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The Feasibility of Doppler Sonar Fish Counting

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***Abstract*—In the course of monitoring and evaluating fish population in the seas, sonar systems have proved a practical and efficient measurement approach. The results obtained, however, from the use of sonar for monitoring fish migration in rivers have been somewhat disappointing—the most troublesome problems being the inability to recognize invalid targets. It has been proposed [1] that a high-resolution Doppler sonar which recognizes a valid target on the basis of its Doppler signature would be a solution to this problem.**

This paper examines the feasibility of such a target identification scheme. In particular, an examination is made of the nature of returns to be expected from a fish, and of interference sources—principally surface reverberation. From this it is concluded that the Doppler approach is indeed feasible, but that the use of a high-resolution pulsed system capable of separating multiple targets is only possible in a channel width of a few meters.

I. INTRODUCTION

IN THE MANAGEMENT and forecasting of population densities of such anadromous species of fish as salmon, it is extremely useful to be able to count the number of fish passing a given point in a river. Counting fences or similar devices where all of the fish migrating in a river are trapped, counted, and classified before being permitted to continue their journey are expensive to install and maintain, as well as often being very unpopular.

Various automatic methods of counting exist [2] but most of these suffer from the disadvantage that the fish are forced to pass through a small opening, perhaps one meter or less in diameter. At least two sonar systems have been described which overcome this problem [3], [4] and, while these have on occasion produced useful results, a continuing problem is the incidence of false counts due to such factors as debris, air bubbles, surface roughness, and bottom irregularities. The elimination of such false counts is relatively difficult because, as sonar targets, fish have few discernible characteristics.

Braithwaite [1] has suggested that an approach which identifies fish by means of the tailbeat-induced Doppler shift in the return could be useful. Unfortunately, in his experimental system, problems were often experienced in separating the Doppler return from reverberation. Because of this difficulty, enthusiasm for the use of such techniques has waned.

It is the purpose of this paper to examine the nature of signal and reverberation to be expected in a fish-counting Doppler sonar and, hence, show the conditions under which separation is possible. In this way, the feasibility of a Doppler sonar counter for a particular application can be determined.

II. TARGET FREQUENCY COMPONENTS

The signal of interest here is the sonar return from the tail of a fish. To maximize the Doppler shift in this return, insonification should be arranged so as to be directly from the side.

Extending standard results for Doppler shift due to moving sources and receivers to the case of reflection from a moving object, one obtains

$$f_o = f_s\left(1 + \frac{2V_t}{c}\right)\cos\theta \tag{1}$$

in which f_s is the frequency emitted by the source, f_o is the observed Doppler frequency, V_t is the target velocity, c is the velocity of propagation of the sound, and θ is the angle between the beam axis and the direction of target motion (i.e., $\theta = 0$ corresponds to motion directly towards or away from the source/receiver).

In order to be useful, the expected Doppler deviation must be expressed in terms related to the fish and its swimming speed. Since the tail speed increases to a maximum constant velocity as the tail approaches the centerline of the fish and decreases after the axis is crossed, the motion may, to a first approximation, be described as sinusoidal. For side-aspect insonification, $\cos\theta$ in (1) is unity, and hence, the maximum Doppler shift, which occurs as the tail crosses the centerline, is

$$f_m = \frac{4\pi A_t f_t}{C} f_s \tag{2}$$

in which A_t is the peak amplitude and f_t is the frequency of the tailbeat.

From the work of Bainbridge [5], which established relationships between tailbeat amplitude, frequency, and swimming speed, one can infer that the tailbeat frequencies between 5 and 15 Hz are most likely for fish up to 1 m in length. Fig. 1, which shows the results of calculations combining the Bainbridge relationships with (2), can be used to predict the maximum Doppler shift due to the tailbeat of a particular fish.

