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LETTERS TO THE EDITOR

EVALUATION OF A RUBBER-COMPOUND DIAPHRAGM FOR ACOUSTIC FISHERIES SURVEYS: EFFECTS ON DUAL-BEAM SIGNAL INTENSITY AND BEAM PATTERNS

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1. INTRODUCTION

Ultrasonic echo-sounder systems used in fisheries applications can operate with transducers that are either fixed to the hull of the survey vessel—directly or on extendable center boards—or deployed alongside in a towed body. The cost and time commitments of hull mounting and periodic vessel haul-outs required for transducer maintenance or calibration, as well as the immediate deployment capability with an existing vessel or portability for multi-vessel duty, make the use of towed bodies an attractive option. However, our experience with towed bodies found they are highly affected by rough sea conditions, though use of towed bodies have been found to provide a stable echo-sounding platform [1]. Even with dampening systems designed to minimize the stresses exerted on the tow cable from vessel pitch and roll in rough seas, we frequently experienced wave-induced motions on the towed body that routinely hindered successful tracking of the bottom return signal that restricted our capability to complete some fisheries surveys. These limitations, as well as equipment wear, would be reduced with hull-mounted transducers.

As a remedy we explored the application of another option for transducer deployment: fish echo sounding through a rubber-compound diaphragm. Silicon rubber compounds with density and sound transmission properties that closely match water have been developed and used principally for underwater use with sonar devices in anti-submarine military applications [2]. Other applications have included the use of this material in oceanographic vessels for general echo sounding, but to date echo sounding through rubber-compound windows have not been used with the scientific-grade systems used in fisheries acoustics. We saw the potential benefits of retro-fitting this product for through-hull echo sounding principally to minimize the effects of weather conditions, with the added advantage that this configuration would also allow access to the internally mounted transducers for maintenance or system calibrations without vessel haul-out.

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2. PROBLEM

The acoustic properties of these silicon rubber compounds have not been extensively described for fisheries acoustics. Of most relevance to such scientific application is the known characteristic of transmission loss of ultrasonic frequency sound through these silicon rubbers. This problem has been shown to be generally greater at higher frequencies, but of varying degrees for different formulations [3]. The manufacturer of the material used in this particular application, B. F. Goodrich,[‡] judged that the acoustic properties of the particular rubber compound was suitable for this application, given our description of the acoustic operational parameters. For installation, the rubber diaphragm is faired into the vessel as a flush, mated surface to the hull to avoid production of bubbles or turbulence near the face of the sound source (Figure 1). The manufacturer vulcanized a 5·1-cm thick rubber diaphragm (compound number 35080) into a 45·7-cm long and 30·5-cm wide steel frame. These dimensions were designed to accommodate two transducers used for multiplex echo sounding. Suitable sites on a vessel for the placement of a rubber diaphragm are typically near the keel, as near to beneath the center of mass as possible to minimize changes in angular aspect due to pitch and roll [4]. In our case, the mounting site on the hull that avoided external structures (other fixed transducers and keel coolers) and that allowed internal access through the bilge resulted in a 20° difference between the face of the transducers and the plane of the window, as shown in Figure 1. This angle of incidence was within the manufacturer's tolerance limits for acoustic performance of the rubber compound. However, quantitative acoustic assessment of fish populations rely on precise knowledge of source level, receiver sensitivity, and beam pattern (directivity) values. We were concerned that any sound absorption by the rubber compound might distort any or all of these system performance parameters, which would compromise the fishery surveys.

To test the performance of the rubber compound for our application to fisheries surveys, we compared the source levels, receiver sensitivities, and beam patterns of dual-beam transducers in water to those through a rubber window situated at various angles in a controlled setting. In addition, *in situ* system calibrations performed on the vessel before and after installation of the rubber window are compared.

