MONOFILAMENT GILL NET ACOUSTIC STUDY

by
Elbert A. Pence

Applied Physics Laboratory, University of Washington
1013 N.E. 40th Street, Seattle, Washington 98105

March 3, 1986

# CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>THEORY</td>
<td>2</td>
</tr>
<tr>
<td>Geometrical Target Size</td>
<td>3</td>
</tr>
<tr>
<td>Impedance Mismatch</td>
<td>3</td>
</tr>
<tr>
<td>Nylon Monofilament</td>
<td>3</td>
</tr>
<tr>
<td>Compressibility</td>
<td>4</td>
</tr>
<tr>
<td>Density</td>
<td>4</td>
</tr>
<tr>
<td>Hollow Monofilament</td>
<td>4</td>
</tr>
<tr>
<td>Filled Monofilament</td>
<td>6</td>
</tr>
<tr>
<td>METHODS AND MATERIALS</td>
<td>7</td>
</tr>
<tr>
<td>RESULTS</td>
<td>8</td>
</tr>
<tr>
<td>Comparison of Theory and Experiment</td>
<td>8</td>
</tr>
<tr>
<td>Comparison of Float Echoes and Net Echoes</td>
<td>10</td>
</tr>
<tr>
<td>Hollow Monofilament Echoes</td>
<td>11</td>
</tr>
<tr>
<td>CONCLUSION</td>
<td>12</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>12</td>
</tr>
<tr>
<td>APPENDIX, Acoustic Polar Plots</td>
<td>A1-A12</td>
</tr>
</tbody>
</table>
INTRODUCTION

The incidental catch of porpoises is a matter of considerable concern in ocean fisheries. The National Marine Mammal Laboratory (NMML) is involved in a joint research program with Japan on the problem of incidental take of Dall's porpoise by the Japanese high seas salmon fisheries. As part of that study, NMML requested the Applied Physics Laboratory to determine the acoustical reflectivity of a typical fishing net and its various components — net mesh (both hollow core and solid monofilament), floats, sinkers, and lines. The intent of this investigation was to examine, through theory and measurement, how the net might appear to the porpoise's acoustic perceptual system. It was hoped that, during this investigation, ways might be noted to enhance the acoustic detectability of the net.
THEORY

The target size (effective area) of a single, infinitely long line, with a circumference that is small compared with the acoustic wavelength, is given by

\[
\text{Target Size} = \left( \frac{9\pi^4 a^4 r}{\lambda^3} \right) \left[ \frac{1/2(1-K) + (\frac{R-1}{R+1})\cos\theta}{1/2 + \cos\theta} \right]^2
\]

(geometrical target size) (impedance mismatch)

where

\begin{align*}
    a &= \text{radius of line} \\
    \lambda &= \text{wavelength} \\
    R &= \text{density relative to water} \\
    K &= \text{compressibility relative to water} \\
    r &= \text{distance to line from source} \\
    \theta &= \text{angle between perpendicular to line and incident acoustic radiation (see sketch).}
\end{align*}

All dimensions are in meters, so target size has the dimension of area, i.e., $(\text{meters})^2$. The conventional acoustic target strength in decibels (referenced to 1 m$^2$) is obtained by taking $10 \log_{10}$ of the expression for target size.
Geometrical Target Size

The geometrical target size of a single line is quite small. The net line diameter is 0.5 mm. (This corresponds approximately to a 20 lb line.) At 150 kHz, the geometrical target strength for such a line at 1 m range, as given by Eq. 1, is

\[
G_s = 10 \log_{10} \left[ \frac{9 \pi^4 a^4 r}{\lambda^3} \right] = -54.7 \text{ dB}
\]

where

\[a = 0.00025 \text{ m}\]
\[\lambda = 0.01 \text{ m (wavelength at 150 kHz)}\]
\[r = 1.0 \text{ m.}\]

For the same line at 230 kHz (\(\lambda = 0.0065 \text{ m}\)), \(G_s = -49.1 \text{ dB}\); at 130 kHz (\(\lambda = 0.0115 \text{ m}\)), \(G_s = -56.6 \text{ dB}\).

Impedance Mismatch

Because the acoustic impedance of nylon is not much different from that of sea water, the impedance mismatch term of Eq. 1 (hereafter referred to as \(Z_m\), in decibels) merits a more extensive analysis.

\[
Z_m = 20 \log_{10} \left[ \frac{1}{2} (1-K) + \frac{R-1}{R+1} \cos \theta \right] \frac{1}{1 + \frac{1}{2} \cos \theta}, \text{ dB.}
\]

The target strength, \(TS\), is simply the algebraic sum of the decibel values obtained for \(G_s\) and \(Z_m\), namely,

\[
TS = G_s + Z_m, \text{ dB.}
\]

Nylon Monofilament

The properties of nylon depend greatly on the chemical formulation, the processing method, and the environment (particularly temperature and humidity).
Compressibility

For an assumed value for Young's modulus of 300,000 psi (quoted values range from 100,000 to 450,000), the metric value is $2 \times 10^9$ Pa. For the quoted value of 0.4 for Poisson's ratio, the bulk modulus of nylon is $3.33 \times 10^9$ Pa. For sea water, the bulk modulus is $2.28 \times 10^9$ Pa. Compressibility is the reciprocal of bulk modulus, so for nylon vs sea water the relative compressibility, $K$, is 0.7.