III. REVERBERATION SPECTRUM

Because the rivers and streams being monitored are typically shallow, returns from the bottom and surface are inevitable. While reflections from the bottom and other fixed targets

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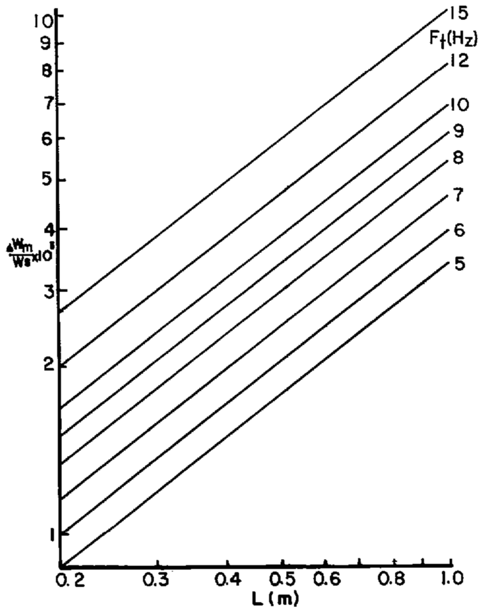

Fig. 1. Relationship between fish length, tailbeat frequency, and maximum Doppler shift.

can be readily rejected because of their lack of frequency shift, surface returns shifted by wave motion can cause problems. Although other factors, such as internal motion of the medium, could also produce Doppler reverberation, the water surface is the main contributor to acoustic variability. Consequently, the strength and frequency spectrum of these returns must be evaluated.

The spectrum of surface returns consists of a Doppler shift due to the velocity of the wind-driven waves, and a spectral broadening about this shift due to surface roughness.

Equation (1) is also valid for the Doppler shift due to waves. Using the expression for wave velocity given by Kinsman [6] and the fact that acoustic waves are only scattered significantly by surface roughness of a length scale comparable to acoustic wavelength [7], one obtains

$$\Delta f = \frac{2\cos\theta}{\lambda}\left(\frac{g\lambda}{4\pi\cos\theta} + \frac{4\pi S\cos\theta}{\rho\lambda}\right)^{1/2} \tag{3}$$

in which g is the gravitational acceleration, ρ is the density of water, and S is the surface tension of water (0.083 N/m for fresh water at 20°C). The maximum value of the shift given by (3) occurs for a wave motion parallel to the acoustic axis ($\theta = 0$); this is plotted as a function of frequency in Fig. 2. Two remarks should be made concerning the above result.

1) The dependence of the Doppler shift on source frequency is not linear because, as the frequency changes, reflection occurs from a different ripple train with a different phase velocity.

2) The sole effect of wind here is to govern the propagational direction of the ripple train.

Sound waves scattered by the surface, in addition to being shifted as a result of the propagational velocity of surface ripple, incur spectral broadening as a result of the up-and-down motion of this ripple on top of the larger high-speed waves. Assuming a sinusoidal particle motion of these larger waves of amplitude A and period T, the maximum Doppler spread Ω_m on either side of the Doppler shift can be determined from (2).

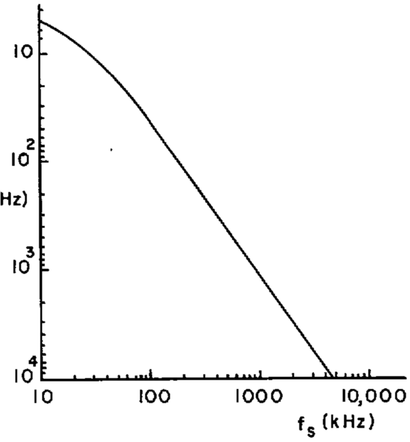

Fig. 2. Doppler shift in surface returns as a function of transmission frequency.

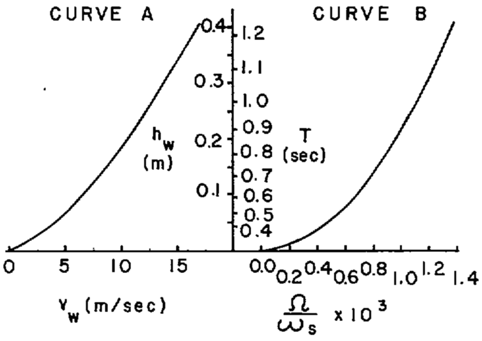

Fig. 3. Frequency spreading in surface returns as a function of wind speed.

$$\Omega_m = \frac{4\pi A}{T}\frac{W_s}{C}. \tag{4}$$

As would be expected, measurements made in a tank [8] confirming the validity of (4) showed that specular reflection in which a considerable amount of energy was concentrated at Ω_m was observed when the surface wavelength was considerably larger than the acoustic wavelength. Otherwise, the scattering was diffuse with the spectrum level being about 20 dB down at Ω_m. The shape of the spectra was consistent with that given by Barlow for radar clutter targets [9].