3. METHODS

3.1. DATA COLLECTION

Source levels and receiver sensitivities were determined for 120 kHz (10° narrow-beam and 25° wide-beam transducer) and 420 kHz (6° narrow-beam and 15° wide-beam transducer) dual-beam systems with calibration hydrophones off a barge in Union Lake near Seattle, Washington on 16 February 1995. Source levels ($\mathrm{dB}\|\mu$ Pa at 1 m) and receiver sensitivity levels ($\mathrm{dB}\|V\mu$ Pa at 1 m) were first measured in water—unfortunately, time and other logistical limitations prevented the collection of receiver sensitivity measurements in water for the 120 kHz transducer. To emulate the through-hull design, the transducers were housed in an aluminum container filled with U.S.P. grade castor oil and were aimed horizontally through the side that was fitted with an identical rubber diaphragm. The transducers were attached to an articulating cam that was positioned to produce incidence angles of 0, 10, and 20° between the face of the transducer and the rubber diaphragm. The

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[‡] Mention of trade names or manufacturer does not imply U.S. government endorsement of commercial products.

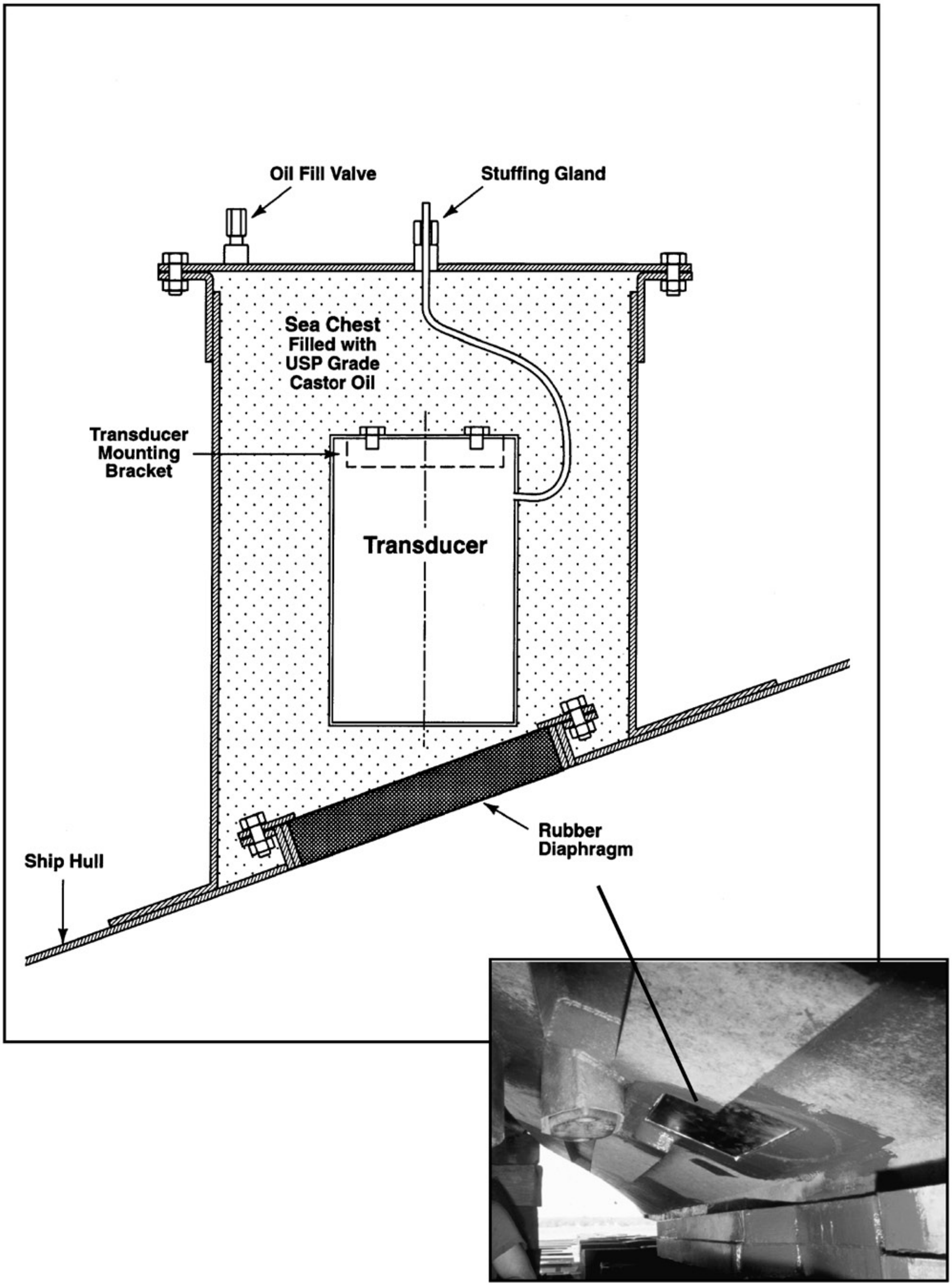

Figure 1. Schematic cross-section view of the hull-mounted rubber diaphragm and photograph of completed installation of diaphragm in ship hull (inset). Acoustic transducers are housed in oil-filled sea chest. Hull aspect in relation to orientation of transducers result in 20° angle difference between face of transducer and rubber diaphragm.

