ICES Journal of Marine Science, 60: 524–531. 2003
doi:10.1016/S1054–3139(03)00032-8

Inferring fish orientation from broadband-acoustic echoes

Timothy K. Stanton, D. Benjamin Reeder, and J. Michael Jech

Stanton, T. K., Reeder, D. B., and Jech, J. M. 2003. Inferring fish orientation from broadband-acoustic echoes. – ICES Journal of Marine Science, 60: 524–531.

A new method has been developed for inferring the orientation of fish through the use of broadband-acoustic signals. The method takes advantage of the high range resolution of these signals, once temporally compressed through cross-correlation. The temporal resolution of these compressed signals is inversely proportional to the bandwidth, thus the greater the bandwidth the higher the resolution. This process has been applied to broadband-chirp signals spanning the frequency range 40–95 kHz to obtain a range resolution of approximately 2 cm from the original, unprocessed resolution of about 50 cm. With such high resolution, individual scattering features along the fish have been resolved, especially for angles well off normal incidence. The overall duration of the compressed echo from live, individual alewife, as measured in a laboratory tank, is shown to increase monotonically with orientation angle relative to normal incidence. The increase is due to the greater range separation relative to the transducer between the echoes from the head and tail of the fish. The results of this study show that with *a priori* knowledge of the length of the fish, the orientation could be estimated from the duration of a single, compressed broadband echo. This method applies to individual, acoustically resolved fish. It has advantages over previous approaches because it derives the orientation from a single ping and it does not use a formal, mathematical scattering model. Design parameters for applications in the ocean are given for a range of conditions and fish size.

Keywords: acoustic scattering, broadband acoustics, fish.

T. K. Stanton, and D. B. Reeder: Department of Applied Ocean Physics and Engineering; Woods Hole Oceanographic Institution, 98 Water Street, MS #11; Woods Hole, MA 02543, USA. J. M. Jech: Northeast Fisheries Science Center; 166 Water Street; Woods Hole, MA 02543, USA; tel: +1 508 495 2353; fax: +1 508 495 2258; e-mail: michael.jech@noaa.gov. Correspondence to T. K. Stanton; tel: +1 508 289 2757; fax: +1 508 457 2194; e-mail: tstanton@whoi.edu.

Introduction

It is important to know the distribution of the orientations of free-swimming fish for two reasons. First, the orientation distribution of fish correlates with the type of behavior the animal is exhibiting, such as feeding or migrating. Knowledge of the orientation distribution under a variety of conditions will therefore contribute to the fundamental understanding of animal behavior. Second, acoustics is commonly used as a means to survey fish rapidly and synoptically. Since acoustic scattering depends strongly upon the orientation of the fish, knowledge of its distribution will help to quantify interpretation of the acoustic-survey data.

Measurement of the orientation of fish is a challenge. The most direct method involves use of cameras (Huse and Ona, 1996). However, this is logistically difficult, involves a small sampling volume, and can induce avoidance reactions that would contaminate the data. Acoustic-scattering techniques are less invasive and involve a much larger sampling volume. One acoustical method has involved tracking individual fish over multiple pings, either directly or through echo-trace analysis, and equating orientation angle to swim angle (Furusawa and Miyanohana, 1990; Ona, 2001). Another method has involved inferring the orientation, or its distribution, from the scattering data using an assumed scattering model (Foote and Traynor, 1988; Chu *et al.*, 1993; Martin Traykovski *et al.*, 1998).

Clearly, it is most desirable, if possible, to use a synoptic, non-invasive method to measure orientation with the fewest assumptions and least data. Broadband-acoustic signals offer advantages for the inference of orientation. A genuinely broadband signal, i.e. one with a bandwidth of approximately one octave or greater, is rich with information as it spans continuously a broad range of frequencies. Because of this inherent property, there is potential for reducing the number of ambiguities in the interpretation of the data. The challenge is in the selection of the optimal approach.

1054–3139/03/000524+08 $30.00

In this paper, we propose a new method that uses broadband-acoustic signals to infer remotely the orientation of individual fish. We take advantage of a pulse-compression technique in which the duration of the received echo is reduced significantly so that individual features of the fish can be resolved in the time domain (Chu and Stanton, 1998; Stanton *et al.*, 1998). The orientation of the fish can be estimated through simple, geometric arguments and *a priori* knowledge of the length of the fish. The information on the (resolved) fish can be extracted from a single ping. Although a formal, mathematical-scattering model is not required in the analysis, it is assumed that there are scattering features distributed along the entire length of the fish and centered about the lengthwise axis of the fish. These features need to produce echoes of sufficient strength for detection. We present broadband (40–95 kHz), acoustic-backscattering data collected in the laboratory, where the scattering was measured as a function of the angle of orientation for a number of individual fish. The duration of the series of detectable, compressed echoes for each ping is shown to increase monotonically with the angle of orientation over a wide range of angles. Furthermore, the echoes are linked directly to scattering features along the length of the fish. A simple, geometry-based equation is used to describe this relationship and is used to predict sonar performance for a range of system parameters for use in the ocean.