To use the results of (4), it is necessary to relate wave amplitude and period to wind, the prime element in generating and maintaining wave motion. Combining the results obtained by Garrison *et al.* [10] relating wave height and wind speed in sheltered waters with the limit in amplitude a wave of given period can attain [11], one obtains the results plotted in Fig. 3 which can be used to provide an indication of the degree of Doppler spreading for a given wind speed. When the wave height corresponding to a particular speed is obtained on curve A, a horizontal line can be projected to curve B to determine the maximum normalized Doppler spread.

IV. SYSTEM CONSIDERATIONS

A. Separation of Target From Reverberation

To detect target Doppler, returns should be zero beat by mixing with the transmission frequency. The operation of a simple zero-beating receiver developed early in this research to verify Fig. 3 proved perfectly satisfactory [8]. The Doppler shifts which would be experienced at the output of such a receiver are summarized for typical transmission frequencies in Table I.

In Table I, it is assumed that the system is sited such that fish will have to maintain at least the relatively modest tailbeat frequency of 5 Hz. Of course, for the maximum target Doppler shifts to be experienced, the beamwidth and pulse repetition rate must be such that a return corresponding to the tail crossing the centerline is assured. Information on the reverberation spectrum is given for two situations: that in which the wind-waveheight relationship is as in curve *A* of Fig. 3 with a maximum wind velocity of 15 m/s (30 knots), and the case of a very narrow channel in which the possibility of wave heights greater than 10 cm is assumed negligible. The upper limit of the reverberation spectrum is obtained by adding the Doppler shift (3) to the maximum Doppler spread (4).

It can be seen from Table I that superior separation of target and interference will result from the use of frequencies in the neighborhood of 30-100 kHz. This follows from the fact that the Doppler shift in the reverberation from the surface increases less rapidly than frequency up to this neighborhood and more rapidly thereafter (Fig. 2).

The ability to separate the target from reverberation depends on considerations other than transmission frequency alone. These are discussed below for both CW and pulsed systems.

B. CW Doppler Systems

Using a transmission frequency in the neighborhood of 30-100 kHz, it can be seen from Table I that fish down to 0.2 m long can be detected, provided that the target-to-reverberation level is sufficient.

Target strength can be estimated using the empirical relationship presented by Love [12] for maximum side-aspect target strength. Love's relationship should be modified by about 10 dB to account for the fact that, since contributions of body undulations to swimming are small [13], only the tail section making up roughly one third of the length of the fish is of interest. This gives

$$\mathrm{TS} = 24.1 \log L - 4.1\lambda - 35 \tag{5}$$

in which L and λ represent the length of the fish and the acoustic wavelength in meters. The validity of (5) was verified by a limited set of measurements using an Atlantic salmon [8].

TABLE I
TARGET AND REVERBERATION DOPPLER
FOR SOME TYPICAL CONDITIONS

		Transmission Frequency				
		30kHz	100kHz	300kHz	1000kHz	2500kHz
Maximum Doppler Shift (Hz) for Slowest Fish (f_t=5Hz)	L=1	120	400	1200	4000	10000
	L=0.5	60	200	600	2000	5000
	L=0.2	27	90	270	900	2250
Upper Limit of Reverberation Spectrum (Hz)	V_{wmax}=15	48	160	580	2250	8100
	h_{max}=0.1	30	100	400	1700	6500

TABLE II
PARAMETERS OF A PULSED DOPPLER SYSTEM SUITABLE FOR
A 5-m CHANNEL

Transmission frequency:	2.5MHz.
Beamwidth:	30°
Pulse width:	200 usec (Resolution = 30cm)
Pulse repetition rate:	100 Hz
Maximum two-way transmission loss:	49 dB
Maximum Doppler shift for 0.5 m fish with f_t = 5H_z:	5 kHz
Maximum shift in reverberation spectrum:	6.5 kHz

Useful predictions of reverberation level cannot be presented for the continuous case, because reverberation will be experienced continuously from all parts of the surface insonified. Therefore, the level will depend critically on the positioning of the transducer and shaping of the sonar beam with, for example, a side lobe striking the surface near the transducer making a far greater contribution than the main lobe insonifying a larger surface but at a greater range. Therefore, *in situ* testing is necessary.