entire container was attached to a cam that was rotated counter-clockwise from $+90$ to -90° off-axis to the hydrophone to measure beam directivity. Source levels and receiver sensitivities were measured at a 10 kHz sampling rate. The transducers were 6·1 m from the calibrated hydrophones in 4·6 m of water at 6·4°C.

The *in situ* performance of the acoustic systems were monitored before and after installation of the rubber window with the use of reference tungsten carbide spheres [5, 6]. The spheres were centered from 10 to 15 m beneath the transducers and ensonified. Mean target strength ($\overline{TS}$) was calculated as the decibel equivalent of the measured mean backscattering cross-section ($\overline{\sigma_{bs}}$) as

$$\overline{TS} = 10 \log \overline{\sigma_{bs}}. \tag{1}$$

This procedure was completed in conjunction with several fisheries surveys in 1994 and 1995.

3.2. DATA ANALYSIS

The directivity relations of the near-axis portions of the main lobe were based on the non-linear fit (quasi-Newton estimation method) of the power function

$$dB = \alpha\, \theta^{\beta}, \tag{2}$$

where dB is the normalized sound pressure levels in decibels, θ is the absolute value of angle off-axis in degrees, and α and β are the estimated function parameters. Sound pressure levels up to a maximum off-axis value of 10° were used for both narrow- and wide-beam readings for the 120 kHz system and for the wide-beam readings for the 420 kHz system; the presence of side lobes allowed a maximum off-axis value of 7° to be used for the narrow-beam measurements for the 420 kHz system. The sound pressure values (dB) at 0·5° angle intervals, calculated from the power function equations, were used to calculate a directivity index with the BioSonics® program BSQUARE. This beam pattern index algorithm, a numerical approximation of the integral of the beam pattern power function, applied the extended Simpson's rule for successive, non-overlapping pairs of intervals as

$$DI = h\left[\tfrac{1}{3}f_1 + \tfrac{4}{3}f_2 + \tfrac{2}{3}f_3 + \tfrac{4}{3}f_4 + \cdots + \tfrac{2}{3}f_{n-2} + \tfrac{4}{3}f_{n-1} + \tfrac{1}{3}f_n\right] + O\left(\frac{1}{N^4}\right), \tag{3}$$

where DI is the directivity index, h is the angular interval of measurements (in radians), f_1 is the on-axis sound pressure value, and even and odd f values represent even and odd off-axis sound pressure measures (f_n is ignored since it is typically a very small value and the O term is an error estimate that was deemed insignificant due to the number of n values used) [7].

Effects of the angle of incidence between the transducer and the rubber diaphragm on beam pattern was tested with the general linear model

$$\log dB = \beta_0 + \beta_1 \log \theta + \beta_2 I, \tag{4}$$

where $\log dB$ is the log-transformed absolute value of the normalized sound pressure in decibels, $\log \theta$ is the log-transformed absolute value of degrees off-axis, I is a classification variable to denote the control (water) and each treatment of incidence angle with the diaphragm, and β_n are the estimated parameters [8]. A significant β_2 indicates a treatment effect. On-axis values (0 dB at 0°) were not included in the logarithmic transformations used for the tests with the linear models.

4. RESULTS AND DISCUSSION

4.1. SOURCE LEVEL AND RECEIVER SENSITIVITY

Source levels and through-system receiver sensitivity levels are shown in Table 1. For the 120 kHz transducer, the differences in source levels and receiver sensitivities between the control and those measured through the rubber-compound diaphragm were minimal and most were within expected measurement error. Source levels and receiver sensitivities with the diaphragm at a 20° angle of incidence were less than compared to water (Table 1). However, only the narrow-beam receiver sensitivity at this angle appeared to be great enough to suggest an effect by the rubber diaphragm.