Pulse-compression processing of broadband signals

Basic properties

The pulse-compression processing used here has been applied to acoustic-backscattering data involving fish by Ehrenberg and Torkelson (2000) and Reeder *et al.* (accepted for publication), and to zooplankton backscattering data by Stanton *et al.* (1998) and Chu and Stanton (1998). The processing is based on, and is quite similar to, the commonly used, matched-filter processing. Matched-filter processing was developed to optimize the detection of a known signal in the presence of random noise (Turin, 1960). It has since been used in a variety of applications, including acoustic propagation and scattering in the ocean (Medwin and Clay, 1998). In the matched-filter approach, the noisy signal is cross-correlated with the known or noiseless signal. Given sufficient bandwidth and a known signal of sufficient duration such as a chirp, matched-filter processing results in a signal with much higher amplitude and shorter duration than the original signal (Figure 1). The shape of the processed signal is characterized by a single, high-amplitude main lobe with smaller side lobes corresponding to artifacts of the processing. Since this process increases the amplitude of the signal but not the (non-reverberative) noise, the result of applying the matched filter to a noisy signal significantly increases the signal-to-noise ratio (SNR). Also, the width of the main lobe is inversely proportional to the bandwidth of the original signal, greatly increasing the possible temporal resolution. For example, the width of a processed 600-μs-long chirp signal spanning the frequency range 40–95 kHz is about 20 μs. For underwater-acoustic signals, this corresponds to an improvement in range resolution from about 50 cm to about 2 cm.

Application to acoustic scattering by marine life

There are significant advantages associated with processing broadband echoes in a manner similar to that of matched-filter processing. One, as discussed above, is that the SNR is improved, which allows detection of targets at greater ranges. Furthermore, the range resolution is improved, which allows targets at greater numerical densities to be resolved. The challenge lies in both the implementation of the algorithm and the interpretation of the processed signal. Since the target affects the properties of the incident acoustic wave because of its inherent scattering properties, the ideal, noiseless signal with which the received echo should be cross-correlated is not known. This problem has been addressed by simply using the transmission or calibration signal as the so-called “replicate” signal. The resulting “compressed pulse”, although different from what a true matched-filter would produce, has the same advantages of increased SNR and decreased duration, although to a lesser degree. The increase in SNR, using pulse-compression processing has been demonstrated both for fish (Ehrenberg and Torkelson, 2000; Reeder *et al.*, accepted for publication) and zooplankton (Chu and Stanton, 1998; Stanton *et al.*, 1998).

A useful consequence of the fact that the cross-correlated, scattered signal deviates from a matched filter is the information contained in that deviation. The resulting signal from a matched filter is a single, short spike with small side lobes (Figure 1, lower-right panel). The shape of this signal is what one would expect when the signal had been scattered by a target that is smaller than the compressed range resolution and possesses a uniform-frequency response. However, for an extended biological target, the cross-correlated, scattered signal will, in general, comprise a series of spikes corresponding to the various scattering features of the scattering object (Chu and Stanton, 1998; Stanton *et al.*, 1998; Barr, 2001; Reeder *et al.*, accepted for publication). These scattering features are resolved through the inherent increase in resolution of the cross-correlated signal and through an appropriate combination of bandwidth and animal size. Animals such as fish contain anatomical variations throughout the length of the body. These variations cause acoustic scattering and, for long pings, there are generally contributions from structure within the entire body to the total received (unprocessed) echo. Once the echo is compressed, echoes due to various features will be separated in time, especially for oblique

