A novel Doppler based speed measurement technique for individual free-ranging fish

Waseem Hassan, Martin Føre
Department of Engineering Cybernetics, NTNU
Trondheim, Norway
waseem.hassan,martin.fore@ntnu.no

Magnus Oshaug Pedersen
SINTEF Ocean AS
Trondheim, Norway
magnus.pedersen@sintef.no

Jo Arve Alfredsen
Department of Engineering Cybernetics, NTNU
Trondheim, Norway
jo.arve.alfredsen@ntnu.no

***Abstract*—A novel Doppler based speed measurement technique for free-ranging acoustically tagged fish was developed and validated through a field experiment in a marine aquaculture farm. For emulated swimming speeds in the range $25\,\mathrm{cm\,s^{-1}}$-$60\,\mathrm{cm\,s^{-1}}$, an rms error of $5\,\mathrm{cm\,s^{-1}}$ with a standard deviation of $4.7\,\mathrm{cm\,s^{-1}}$ was achieved, and with a relative error typically less than 10% of measured speed. The technique is designed to integrate easily with existing acoustic fish telemetry systems and requires only three hydrophones to determine swimming speeds. Measurement of fish swimming speed has a wide range of applications within fisheries sciences and may become a valuable tool for assessing fish behavior and performance in marine farms.**

***Keywords*—** Acoustic telemetry; Doppler measurement; marine aquaculture; signal processing; sensor phenomena

I. INTRODUCTION

Fish swimming arises from coordinated motion of various body systems and is a key parameter in understanding fish behavior, and more intrinsic properties such as energy expenditure, stress and hunger levels. Knowing the swimming speed of the fish can therefore be essential for improving farm management operations and animal welfare conditions in the marine aquaculture industry [2, 6, 12]. Fish swimming performance is possible to assess accurately in controlled laboratory trials [16], but such data may not reflect the true swimming speeds seen in free-ranging fish [13]. Achieving adequate speed measurements on fish in large marine fish farms is also considerably more challenging than in a confined laboratory setup.

Underwater speeds are often measured using acoustic instruments such as Acoustic Doppler Current Profilers (ADCPs) [10] and Acoustic Doppler Velocimeters (ADVs) [18], but these methods are unsuitable for measuring individual fish speeds. Other technologies such as split beam sonars [13] and camera solutions coupled with machine vision techniques [15] can estimate individual swimming speeds, but only for the group of fish that are within their field of view at any given time. None of these solutions are therefore able to track the speeds of specific individuals over time, which is essential to obtain individual data histories. Such data would facilitate more precise evaluations of e.g. the ultimate welfare impacts of being exposed to strong and sustained currents [8], as these are important to consider on the individual level [9]. This highlights the need for new technological tools to objectively assess individual swimming speeds in fish farms.

Acoustic telemetry is a monitoring method where individual animals are equipped with miniature electronic tags that contain an acoustic transmitter for wireless underwater data transmission and sensor circuitry for sensing relevant parameters in or near the fish [4, 17]. A typical acoustic telemetry system consists of acoustic transmitter tags and one or more matching acoustic receivers (i.e. specialized hydrophone devices that receive and decode acoustic signals emitted by the tags). Although this method has been used to measure behavior in aquaculture settings (e.g. depth [5], activity [2, 11]), no existing systems measure instantaneous fish swimming speed. Many acoustic telemetry systems employ modulation schemes where information is encoded in the time domain as the time interval between uniform acoustic pulses of fixed frequency and duration [14]. Transmitter movement will inevitably cause Doppler shifts in the carrier frequency of these pulses, potentially representing a novel approach to acquiring the swimming speeds of individual fish through frequency analysis of the received signals.

In this study, we propose a system for measuring individual fish speed using the Doppler shift in the carrier wave of acoustic transmitter tags. By using the already existing carrier wave, the method does not add complexity on the transmitter side or consume extra acoustic bandwidth. This keeps the most resource constrained end of the system (i.e. the tag) intact, while all signal processing to obtain the Doppler Shifted Frequency (DSF) is conducted by the less resource constrained acoustic receivers. A field experiment to validate the speed measurement principle was executed in a marine fish farm stocked with Atlantic salmon at commercial density.