Lower source levels and through-system receiver sensitivity values were evident in all measurements made through the rubber diaphragm at 420 kHz (Table 1). Source levels were 0·7–1·1 dB lower and receiver sensitivity values declined by 2·8–3·6 dB for measurements made through the rubber diaphragm. Lower source levels and reduced through-system receiver sensitivities indicated signal loss in both transmission and reception through the rubber diaphragm for this frequency. No effect of incidence angle was apparent. Based on these measurements, a 3–4 dB signal loss would be anticipated at 420 kHz.

The *in situ* target strengths of carbide reference spheres before and after installation of a rubber-compound diaphragm on the vessel are shown in Table 2. The mean target strength values at 120 kHz showed no discernable difference between those measurements made with and without the rubber diaphragm. The target strengths of the reference sphere were less consistent at 420 kHz, with through-diaphragm measurements up to 1·7 dB lower. The differences at 420 kHz were less than expected based on the calibration experiment and is likely due to the effects of ambient water temperature. The calibration experiment was performed in water 6·4°C whereas the target strength measurements of the reference sphere at water temperatures between 15 and 18°C. Sound velocities in water and in rubber are indistinguishable at warmer temperatures; however, signal attenuation through the rubber varies inversely with temperature, as shown in Figure 2. In addition, the sound attenuation of this material increases with increased frequency and becomes appreciable at frequencies above 500 kHz (Figure 2). The frequency–temperature effects on the acoustic

Table 1

Comparison of source levels (dB||μ Pa at 1 *m) and through-system narrow-beam (NB) and wide beam (WB) receiver sensitivity levels (dB||Vμ Pa at* 1 *m) for* 120 *and* 420 *kHz dual-beam echo sounders in water and through a rubber-compound diaphragm at three angles of incidence*

			Rubber-compound diaphragm		
		Water	0°	10°	20°
120 kHz	Source level	213·99	214·12	213·91	213·63
			(0·13)	(−0·08)	(−0·36)
	Receiver sensitivity (NB)	−162·95	−162·67	−162·88	−163·88
			(0·28)	(0·07)	(−0·93)
	Receiver sensitivity (WB)	−156·24	−155·93	−156·03	−156·60
			(0·31)	(0·21)	(−0·36)
420 kHz	Source level	219·20	218·52	217·91	218·11
			(−0·68)	(−1·29)	(−1·09)
	Receiver sensitivity (NB)	−169·97	−172·81	−173·56	−173·23
			(−2·84)	(−3·59)	(−3·26)
	Receiver sensitivity (WB)	−171·15	−174·17	−174·07	−174·55
			(−3·02)	(−2·92)	(−3·40)

Note: Parentheses indicate difference in values between water and diaphragm.

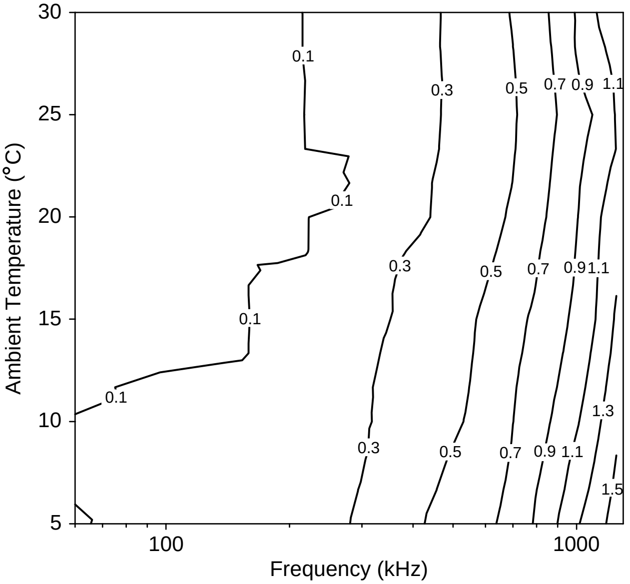

Figure 2. Signal loss (dB/cm) as a function of frequency and temperature for rubber compound number 35080 as measured in freshwater. Data provided by B. F. Goodrich.