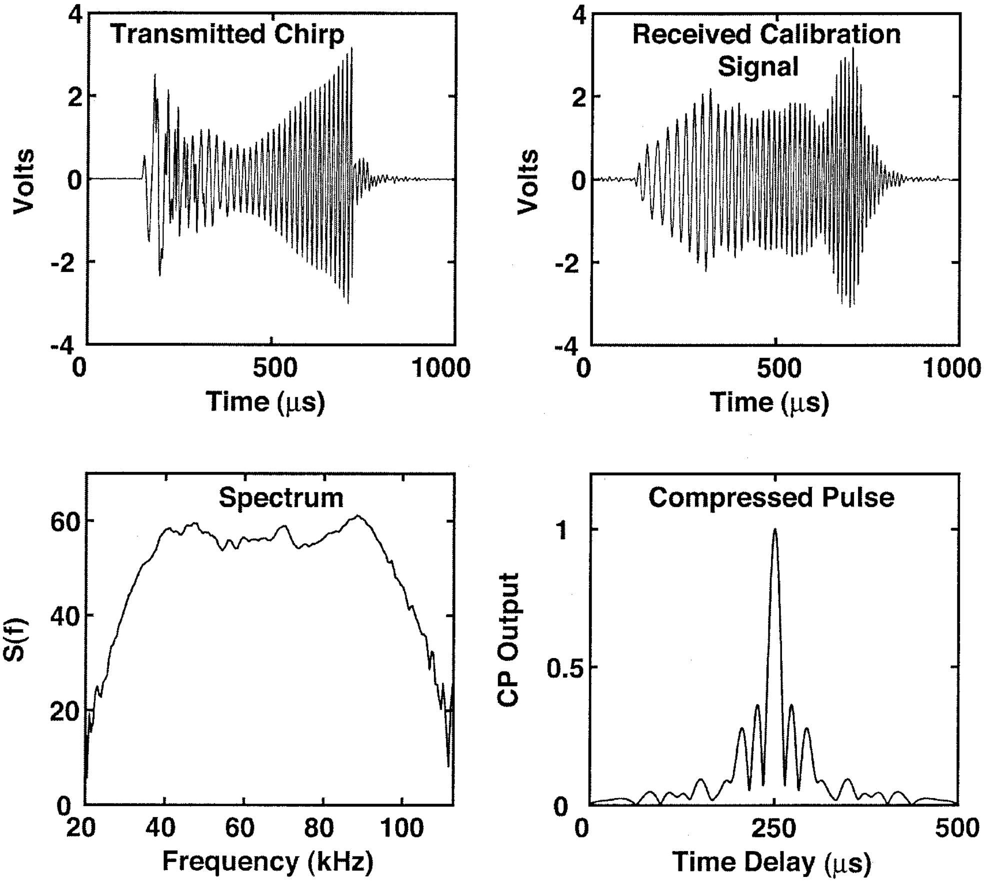

Figure 1. Broadband-acoustic signals. (Upper-left panel) Shaped, chirp signal as applied to the transmitting transducer. This signal was used in both the scattering and the calibration measurements. (Upper-right panel) Signal at output of the receiving transducer in the calibration setup with the transmitting transducer using the same signal as illustrated in the upper left panel and aimed at the receiving transducer. (Lower-left panel) Frequency spectrum of signal (in dB) at output of the receiver transducer in the calibration setup. (Lower-right panel) Envelope of the autocorrelation function, corresponding to matched-filter output, of the received signal from the upper-right panel. The great reduction in pulse duration of the compressed pulse relative to the applied chirp in the upper-left panel is illustrated. The amplitude is normalized to unity.

angles (Figure 2). For angles near normal incidence, the echoes from the various features will tend to arrive at approximately the same time. However, as the angle departs significantly from normal incidence, the times of arrivals will deviate according to the orientation of the fish relative to the direction of the incident wave.

For a sufficiently short, compressed pulse, an orientation angle well away from normal incidence, and given a long enough fish, the arrivals can be resolved. The separation in time, $\Delta\tau$, between the first and last arrival can be determined approximately through simple geometry:

$$\Delta\tau = (2L_{\mathrm{eff}}/c)\ |\cos\theta| \qquad (1)$$

where c is the speed of sound in water, L_{eff} is the effective acoustic length of the fish, and θ is the angle between the direction of propagation of the incident acoustic signal and the lengthwise axis of the fish (e.g. for tail-on incidence, $\theta = 0°$; normal incidence, $\theta = 90°$; head-on incidence, $\theta = 180°$). This coordinate system is convenient for analyzing data over the full range of angles of incidence in a given plane of rotation (0–360°). For the coordinate system involving the commonly used "tilt angle", which is the angle of the fish axis relative to the horizontal plane, that angle is equal to θ–90° for the case of a downwards-looking echosounder. In the above equation, $\cos\theta$ would be replaced by sin (tilt angle). Also, as discussed above, ideally there would be significant sources of scattering along the entire length of the fish. Since, generally, there are no significant anatomical variations at the tail of the fish, the effective length L_{eff} is used to describe the length of the line of scattering features. As described below, for the alewife used in this study, L_{eff} is about 90–95% of the actual length of the fish.

The above equation relates the orientation of the fish to the temporal extent of the processed acoustic echo. It is