C. Pulsed Doppler Sonar System

In addition to allowing the recognition of multiple targets, a pulsed system has the advantages of a lower reverberation level and of permitting the use ot time-varying gain to allow easier signal processing.

The penalty paid for these advantages is a decrease in range capability except in those cases in which very-low resolution is required. The reason for this is that high transmission frequencies are necessary to avoid aliasing problems which will arise unless the target Doppler shift exceeds the bandwidth of the transmitted pulse. For example, with a pulsewidth of 1 ms, corresponding to a relatively low resolution of 1.5 m, aliasing will occur unless the target Doppler shifts exceed 1 kHz. Thus in this case, a transmission frequency of over 1 MHz is required to detect 0.2-m fish (Table I). The use of such high transmission frequencies results in two difficulties: a reduction in the separation between echo and reverberation spectra (Table I), and a decrease in range capability because of excess absorption [14] (0.33 dB/m at 1 MHz, 33 dB/m at 10 MHz) causing, for any reasonable source level, both echo and reverberation to disappear into noise for targets at long range.

The use of pulsed systems, therefore, is limited to very narrow channels, either as found in fish ladder, weir, and counting fence constructions, or as a component of a system which uses several transducers spaced along the bottom of a stream.

1) Typical System Parameters: To give an idea of what is possible, Table II presents the significant parameters of a system suitable for monitoring the passage of fish from 0.5 to 1 m long in a 5-m channel, the tailbeat frequency of the fish being at least 5 Hz. The maximum wave height in the channel is assumed to be 10 cm.

In Table II, the beamwidth was chosen to ensure that the entire tail of fish 70 cm or more from the projector is insonified, and the repetition rate was chosen to ensure that the tailbeat is sampled sufficiently frequently during a period to ensure that shifts of 5 kHz or more are experienced for all fish. From Table II it is seen that, under the worst set of conditions (maximum wind along sonar axis, small fish swimming with minimum tailbeat frequency), the reverberation spectrum will contain some energy slightly beyond the maximum Doppler shift. There will be no problem, however, in detecting the echos with a bandpass filter followed by a threshold test since, as is shown below, the echo-to-reverberation level is significantly greater than 0 dB.

Echo-to-Reverberation Ratio Estimate: Provided that source level and grazing angles are low enough that multiple reflections do not produce significant returns except from the surface area immediately above the target, the reverberation level (RL) can be calculated from

$$\mathrm{RL} = S_s + 10 \log \left(\frac{c\tau_w}{2} R\phi \right) \tag{6}$$

in which S_s is the surface scattering strength, τ_w is the insonification pulsewidth, R is the range to the target, and ϕ is the sonar beamwidth (assumed small). To estimate S_s in (6), the experimental determination of surface scattering strength for high frequencies carried out by Garrison *et al.* [10] is most appropriate. Thus for grazing angles between 10 and 80°, Garrison's findings may be approximated by

$$S_s = 56 \log \nu_w - 80 \tag{7}$$

in which ν_w is the wind velocity in m/s. This relationship is valid for wind speeds up to about 7.5 m/s (15 knots; $S_s = -31$); above this speed scattering strength varies little. By carefully positioning the sonar beam, it may be possible to ensure surface grazing angles of less than 10° causing (7) to be overly pessimistic.

Using (5) to calculate target strength and (6) to calculate reverberation level, the echo-to-reverberation ratio is found to at least 6 dB for the worst conditions (0.5-m fish at a 5-m range) with the system parameters of Table II. In fact, the relationship of (5) was developed to approximate target strength in the region $1 < L/\lambda < 100$. For larger values of L/λ, such as would be the case for the transmission frequency suggested in Table II, experimental data are sparse. The important thing, however, is that target strength increases more rapidly with frequency (proportional to $1/\lambda^2$ [15]) than is indicated by (5). Therefore, (5) gives a pessimistic estimate of target strength, and a minimum echo-to-reverberation ratio of even greater than 6 dB will be achieved.

V. CONCLUSION

We have analyzed echo and interference characteristics to arrive at two important conclusions with regard to the use of Doppler sonar for fish counting. The first is that with a CW system, targets will be most easily detected through the use of a transmission frequency in the range of 30-100 kHz. The second is that with a pulsed system, high resolution necessitates a high transmission frequency. This limits the use of high-resolution pulsed systems to channels a few meters wide.

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