Table 2

Comparison of mean backscattering cross-section (expressed in dB) of reference tungsten carbide spheres with 120 *and* 420 *kHz dual-beam echo sounders before and after installation of a rubber diaphragm*

	Without diaphragm		With diaphragm	
120 kHz	−41·7	−41·7	−41·3	−41·7
420 kHz	−53·4	−55·1	−53·7	—[†]
Date	July 1994	July 1994	September 1994	September 1995

Note: Measurements were made *in situ* aboard a research vessel during 1994–1995. Target strength values shown for the 120 kHz system are for a 33-mm diameter reference sphere and for the 420 kHz system for a 17-mm diameter reference sphere.

[†] Measurements not made.

properties of the rubber compound explains the increased signal attenuation observed, especially at 420 kHz, in the calibration experiment.

4.2. BEAM PATTERNS

Transmit (narrow) beam patterns for both frequencies in water and through the rubber diaphragm at each incidence angle are shown in Figure 3. These plots show that distortion of the beams were limited to the side lobes, and this distortion was more pronounced at increased angle of incidence of the rubber diaphragm. The observation that the main lobes at either frequency were not affected was confirmed by the general linear models which did not detect any angle effects on beam pattern ($P > 0{\cdot}05$).

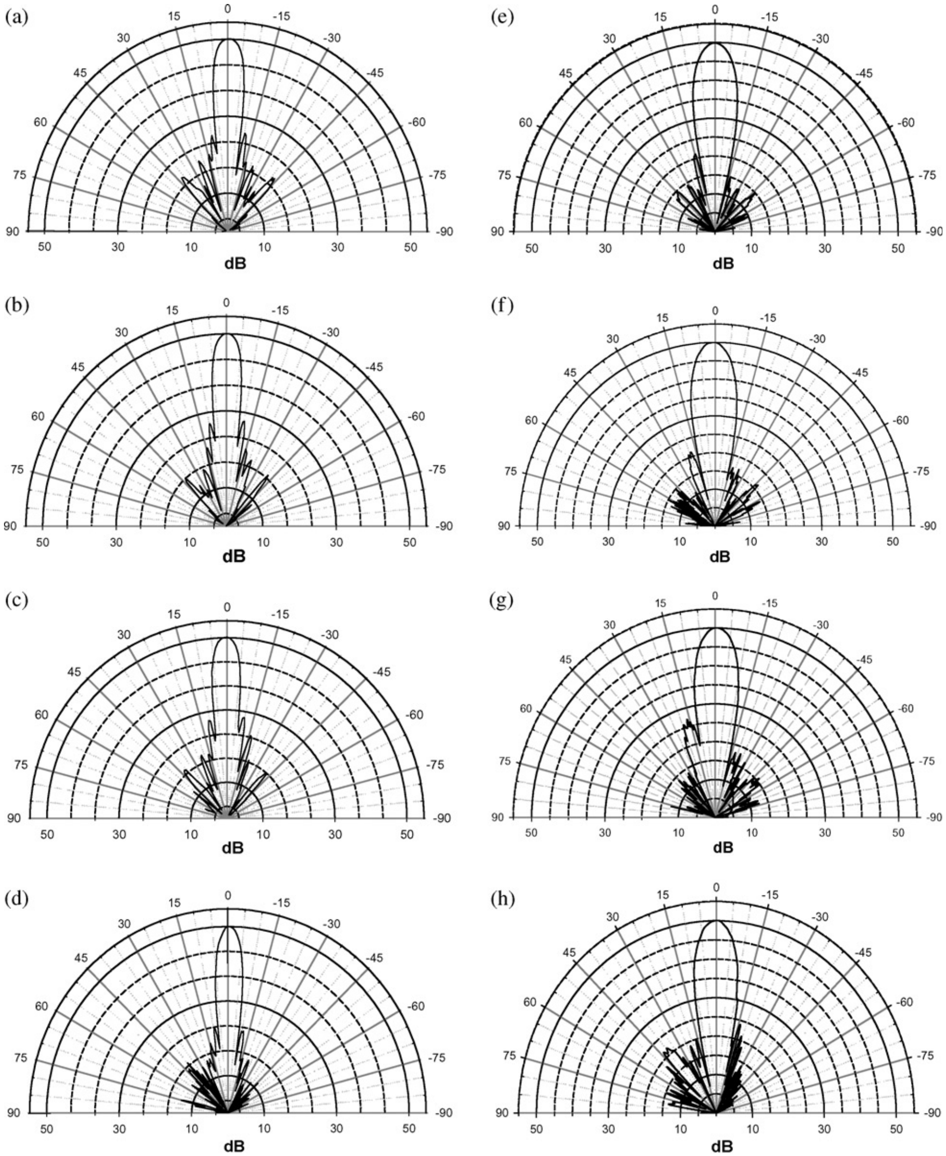