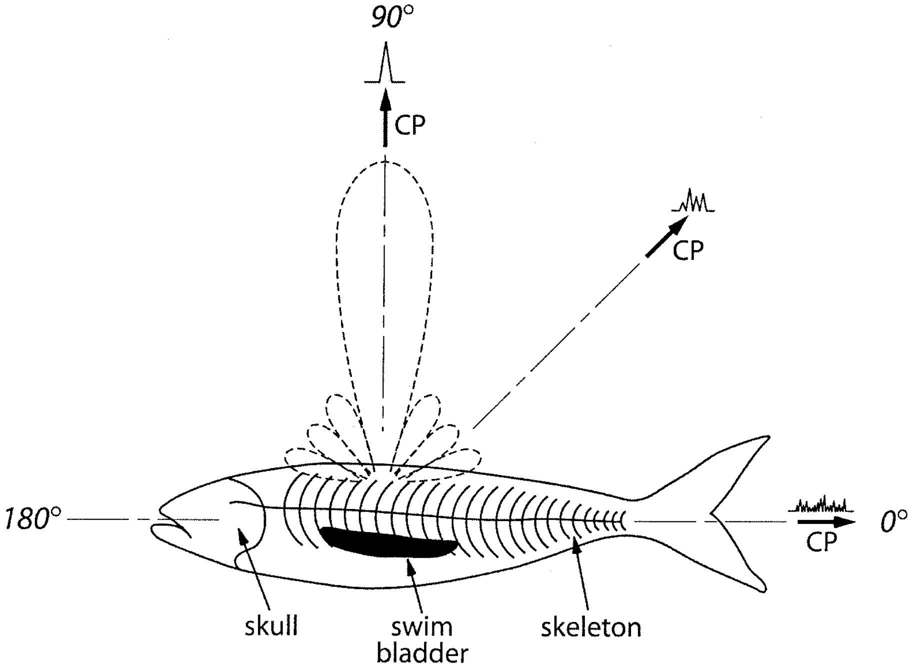

Figure 2. A schematic illustration of a compressed echo or pulse (CP) as a function of backscatter direction. The duration of the pulse is short for near-normal incidence and longer for oblique angles. The characteristics of the compressed pulse are illustrated for three values of θ (0, 45, and 90°).

very simple and relies principally on knowledge of the length of the fish and the duration, i.e. the time between first and last arrival of the processed echo. This relationship will be explored through the analysis of laboratory data in the next section. Specifically, the relationship will be examined in terms of the inherent limitations of a finite-bandwidth, acoustic system as well as deviations of the fish from an idealized line scatterer. These deviations include the facts that the organs or scattering features that give rise to significant echoes do not necessarily extend along the full length of the fish, are finite in size, and are not necessarily co-linear.

Experiments

A series of measurements of broadband-acoustic backscattering by live, individual fish has recently been completed (Reeder *et al.*, accepted for publication). The laboratory measurements were conducted in a 6 × 6 × 6 m^3 tank filled with fresh water, using alewife (*Alosa pseudoharengus*), a swimbladder-bearing fish similar to Atlantic herring (*Clupea harengus*). The 17 fish, all ensonified separately, were similar in length with an average caudal length (i.e. the length measured between the nose and the end of the flesh near the tail) of approximately 22 cm. All measurements involved the use of a pair of closely spaced, broadband transducers, one used as a transmitter and the other a receiver. A shaped, linearly-swept, frequency-modulated signal (chirp) spanning the frequency range 40–95 kHz was used. The scattering was measured over all angles of orientation (1° increments) in two planes of rotation as the tethered fish were rotated within the acoustic beam. The anatomy and morphology of the fish were characterized through a combination of physical measurement, dissection, traditional X-rays, computerized-tomography (CT) scans, and phase-contrast X-rays. Details of the experiments and results are presented in Reeder *et al.* (accepted for publication) and a preliminary report of their pulse-compression results is given in Stanton *et al.* (2001).

A particularly noteworthy result of the experiment was the ability of the system to resolve individual scattering features along the length of the body of the fish (Figures 3 and 4). As reported earlier in the article, the range resolution of the unprocessed 600-μs ping for this laboratory system was approximately 50 cm and after pulse compression it was about 2 cm. For the 22-cm long fish with major features, such as the skull and swimbladder separated by more than 2 cm, several features were acoustically resolved in the compressed pulse, especially at angles well away from normal incidence. The general characteristics of all data were broadly similar: the compressed pulse was a short, single spike near normal incidence (dorsal/ventral plane or lateral plane), but once the orientation was well

