathrm{cm\,s^{-1}}$ (std. dev. $<4\,\mathrm{cm\,s^{-1}}$) when using the modal method, respectively.

B. Fjord Based Experiments

The rms error when using the averaging method was found to be about $7\,\mathrm{cm\,s^{-1}}$ (std. dev. $<7\,\mathrm{cm\,s^{-1}}$) for speeds $<50\,\mathrm{cm\,s^{-1}}$ and $23\,\mathrm{cm\,s^{-1}}$ (std. dev. $<23\,\mathrm{cm\,s^{-1}}$) for speeds $>50\,\mathrm{cm\,s^{-1}}$. The rms errors were slightly higher when using the modal method, and were $12\,\mathrm{cm\,s^{-1}}$ and $31\,\mathrm{cm\,s^{-1}}$ for speeds $<50\,\mathrm{cm\,s^{-1}}$ and $>50\,\mathrm{cm\,s^{-1}}$ respectively (see Fig. 5a for excerpts of data from the fjord experiments).

C. Fish Cage Experiments

Since the modal method yielded slightly higher errors, speeds found using the averaging method were used in the further analyses (Fig. 5b). The correlation coefficient between measured speed and true speed was 0.9286 for complete speed range (i.e. $20\,\mathrm{cm\,s^{-1}}$-$110\,\mathrm{cm\,s^{-1}}$) with a sample count of N = 357 (Fig. 6). The rms error for the averaging method was $7.85\,\mathrm{cm\,s^{-1}}$ (std. dev. $<7.5\,\mathrm{cm\,s^{-1}}$, mean $<-2.35\,\mathrm{cm\,s^{-1}}$) for the entire speed range (Fig. 7).

D. Position Sensitivity

When assuming a CEP of 1.5 m, simulations implied that the absolute error in the speed computation was highest near the hydrophone position (Fig. 8).

IV. Discussion

The results from this study suggest that the Doppler based speed measurement method presented here is feasible for tracking individual fish speeds in commercial fish farms. The low errors compared with ground truth speed measurements obtained with independent methods in all three experiments thus served to validate the method through incremental stages. Moreover, the acceptable results achieved at full scale also showed that this method is applicable under realistic environmental conditions (i.e. the prevailing soundscape at a fish farm), and with arbitrary directions of movement.

For the fjord and fish cage based trials, the data were grouped into low ($25\,\mathrm{cm\,s^{-1}}$-$50\,\mathrm{cm\,s^{-1}}$, sample count N = 190) and high ($50\,\mathrm{cm\,s^{-1}}$-$110\,\mathrm{cm\,s^{-1}}$, sample count N = 167) speed data-sets. The two sub speed data-sets were analysed separately to capture possible differences in the assessment of the method's performance between low (sustained swimming speed of Atlantic salmon for longer duration) and high (critical swimming speed of Atlantic salmon for shorter duration) movement speeds [13]. The rms error using the averaging method was $5\,\mathrm{cm\,s^{-1}}$ (mean $-1.9\,\mathrm{cm\,s^{-1}}$, std. dev. $<4.7\,\mathrm{cm\,s^{-1}}$) for low and $10.1\,\mathrm{cm\,s^{-1}}$ (mean $-2.9\,\mathrm{cm\,s^{-1}}$, std. dev. $<9.7\,\mathrm{cm\,s^{-1}}$) for high speed data-sets respectively, implying that the error in measured speed for Atlantic salmon's sustained speed range was relatively lower than the overall