II. MATERIALS AND METHODS

A. *Theory and Speed Computation Algorithm*

Relative motion between an acoustic source and a receiver will shift the acoustic frequency of the received signal through what is known as the Doppler effect. This effect is widely employed to calculate the speed and position of a moving source based on the DSF received by a stationary receiver. The method can be used as a reliable speed measurement tool if the position of the acoustic transmitter and the transmitted signal frequency are known since a closed form solution for speed based on DSF is then possible [1]. A DSF (f_d) relates to the transmitted source frequency (f_s) and the frequency (f_r) received at a receiver by:

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

A DSF can have both positive and negative values, with positive values meaning that the transmitter is moving towards the receiver while a negative DSF implies movement away from a receiver. Since a DSF is proportional to the velocity component parallel to the direct line between receiver and transmitter, the angle between the velocity vector and this line (θ_s) needs to be considered. The relationship between transmitter speed relative to a stationary receiver (v_s) and the resulting DSF (f_d) is given by:

$$v_s = \frac{f_d c}{f_s cos\theta_s} \tag{2}$$

Where c is speed of acoustic signal inside propagation medium and f_s is the source frequency. Equation 2 can thus be used to calculate v_s for a moving source if θ_s and f_d are known. To illustrate how this method works, a case of 2D ($xy-$plane) speed extraction is shown in Fig. 1. An acoustic transmitter tag at position O is moving with velocity v_s at an angle θ_s with respect to the local $x-$axis.The first step in calculating v_s is to find the angles θ_A and θ_B between the velocity vector and the lines between the receivers at positions A and B and the tag. Based on the known positions O, A and B it is possible to find the angle $\angle AOB$, which relates to θ_A and θ_B as:

$$\angle AOB = \theta_B - \theta_A \tag{3}$$

Once $\angle AOB$ is known, θ_A and θ_B can be obtained by applying (2) and the measured DSFs f_{dA} and f_{dB} to each of the acoustic receivers separately along with (3). θ_A is then found as:

$$\theta_A = atan(\frac{cos(\angle AOB) - \frac{f_{dB}}{f_{dA}}}{sin(\angle AOB)}) \tag{4}$$

, while θ_B is found by inserting (4) into (3). Assuming that the acoustic telemetry systems use a fixed known transmission frequency (f_s), v_s can be calculated from (2), by inserting θ_A and f_{dA} or θ_B and f_{dB} to obtain the components along lines AO and BO, respectively. The angle θ_s can then be found as:

$$\theta_s = 360° - \theta_B - \angle BOX \tag{5}$$

In the case shown in Fig. 1, the velocity vector is in the 2^{nd} quadrant, however $\angle AOB$ can be found using the same angle difference equation (3) in the other three quadrants as long as angles are similarly defined in a counter-clockwise manner. The position of the acoustic tag must be known for this method to work, which may pose a challenge when the tag is carried by a fish. However, if a third receiver, as indicated by C in Fig. 1, is used, a hyperbolic Time Difference of Arrival (TDoA) approach can be used to obtain tag position if all three receivers have known positions A, B and C and are time synchronized [7, 14].

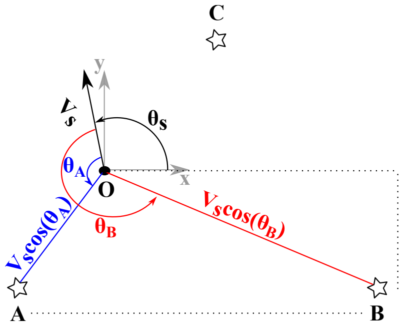

Fig. 1. A transmitter tag located at O moving with a velocity $\vec{v_s}$ in the horizontal plane. The Doppler shift measured at receiver locations A and B will be proportional to the components of the transmitter speed v_s along the lines AO and BO, respectively, defined by the angles θ_A and θ_B. A third receiver at location C enables TDoA-based transmitter localization.