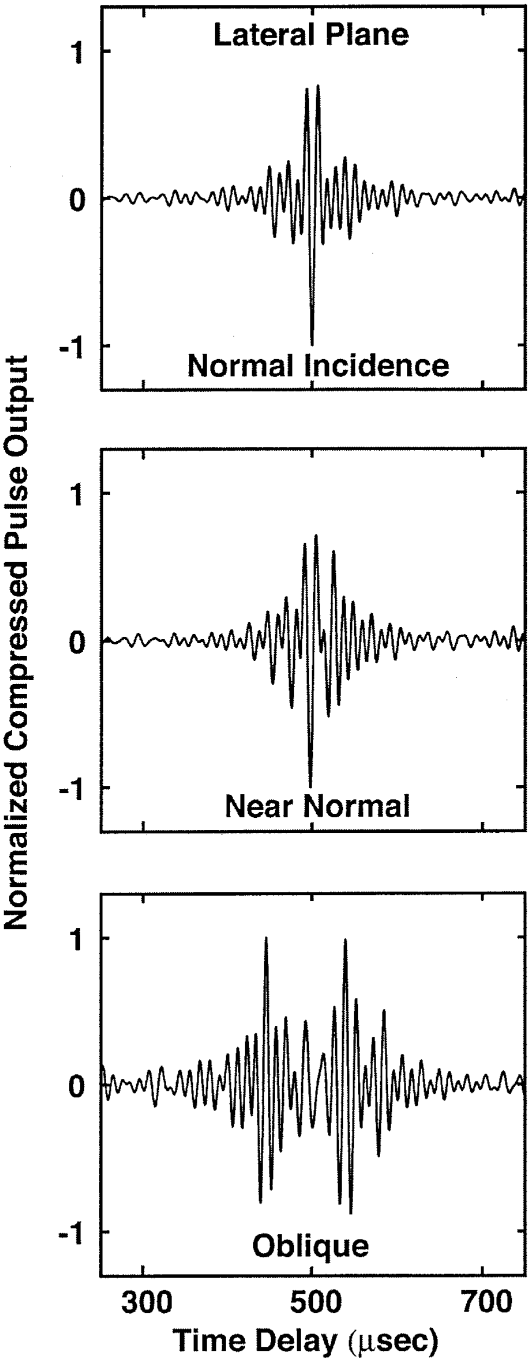

Figure 3. Compressed pulses from the echoes measured from an alewife at three orientation angles in the lateral plane. "Near normal" and "oblique" incidence correspond to angles that were 5 and 60° off-normal incidence, respectively. At the oblique angle, the echo comprises two major resolved peaks. Time delays (horizontal-axis) are relative to 5 ms, thus a time delay of 300 μs corresponds to 5.3 ms after the initial transmission.

away from normal, the single spike separated into a series of peaks. These observations are consistent with the fact that echoes from scattering features along the body will arrive at approximately the same time at angles near normal incidence. Once the orientation is well away from normal incidence, anatomical features closer to the transducers will produce echoes that arrive sooner than the features at the far end of the body.

All the data showed the trend of monotonic increase in separation between the first and last arrival ($\Delta\tau$) relative to orientation angle for angles out to 40–50° from normal incidence (Figure 4). Although Equation (1) generally accounts for this trend over that range, the scatter of points increases with increasing angle toward end-on incidence (Figures 5 and 6). At angles near end-on (tail-on or head-on), the relationship between orientation angle and peak separation is more complicated and Equation (1) does not describe the separation adequately. The increasing deviation between the data and model is due to the fact that with near end-on incidence, the echoes from the scattering features at the far side of the body are shadowed and therefore possibly not detected. However, since there is no or little shadowing for angles closer to normal incidence, and given the consistency of the data in that region, there is potential for extracting orientation information from the time signature of the compressed-pulse output.

Recommendations for field applications

These data show a trend of monotonic increase in the time separation between the first and last arrivals of the compressed-pulse output as the orientation angle near normal incidence deviates away from normal incidence (Figures 5 and 6). Given this consistency, there is potential for extracting orientation information from a processed broadband echo. A few questions remain regarding the accuracy and precision of the results and the optimal design of an acoustic system to take advantage of such a method. The answers involve the bandwidth of the system, the distribution of the scattering features with respect to position (length- and depth-wise) within the fish, and artifacts in the echo due to scattering-related interference phenomena.

Although there is a general trend of monotonic increase in the time separation between the first and last echoes with angle of orientation near normal incidence, there is variability about that trend. There are several possible causes of that spread, one being related to the experimental approach. This experiment involved live fish constrained in an acoustically-transparent harness. The harness was made tight enough to constrain the fish within the acoustic beam but loose enough so as not to cause too much stress on the fish during the measurements. Movement of the fish was apparent in some of the data (not shown). It is reasonable to believe that, although the harness was rotated in 1° increments, the fish may have moved at least that much