Figure 3. Polar plots of transmit (narrow) beam patterns for 420 kHz (a)–(d) and 120 kHz (e)–(h) dual-beam transducers measured in calibration experiment. Beam patterns are for water (a) and (e) and through a rubber diaphragm at aspect angles of 0° (b) and (f), 10° (c) and (g), and 20° (d) and (h). Radial measures are decibels and angular measures range from +90 to −90° off axis to the hydrophone.

Through-diaphragm receive (narrow and wide) beam patterns for both frequencies are shown in Figure 4. Like the transmit beam patterns, the receive beam patterns only show distortion to the side lobes. Furthermore, the side lobes on the wide beams seem to be affected more than the narrow-beam side lobes because of the increased asymmetry of the side lobes at increased angles of incidence (Figure 4).

The parameter estimates for the non-linear directivity relations for narrow and wide beams of both frequencies were characterized by a high degree of fit (Table 3) and appear

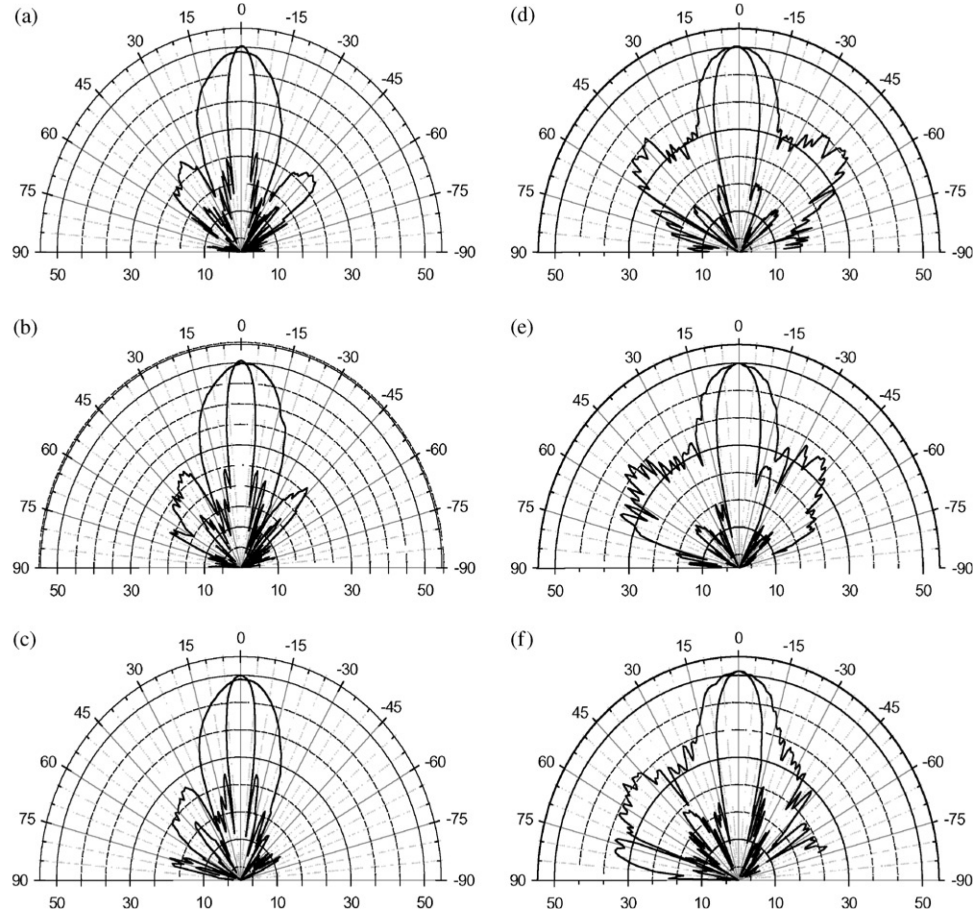

Figure 4. Polar plots of receive (narrow and wide) beam patterns for 420 kHz (a)–(c) and 120 kHz (d)–(f) dual-beam transducers measured in calibration experiment. Beam patterns through a rubber diaphragm at aspect angles of 0° (a) and (d), 10° (b) and (e), and 20° (c) and (f). Radial measures are decibels and angular measures range from +90 to −90° off-axis to the hydrophone.