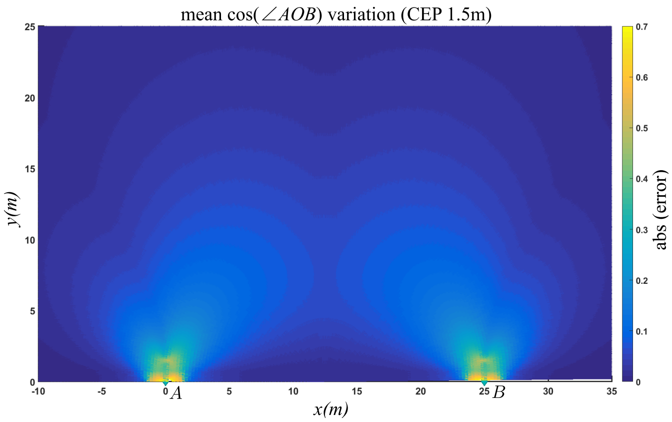


Fig. 8. Error in cosine value of $\angle AOB$ due to simulated variations in tag position. The error is relatively high close to the acoustic receivers (A and B), whereas it approaches to zero as the distance from the tag to the receivers increases.

speed range. Although the absolute error values were generally larger for higher than for lower movement speeds, the relative error vs speed ratio was almost constant at approximately 10% across all speeds. This implies that the method is consistent in deriving movement speeds and a robust approach for assessing underwater movement speeds. For low speed ranges, the averaging and modal methods had comparable error levels, while the modal method had larger errors for higher speed ranges. The averaging method therefore appeared to be most suitable for use in applications in sea-cages as it was acting as a filter, filtering out unwanted peaks at higher speeds. Both methods led to larger errors in the lab experiments than in the field trials. This can be attributed to very strong reflections and hence poor acoustic conditions, which are typical in tanks of relatively small volume [1].

The error was lower in the fish cage experiments than in the fjord based experiments for all speeds. This is probably because acoustic reflections had a larger impact during the fjord experiments than in the sea-cages. When applying the Doppler shift based technique, it is ideal to use only the first pulse arriving after signal emission for speed measurements, as this reduces the chance that multipathing will affect the results. In a real-world scenario such as a fjord or sea-cage environment, additional pathways of signal arrival may arise due to acoustic reflections from the surface, the seabed and other structures in the water column. This can potentially cause errors in the speed calculations [5]. Surface reflections can generally not be avoided when applying acoustic telemetry in aquaculture, as fish production is predominantly conducted in the upper parts of the water column, and will thus be a constant source of error. However, it is possible to avoid or reduce the impacts of bottom reflections and reflections from other structures by simply increasing the depth and the distance to those other structures, respectively. Increased distances will result in reflections that are both heavily attenuated and arrive more delayed at the receiver. While the fjord based experiments were conducted very close to shore at a depth of around 8 m, the fish cage experiments were conducted in a cage located several hundred meters from shore with a water depth of 75 m to 100 m under the farm. These conditions are typical for marine fish farming sites, and were probably instrumental in reducing the effects of reflections from the bottom and the coastline.

Apart from the surface, bottom and nearby structure reflections, the acoustic signal would also reflect from the fish/biomass present in the sea-cage. The fish cage experiments were performed inside a sea-cage stocked with approximately 200,000 animals. The 10% relative error in measured speed for the fish cage experiments implies that the Doppler principle works reliably under the realistic scenarios it is targeted for. The experiments in this study were performed by using only one acoustic tag at a given time. In a practical fish behaviour monitoring study, multiple fish would be tagged in a single fish cage. In such a multi-tag situation, the acoustic receivers would differentiate the overlapping signals by first processing the received signals in time domain to decode ID. Afterwards, the receivers would perform FFT to measure speed of the tagged fish corresponding to the decoded tag ID using the Doppler principle.

The duration of the individual pulses comprising a signal burst is an important parameter in determining the resolution of the DSF method ([11] Eq. 24). By inserting the typical pulse duration of commercial off the shelf acoustic tags (10 ms) into this equation, a maximum speed resolution of $100\,\mathrm{cm\,s^{-1}}$ is predicted. This means that it is impossible to monitor common swimming speeds of farmed fish using a 10 ms pulse length, as these are predominantly lower than $100\,\mathrm{cm\,s^{-1}}$. By using a pulse duration of 128 ms (as used in these experiments) in the same equation, a resolution of $8\,\mathrm{cm\,s^{-1}}$ is obtained. Based on these theoretical observations and the outcomes from the present study, it is thus reasonable to conclude that the pulse duration should be at least 100 ms when aspiring to use DSF to measure the swimming speeds of farmed fish.