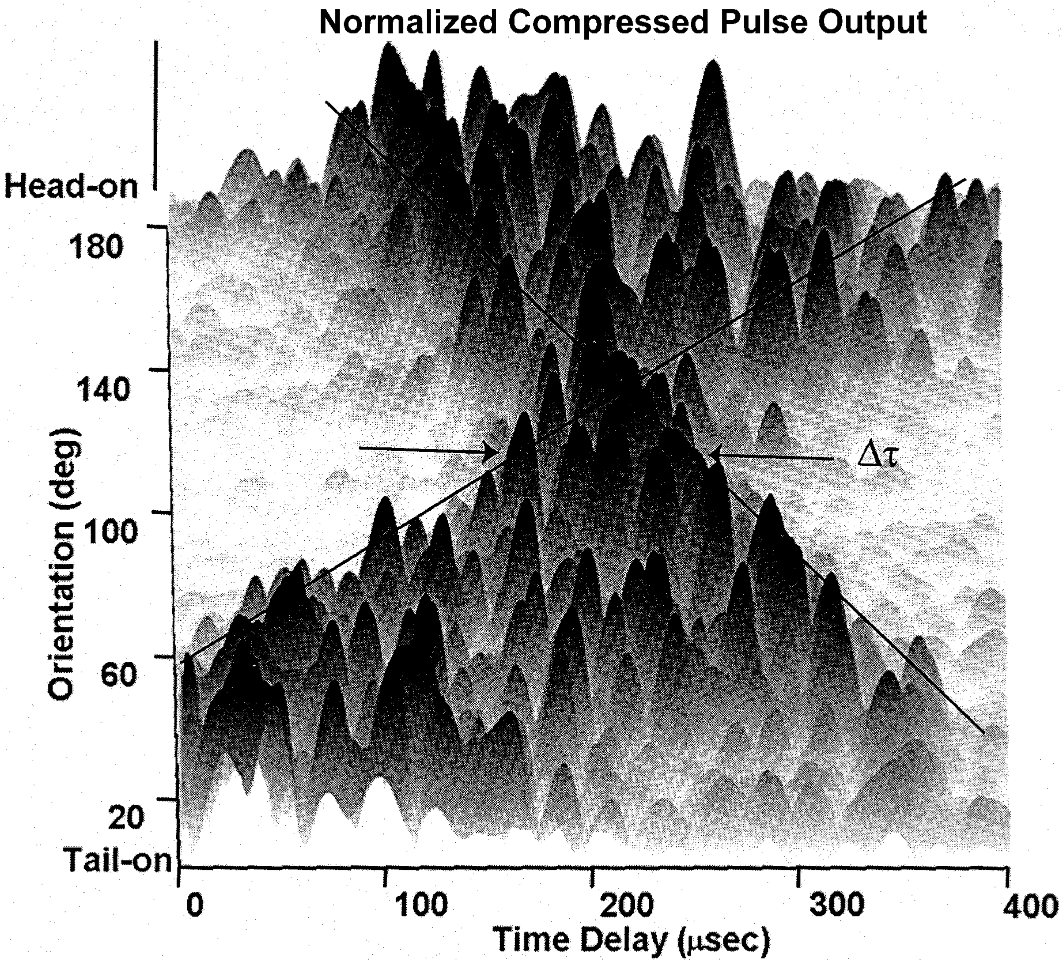

Figure 4. Envelopes of compressed echoes for a range of orientation angles (θ) from an alewife that was rotated in the dorsal/ventral plane. The straight lines are drawn to illustrate the trends of the locations of the leading and trailing edges of the first and last arrivals, respectively. The minimum value of Δτ occurs near 90° (normal incidence), although it has the appearance of occurring at a larger angle due to the perspective of this three-dimensional plot. Time delays (horizontal-axis) are relative to 5 ms, thus a time delay of 0 μs corresponds to 5 ms after the initial transmission.

in the course of the measurement and thus cause error in the reported value of orientation.

Other sources of variability involve the location of the scattering features and interference between them. This is not a laboratory artifact and will occur in the natural ocean environment. Our model assumes that the scattering features in the fish are all located along its lengthwise axis and that there are scattering centers at both ends of the fish. Thus at normal incidence, the associated echoes would all arrive at precisely the same time. However, anatomical features are distributed throughout the depth of the body of the fish and these scattering features vary in thickness. The composite effect of these two facts results in echoes that arrive at *approximately*, but not exactly, the same time when the fish is at normal incidence. This variation is bounded by the thickness of the fish and will certainly be associated with a small fraction of the thickness. Furthermore, because of interference between the arrivals, there will be some variation in the leading or trailing edge of the first and last arrivals, respectively, of the compressed pulse, causing further distortion of the results. The error associated with this interference will be bounded by the temporal resolution of the compressed pulse. Finally, significant scattering may not necessarily arise from parts of the fish near the tail, resulting in an effective acoustic length for use in Equation (1) that is shorter than the true length. If not taken into account, the error in the inferred angle of orientation would be approximately 5–10% for the fish and the acoustic parameters used in our study.

One important limiting factor in this approach involves the bandwidth, since this dictates the temporal resolution of the process. As mentioned above, the resolution is inversely