B. Experimental Setup

A field experiment was conducted inside a large-scale fish cage containing Atlantic salmon to validate the proposed speed measurement technique in a relevant environment. A custom-made acoustic tag generating an acoustic burst signal at $68.968\,\mathrm{kHz}$, representative of frequencies typically employed in acoustic fish telemetry systems, was used in the experiment. The tag was mounted to a rod attached to a small remotely controlled catamaran, placing it at a constant depth of $1\,\mathrm{m}$. The catamaran was moved with speeds in the range of $25\,\mathrm{cm\,s^{-1}}$-$60\,\mathrm{cm\,s^{-1}}$, which is similar to sustained swimming speeds commonly observed in Atlantic salmon [8], thus emulating fish movement. Movement trajectories were kept circular to generate a data-set where the tag position varied sufficiently to cover a wide range of geometries, and where the velocity vector covered all possible directions relative to the hydrophones. A Real Time Kinematics (RTK) GPS with position accuracy of $< \pm 5cm$ was employed to determine the exact position and speed of the tag and was used as ground truth for the Doppler speed calculations. In this case, the GPS position was also used as a substitute of TDoA based localization of the tag to calculate $\angle AOB$, θ_A and θ_B. An embedded computer installed in the catamaran synchronized the transmission of the acoustic pulses with the RTK GPS positions and stored continuous records of reference data. Three icListen HF recording hydrophones (Ocean Sonics Ltd., Nova Scotia, Canada) were placed at $1\,\mathrm{m}$ depth in a configuration similar to that of A, B and C in Fig. 1, and were set to record the acoustic signal at a sampling rate of $256\,\mathrm{kS\,s^{-1}}$. The data from the hydrophones were processed in Matlab (The MathWorks, Inc., Natick, Massachusetts, USA) using Fast Fourier Transform (FFT), and the average value of DSF peaks for each pulse in a single burst was applied in the speed calculations.

III. RESULTS

A mean error of $-1.9\,\mathrm{cm\,s^{-1}}$ with a standard deviation of $4.7\,\mathrm{cm\,s^{-1}}$ and an rms error of $5\,\mathrm{cm\,s^{-1}}$ was achieved for all data-sets (190 samples), giving a relative error of 10% or less in the speed measurements. Fig. 2a shows normalized histograms of all true and measured speeds together with their respective probability distribution functions fitted to the normal distribution. The corresponding error distribution is shown in Fig. 2b.

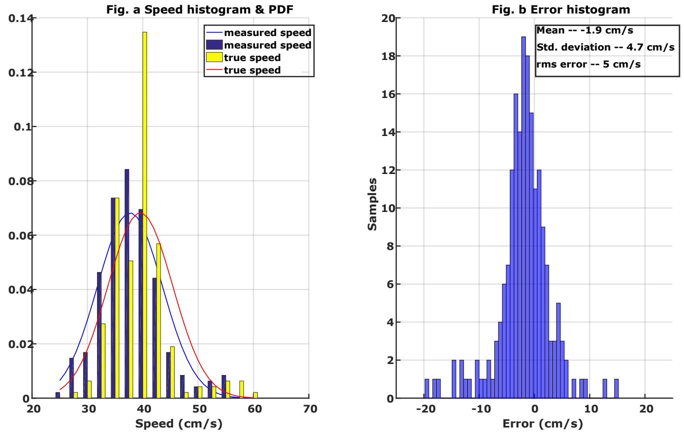

Fig. 2. (a) Speed distributions and histograms (b) error in measured and reference speed histogram.