The simulated speed errors when positioning was subjected to a known error were relatively high when the simulated tag was placed closer to acoustic receivers but reached to zero for tag positions further away from the receivers (Fig. 8). This suggests that it might be reasonable to use the receivers furthest away from the current tag position to compute speeds, implying that it might be useful to have more receivers than strictly needed in a particular setup. For instance, this can be realised for the 2D-speed case, by using three receivers for both TDoA positioning and frequency, as the acoustic receiver pair furthest away from the tag could then be used for speed computations.

V. Conclusion

The proposed Doppler shift based speed measurement technique was proven to be a promising method for measuring fish swimming speed in a marine aquaculture environment. An rms error of $5\,\mathrm{cm\,s^{-1}}$ for Atlantic salmon's sustained swimming speed i.e. $<50\,\mathrm{cm\,s^{-1}}$ makes the proposed technique a highly relevant tool for measuring fish speeds, while rms errors less than $10\,\mathrm{cm\,s^{-1}}$ for speeds up to $100\,\mathrm{cm\,s^{-1}}$ proved that the technique can be used to reliably monitor fish close to their critical swimming speed. Experiments conducted inside a fully stocked fish cage also proved that the technique can be used for speed measurements on Atlantic salmon during commercial aquaculture production.

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Waseem Hassan received the B.E. degree in electronics from PNEC-NUST, Pakistan, in 2012, and the M.Sc. degree in embedded systems jointly from NTNU Norway and TU Kaiserslautern, Germany (Erasmus Mundus EMECS Program, 2016). He is currently pursuing the Ph.D. degree with the Department of Engineering Cybernetics, Norwegian University of Science and Technology (NTNU), Norway. His main research area is real-time acoustic fish telemetry for marine aquaculture applications. He has been working with the development of new sensing principles for measuring fish behavior and embedded systems for providing real-time support to the existing acoustic telemetry systems.

Martin Føre received the M.Sc. degree from NTNU in 2006 and the Ph.D. degree in individual-based modeling and monitoring of fish in sea-cages in 2011. He is currently an Associate Professor with the Department of Engineering Cybernetics, Norwegian University of Science and Technology (NTNU). His main research area is the application of cybernetic methods (e.g., instrumentation, control theory, modeling, simulation, and estimation) to challenges in the aquaculture industry. Some of the highlights of his research career thus far are his work on fish modeling and instrumentation, and his role in defining the Precision Fish Farming (PFF) concept.

Magnus Oshaug Pedersen received the bachelor’s degree in instrumentation with HIST in 2014. He is currently working as a Senior Engineer with SINTEF Ocean AS. During his career at SINTEF Ocean AS, he has played an important role in development of instrumentation solutions for the full-scale ACE test facility in Norway. He has prepared and performed instrumentation assignments at several locations, both for open and closed fish farming systems. He has in this way contributed to the development of methodology for data collection, which has been important to the researchers in their work. In this particular article, he developed the catamaran which was used during the experiments.

Jo Arve Alfredsen received the M.Sc. and Ph.D. degrees in engineering cybernetics in 1992 and 2000, respectively. He worked several years in the Maritime industry developing ship control systems. He is currently an Associate Professor in engineering cybernetics with the Department of Engineering Cybernetics, Norwegian University of Science and Technology (NTNU), with specialization in embedded systems design and applications to ocean biomonitoring and aquaculture control systems. His research interests are currently focused towards sensors, instrumentation and remote monitoring technology for observing processes and living resources in the ocean, and automation and control systems for aquaculture production.