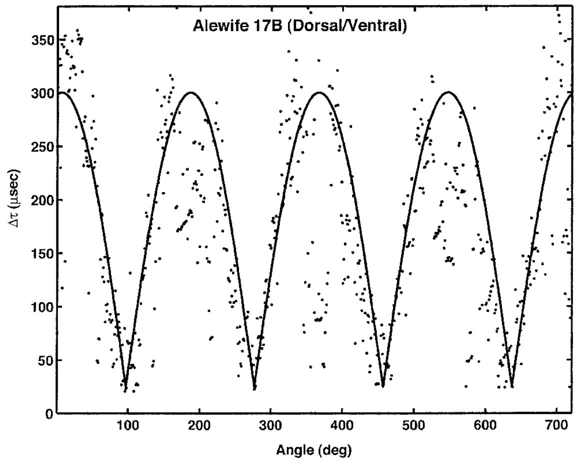

Figure 5. The time difference between the beginning of the first arrival of the compressed-pulse echo and the end of the last arrival for a superset of the orientation angles (θ) shown in Figure 4. The alewife was rotated through 720°. Detection criteria for these outer tails of the time-series involved starting or stopping the count when the time-series reached 40% of the maximum level for a given orientation angle. This detection threshold was chosen to be just above the processing side lobes of the autocorrelation function of the calibration signal as shown in Figure 1 in order to ensure that each compressed pulse represents an actual echo and is not a processing artifact. Equation (1) is superimposed for comparison (with offsets), using an effective acoustic length of 90% of the measured caudal length. The horizontal offset is incorporated to account for deviations of the fish from an ideal line scatterer—which could cause additional time shifts—as well as the possible misalignment of the fish in the measurement. The vertical offset accounts for the bandwidth and hence finite temporal resolution of the acoustic system.

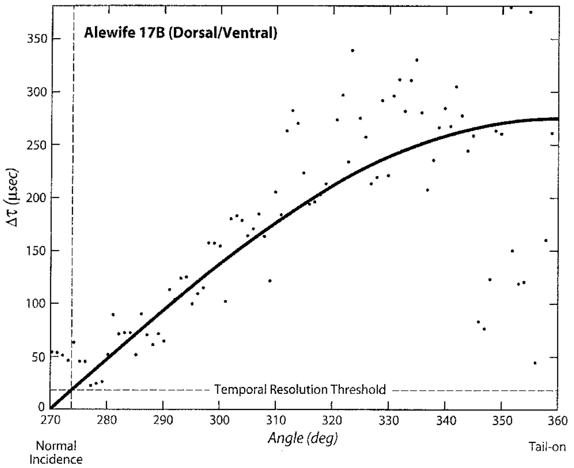

Figure 6. An expanded plot of one angular section of Figure 5. The minimum angle of inference relative to normal incidence (vertical dashed line) corresponds to the inverse bandwidth or minimum compressed-pulse width of the signal (horizontal dashed line). The effective acoustic length used in Equation (1) is 95% of the measured caudal length. The small difference in the effective acoustic length between this plot and that in Figure 5 is attributed to the fact that different sections of data were used and there are random differences between the two sections, as well as the fact that no vertical offset was used for Equation (1).

proportional to bandwidth of the signal. It is therefore important to use a system with a high bandwidth. The 2-cm range resolution of the processed echo in the system described in this article resulted in a detection threshold of about 4° relative to normal incidence for the 22-cm-long fish (e.g. the 274° point in Figure 6). Increasing the bandwidth of the system would decrease the threshold to the point where other limitations involving the non-co-linear nature of scattering features become important.

The choice of bandwidth of the system should therefore be based on the expected size of fish and corresponding deviations of scattering features from a straight line, and the desired threshold of detection of orientation angle relative to normal incidence (Table 1). It is important to stress that the criteria involving bandwidth are independent of the particular frequencies involved (e.g. a 100 kHz bandwidth could be derived from a 50–150 kHz system or a 150–250 kHz system). Since it is easier to fabricate efficient high-bandwidth systems at higher frequencies because the corresponding *fractional* bandwidth is smaller, then the trade-off between higher frequencies and shorter ranges of detection must be considered: signals at higher frequencies travel shorter distances.

Finally, for a practical field system, the effects of the beam pattern must somehow be accounted for, since beam widths are a strong function of frequency. This can, in principle, be accomplished by several methods. One, using conventional technology, could involve the simultaneous use of a narrow-band, split-beam echosounder co-located with a broadband, single-beam system. The split-beam system could be used to locate the position of the fish in the single beam and the effects of the beam pattern of the single beam could be removed. More advanced approaches could involve the development of a broadband, split-beam system or a system with a frequency-independent beam width.

Table 1. The bandwidth required for a range of minimum, inferred orientation angles relative to normal incidence and two lengths for an ideal line scatterer. The bandwidth was calculated using the approximate relationship, bandwidth $\simeq (\Delta\tau)^{-1}$ and Equation (1). The minimum angles for a fish will be larger because of effects such as the non-co-linearity of scattering features.