IV. Discussion

The speed measured using the proposed Doppler based technique matched closely with the reference speed measurements from the RTK GPS. This study has therefore validated the feasibility of the proposed Doppler based technique as a method for measuring the horizontal swimming speed of acoustically tagged fish, either free-ranging or within the confines of a fish farm. Although the method needs an accurate characterization of the carrier frequency and its variability due to e.g. temperature fluctuations and drift, it requires no major modifications to the transmitter tags commonly used in commercial telemetry systems [5, 17]. This implies that the technique can extend the capabilities of existing solutions solely by adding the required signal processing capacity at the receiver end, either embedded as part of the real-time receiver function or as a post processing feature. The speed range selected for the experiment was motivated by wanting to cover swimming speeds typically observed in farmed Atlantic salmon during production, as this represents a prospective application area for the method [6, 8]. A relative measurement error of less than 10% throughout this range suggests that the technique may be applied reliably to characterize individual swimming speeds in salmon farms. The frequency resolution of the FFT analyses was set to $1\,\mathrm{Hz}$, yielding a speed resolution of $2.17\,\mathrm{cm\,s^{-1}}$. An rms error of $5\,\mathrm{cm\,s^{-1}}$ thus indicates that speed was measured with an accuracy close to the resolution of the system. To benefit from future improvements in accuracy, a higher resolution FFT would be required. However, increasing measurement accuracy in this way would represent a trade-off against availability of computing resources and energy efficiency on the receiver side. TDoA positioning systems will typically be necessary to obtain the position of a tag when it is carried by a fish. Such systems have a resolution/Circular Error Probability (CEP) in range of a few meters down to $1\,\mathrm{m}$ [7, 14]. Since $\angle AOB$ is estimated by using arc tangent of the ratio of distances OA and OB, this resolution may also impact the accuracy of the Doppler method. Errors in $\angle AOB$ due to imprecise position will be highest when the distances OA and OB (Fig. 1) are short, as even small errors ($1\,\mathrm{m}$ or less) then will strongly affect the angle estimate. However, assuming that the resolution/CEP value is kept constant, increasing distances OA and OB will gradually reduce the impact of this effect on the estimated $\angle AOB$, as the ratio between OA and OB and the potential error would then decrease. Since the Doppler based speed measurement principle requires only two acoustic receivers for speed measurement, whereas TDoA employs three or four receivers, the error due to variation in tag's position can be avoided in speed measurement by selecting the receivers having longest OA and OB distances. Moreover, although the proposed speed measurement technique has been outlined and demonstrated for the horizontal case, it could readily be extended to accommodate 3D speeds by including a third hydrophone. This could be done without requiring any principal changes to the derivation of the algorithm in itself, underlining the suitability of combining this method with TDoA. An underlying assumption for the measurement technique presented here is that the acoustic wave travels in a direct path between transmitter and receiver. However, in a real-world applications, acoustic waves are subject to multipath propagation and various fading effects that may arise at the receiver end [3]. Doppler spread caused by strong and moving reflectors could potentially have detrimental effects on the accuracy of the speed measurements. Although some such effects can be avoided, reflections from the sea surface will often occur in acoustic telemetry applications since the fish often reside near the surface. Surface reflections did not appear to contribute significantly to the measurement error in the present study, however error contribution due to reflections may be more substantial during rough or less calm sea conditions that what was the case during the experiment.

V. Conclusion and Future work

This study demonstrates the feasibility of using Doppler shift measurements on acoustic tag signals to determine the movement speeds of individual fish. An rms error of $5\,\mathrm{cm\,s^{-1}}$ with a relative error of less than 10% was achieved for a speed range relevant for farmed Atlantic salmon. This suggests that the technique can be used to study individual swimming behavior of fish in large-scale fish farms, observations that otherwise would be hard to obtain. Finally, the proposed method requires minimal modifications of existing tag designs as the speed measurements are extracted solely based on the acoustic carrier wave, allowing easy integration with existing telemetry systems. Future work will include testing of the system close to Atlantic salmon critical swimming speeds [8] and a test involving live fish in a large-scale fish farm to investigate the properties and long-term robustness of the method as scientific tool for studying swimming behaviour in fish.

ACKNOWLEDGMENT

The authors would like to thank the NTNU-ITK mechanical workshop for their help on the mechanical setup of the experiment. This work was funded by the Norwegian Research Council through the Centre for research-based innovation in Exposed Aquaculture Technology (grant number 237790).

REFERENCES

[1] Y. T. Chan and J. J. Towers. Passive localization from doppler-shifted frequency measurements. *IEEE Transactions on Signal Processing*, 40(10):2594–2598, Oct 1992.

[2] S. J. Cooke, E. B. Thorstad, and S. G. Hinch. Activity and energetics of free-swimming fish: insights from electromyogram telemetry. *Fish and Fisheries*, 5(1):21–52, 2004.

[3] B. G. Ferguson. Doppler effect for sound emitted by a moving airborne source and received by acoustic sensors located above and below the sea surface. *The Journal of the Acoustical Society of America*, 94(6):3244–3247, 1993.