similar at the different angles of incidence, based on the confidence intervals. This observation was verified by the linear models, which showed that no significant incidence angle effect was detected ($P > 0{\cdot}05$) for either the narrow and wide beams for either frequency. Directivity index values also show the similarity of the receive beam patterns between the control and at the various angles with the diaphragm (Table 4). These results agree with the transmit beam pattern tests, indicating that the rubber diaphragm does not appear to have any effect on the directivity of the main lobe of the sound beam, even at the most severe angle of incidence tested.

5. CONCLUSIONS

The use of rubber-compound windows for fisheries acoustics must consider operating frequency and ambient water temperatures. Signal attenuation by the rubber becomes pronounced with increased frequency and decreased temperature. Based on our results, a

TABLE 3

Parameter estimates, 95% *confidence intervals (CI), and corrected* R^2 *values for directivity relations of narrow- and wide-beam patterns measured through a rubber diaphragm at three angles of incidence*

Angle of incidence		Narrow beam		Wide beam	
		β	α	β	α
		120 kHz			
0°	Estimate	2·318	−0·070	1·956	−0·046
	Upper 95% CI	2·614	−0·118	2·296	−0·081
	Lower 95% CI	2·021	−0·220	1·617	−0·010
	R^2 (corrected)	0·97		0·9	
10°	Estimate	2·386	−0·065	1·706	−0·081
	Upper 95% CI	2·529	−0·044	1·912	−0·045
	Lower 95% CI	2·241	−0·086	1·500	−0·117
	R^2 (corrected)	0·99		0·9	
20°	Estimate	2·453	−0·056	1·580	−0·108
	Upper 95% CI	2·733	−0·021	1·772	−0·064
	Lower 95% CI	2·173	−0·090	1·388	−0·153
	R^2 (corrected)	0·98		0·9	
		420 kHz			
0°	Estimate	3·015	−0·064	2·201	−0·029
	Upper 95% CI	3·347	−0·022	2·587	−0·006
	Lower 95% CI	2·683	−0·105	1·815	−0·052
	R^2 (corrected)	0·98		0·9	
10°	Estimate	2·671	−0·111	2·065	−0·041
	Upper 95% CI	2·994	−0·038	2·769	0·020
	Lower 95% CI	2·348	−0·184	1·361	−0·103
	R^2 (corrected)	0·99		0·8	
20°	Estimate	2·888	−0·072	1·956	−0·054
	Upper 95% CI	3·160	−0·036	2·501	0·011
	Lower 95% CI	2·616	−0·107	1·351	−0·119
	R^2 (corrected)	0·99		0·9	

Note: Equations based on fit of power function $dB = \alpha\theta^{\beta}$, where dB is normalized sound pressure in decibels and θ is degrees off-axis.

420 kHz system could be expected to lose up to 3–4 dB in colder water through a 5·1-cm thick rubber diaphragm. At 120 kHz, signal loss was negligible and would undoubtedly also be inconsequential for even lower frequencies used in fisheries applications (e.g., 70, 38 kHz).

For both frequencies tested, the effects on beam pattern by the rubber diaphragm were limited to the side lobes and the different incident angles had no detectable effect on directivity of the main lobes. This is not a substantial effect for accurate measures of total backscattering for echo integration or more importantly for individual echoes, since echoes only within a beam pattern threshold of 3 dB, or approximately one-half the nominal beam width, should be used for calculation of mean target strength with dual-beam system [9].

TABLE 4

Comparison of directivity index values calculated for narrow and wide (receive) beams of 120 *and* 420 *kHz dual-beam echo sounders in water and through a rubber diaphragm at three angles of incidence*

		Water	Rubber-compound diaphragm		
			0°	10°	20°
120 kHz	Narrow beam	—	26·05	26·21	26·13
	Wide beam	—	24·76	24·95	24·95
420 kHz	Narrow beam	29·54	29·48	29·81	29·30
	Wide beam	27·96	27·82	27·82	29·79

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