Minimum angle (deg)	Length (cm)	Bandwidth (kHz)
3	20 (40)	72 (36)
5	20 (40)	43 (21.5)
10	20 (40)	22 (11)
20	20 (40)	11 (5.5)

Summary and conclusion

We have conducted laboratory measurements of broadband scattering by swimbladder-bearing fish as a function of the angle of orientation. The temporally-compressed echoes had a 2-cm range resolution and were able to resolve individual scattering features within the fish. We observed that the time separation between the first and last returns of the compressed echoes was strongly correlated with the angle of orientation for a wide range of angles (normal incidence ±40°). Using this information, we conclude that the orientation of individual (resolved) fish can be inferred from the processed broadband echo from a single ping. Although some of the error in the inference is associated with artifacts of the laboratory measurement, e.g. movement of the fish within the harness and its imperfect alignment, there is also error associated with the non-co-linear nature of the scattering features along the length of the fish as well as interference between unresolved features. We recommend that the bandwidth be chosen to be as large as possible until the range resolution of the processed signal is comparable to the error associated with the non-co-linearity. Certainly, further assessment of the errors should involve free-swimming fish of various species with careful measurement of orientation.

In conclusion, broadband-acoustic signals are rich with information. As demonstrated in this article, one important quantity that can be inferred from a single ping is the orientation of resolved fish. Advantages of this approach over others are that only one ping is required and a formal mathematical-scattering model is not required. The design criteria of such an acoustic system involve the trade-off of bandwidth and the desired threshold of orientation relative to normal incidence as well as the desired range of detection. The design must also take account of the non-co-linearity of features along the fish that are species-dependent.

Acknowledgements

This research was supported by the U.S. Navy, the U.S. Office of Naval Research (grant nos. N00014-98-1-0879 and N00014-00-F-0148), NOAA (cooperative agreement NA87RJ0445), and the Massachusetts Institute of Technology/Woods Hole Oceanographic Institution Joint Graduate Education program. We are grateful to Robert Kieser of the Pacific Biological Station, Nanaimo, BC for his helpful suggestions. This is Woods Hole Oceanographic Institution contribution number 10788.

References

Barr, R. 2001. A design study of an acoustic system suitable for differentiating between orange roughy and other New Zealand deep-water species. Journal of the Acoustical Society of America, 109: 164–178.

Chu, D., and Stanton, T. K. 1998. Application of pulse compression techniques to broadband acoustic scattering by live individual zooplankton. Journal of the Acoustical Society of America, 104: 39–55.

Chu, D., Foote, K. G., and Stanton, T. K. 1993. Further analysis of target strength measurements of Antarctic krill at 38 kHz and 120 kHz: comparison with deformed cylinder model and inference of orientation distribution. Journal of the Acoustical Society of America, 93: 2985–2988.

Ehrenberg, J. E., and Torkelson, T. C. 2000. FM slide (chirp) signals: a technique of significantly improving the signal-to-noise in hydroacoustic assessment systems. Fisheries Research, 47: 193–199.

Foote, K. G., and Traynor, J. J. 1988. Comparison of walleye pollock target strength estimates determined from *in situ* measurements and calculations based on swimbladder form. Journal of the Acoustical Society of America, 83: 9–17.

Furusawa, M., and Miyanohana, Y. 1990. Behaviour and target-strength observation through echo traces of individual fish. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 189: 283–294.

Huse, I., and Ona, E. 1996. Tilt angle distribution and swimming speed of overwintering Norwegian spring spawning herring. ICES Journal of Marine Science, 53: 863–873.

Martin Traykovski, L. V., O'Driscoll, R. L., and McGehee, D. E. 1998. Effect of orientation on broadband acoustic scattering of Antarctic krill *Euphasia superba*: implications for inverting zooplankton spectral acoustic signatures for angle of orientation. Journal of the Acoustical Society of America, 104: 2121–2135.

Medwin, H., and Clay, C. S. 1998. Fundamentals of Acoustical Oceanography. Academic Press, Boston, 712 pp.

Ona, E. 2001. Herring tilt angles, measured through target tracking. *In* Herring: Expectations for a New Millennium, pp. 509–519. Ed. by F. Funk, J. Blackburn, D. Hay, A. J. Paul, R. Stephenson, R. Torenson, and D. Witherell. University of Alaska, Fairbanks, University of Alaska Sea Grant, AK-SG-01-04. Fairbanks.

Reeder, D. B., Jech, J. M., and Stanton, T. K. Broadband acoustic backscatter and high-resolution morphology of fish: measurement and modeling. Journal of the Acoustical Society of America (accepted for publication).

Stanton, T. K., Chu, D., and Wiebe, P. H. 1998. Sound scattering by several zooplankton groups. I. Experimental determination of dominant scattering mechanisms. Journal of the Acoustical Society of America, 103: 225–253.

Stanton, T. K., Chu, D., Martin Traykovski, L. V., Reeder, D. B., Warren, J. D., and Wiebe, P. H. 2001. Broadband acoustic classification of individual zooplankton and fish: a review of recent work. pp. 181–188 in Proceedings of the Institute of Acoustics Conference on Acoustical Oceanography, April 2001.

Turin, G. L. 1960. An introduction to matched filters. Institute of Radio Engineers Transactions on Information Theory, IT-6: 311–329.