[4] M. Føre, J. A. Alfredsen, and A. Gronningsater. "Development of two telemetry-based systems for monitoring the feeding behaviour of Atlantic salmon (Salmo salar L.) in aquaculture sea-cages". *Computers and Electronics in Agriculture*, 76(2):240 – 251, 2011.

[5] M. Føre, K. Frank, T. Dempster, J. Alfredsen, and E. Høy. Biomonitoring using tagged sentinel fish and acoustic telemetry in commercial salmon aquaculture: A feasibility study. *Aquacultural Engineering*, 78:163 – 172, 2017.

[6] M. Føre, K. Frank, T. Norton, E. Svendsen, J. A. Alfredsen, T. Dempster, H. Eguiraun, W. Watson, A. Stahl, L. M. Sunde, C. Schellewald, K. R. Skøien, M. O. Alver, and D. Berckmans. Precision fish farming: A new framework to improve production in aquaculture. *Biosystems Engineering*, 173:176 – 193, 2018. Advances in the Engineering of Sensor-based Monitoring and Management Systems for Precision Livestock Farming.

[7] W. Hassan, M. Føre, H. A. Urke, T. Kristensen, J. B. Ulvund, and J. A. Alfredsen. System for Real-time Positioning and Monitoring of Fish in Commercial Marine Farms Based on Acoustic Telemetry and Internet of Fish (IoF). *(Accepted, 29th International Society of Offshore and Polar Engineers (ISOPE) conference)*, June 2019.

[8] M. Hvas and F. Oppedal. Sustained swimming capacity of atlantic salmon. *Aquaculture Environment Interactions*, 9:361–369, 2017.

[9] K. E. Jónsdóttir, M. Hvas, J. A. Alfredsen, M. Føre, M. O. Alver, H. V. Bjelland, and F. Oppedal. Fish welfare based classification method of ocean current speeds at aquaculture sites. *Aquaculture Environment Interactions*, 11:249–261, 2019.

[10] P. Klebert, Øystein Patursson, P. C. Endresen, P. Rundtop, J. Birkevold, and H. W. Rasmussen. Three-dimensional deformation of a large circular flexible sea cage in high currents: Field experiment and modeling. *Ocean Engineering*, 104:511 – 520, 2015.

[11] J. Kolarevic, Ø. Aas-Hansen, Å. Espmark, G. Baeverfjord, B. F. Terjesen, and B. Damsgård. The use of acoustic acceleration transmitter tags for monitoring of Atlantic salmon swimming activity in recirculating aquaculture systems (RAS). *Aquacultural Engineering*, 72-73:30 – 39, 2016.

[12] F. Oppedal, T. Dempster, and L. H. Stien. Environmental drivers of atlantic salmon behaviour in sea-cages: A review. *Aquaculture*, 311(1):1 – 18, 2011.

[13] J. Pedersen. Hydroacoustic measurement of swimming speed of north sea saithe in the field. *Journal of Fish Biology*, 58(4):1073–1085, 2001.

[14] D. G. Pincock and S. V. Johnston. Acoustic telemetry overview. In N. S. Adams, J. W. Beeman, and J. H. Eiler, editors, *Telemetry Techniques: A User Guide for Fisheries Research*, pages 305–308. American Fisheries Society, Bethseda, Maryland, 2012.

[15] T. Pinkiewicz, G. Purser, and R. Williams. A computer vision system to analyse the swimming behaviour of farmed fish in commercial aquaculture facilities: A case study using cage-held atlantic salmon. *Aquacultural Engineering*, 45(1):20 – 27, 2011.

[16] M. Remen, F. Solstorm, S. Bui, K. Pascal, T. Vågseth, D. Solstorm, M. Hvas, and F. Oppedal. Critical swimming speed in groups of atlantic salmon salmo salarã?â? *Aquaculture Environment Interactions*, 8:659–664, 2016.

[17] C. Rillahan, M. Chambers, W. H. Howell, and W. H. Watson. A self-contained system for observing and quantifying the behavior of atlantic cod, gadus morhua, in an offshore aquaculture cage. *Aquaculture*, 293(1):49 – 56, 2009.

[18] P. Rundtop and K. Frank. Experimental evaluation of hydroacoustic instruments for rov navigation along aquaculture net pens. *Aquacultural Engineering*, 74:143 – 156, 2016.