Density

For an assumed nylon density of 1140 kg/m$^3$ (quoted values range from 1120 to 1160) and a sea water density of 1030 kg/m$^3$, the relative density, $R$, is 1.1.

It is noted that $Z_m$ is not frequency dependent and, when evaluated for nylon monofilament ($R = 1.1, K = 0.7$) gives a value of -17.6 dB for $\theta = 0$ (for $\theta = 15, 30$, and $45^\circ$, respectively, the values are -17.5, -17.1, and -16.4), so that the effect due to angle is relatively small for a broadside approach. At an angle of $80^\circ$, $Z_m = -12.6$, and a porpoise would be better able to detect the net. It is also instructive to compare this term with the results for a hypothetical, perfectly rigid, dense wire and with the results for a real wire.

For a hypothetical wire, $K \to 0$ (absolutely incompressible), $R \to \infty$ (infinitely dense), and $Z_m \to 0$ dB. Thus, for a given diameter and frequency, the target strength is 17.6 dB lower for a nylon monofilament line than for the hypothetical wire. When compared with real wires, below, the target strength is approx. 16 dB lower for nylon than for various metal wires.

- For steel, $K = 0.014$, $R = 7.5$, $Z_m = -1.5$ dB
- For brass, $K = 0.017$, $R = 8.3$, $Z_m = -1.4$ dB
- For copper, $K = 0.014$, $R = 8.7$, $Z_m = -1.3$ dB
- For lead, $K = 0.055$, $R = 11.0$, $Z_m = -1.2$ dB

Hollow Monofilament

Because the monofilament's diameter (0.5 mm) is small compared with the acoustic wavelength (10 mm at 150 kHz, 6.5 mm at 230 kHz), the hollow monofilament line can be treated simply as a composite material with bulk properties different from those of the solid monofilament. Because of the hollow interior, the bulk density will be less and the bulk compressibility will be greater. In Figure 1, $Z_m$ is plotted as a function of $d_t/d_d$, where (if the air in the hollow core is assumed to have zero density and infinite compressibility)
Figure 1 shows that hollow monofilament will have a lower target strength than solid monofilament unless the air tube diameter is greater than about 0.6 of the filament diameter.

\[ R = [1 - (d_i/d_o)^2] 1.1 \]  \hspace{1cm} (5)

and

\[ K = \left[ \frac{0.7}{1 - (d_i/d_o)^2} \right]. \]  \hspace{1cm} (6)

Figure 1. Impedance mismatch as a function of air tube diameter.
Filled Monofilament

For comparison purposes, let us assume that the hollow monofilament contained a metal core, for example, copper. In this case, the relative density would increase to

$$R = \left[ 1 - \left( \frac{d_i}{d_o} \right)^2 \right] 1.1 + \left( \frac{d_i}{d_o} \right)^2 8.7$$

(7)

and the relative compressibility would decrease to

$$K = \left[ 1 - \left( \frac{d_i}{d_o} \right)^2 \right] 0.7 + \left( \frac{d_i}{d_o} \right)^2 0.014.$$  

(8)

In Figure 2, $Z_m$ is plotted as a function of (copper core diameter)/(nylon outside diameter), $d_i/d_o$. The plot shows that a nylon-jacketed wire filament will have a substantially higher target strength at all frequencies than a solid or hollow nylon filament of the same overall diameter.

<table>
<thead>
<tr>
<th>$d_i/d_o$</th>
<th>$R$</th>
<th>$K$</th>
<th>$Z_m$, dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>(solid nylon)</td>
<td>0</td>
<td>1.1</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>1.18</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>1.4</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>1.78</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>2.3</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>3.0</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>3.8</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>4.8</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>6.0</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td>7.3</td>
<td>0.14</td>
</tr>
<tr>
<td>(solid copper)</td>
<td>1.0</td>
<td>8.7</td>
<td>0.014</td>
</tr>
</tbody>
</table>

Figure 2. Impedance mismatch as a function of metal core diameter.
METHODS AND MATERIALS

The acoustic target strengths of single strands and of woven nets (both solid and hollow monofilament) with floats, float lines, sinkers, and sinker lines were measured at the APL acoustic test facility. Several frequencies were used for the tests. Because the Dall's porpoise echo-locates at frequencies from 100-200 kHz, the tests on the woven net, single floats, single sinkers, and net lines were conducted in this frequency region, namely, at frequencies of 150, 170, and 200 kHz. At these frequencies and with the transducers available, echoes from single strands were too low to be measured in the presence of ambient noise, so a higher frequency (230 kHz) was used to check the theory of thin-line target strengths experimentally. This particular frequency (230 kHz) was chosen because of the availability of a pair of narrowbeam (-6°) transducers with a high electroacoustic efficiency (>50%) and exceptionally low side lobes (= -30 dB). With these transducers, the signal/noise ratio was great enough to measure target strengths as low as -70 dB; this level of sensitivity was necessary to verify the theoretical predictions of the preceding analysis.

Attempts were first made to measure the net mesh at a range of 1.65 m, but the returns were below the background noise level. The range was therefore shortened to 1 m. The floats and supporting lines were measured before measuring the net in order to get above the background noise levels and to validate the measurement process. (Floats and lines present larger targets than the net, so the signals were well above the noise.) With the experience thus gained, it was possible to measure the target strength of the (unmodified) net mesh at 1 m range. Measurements on single filaments, at 230 kHz, were made at a range of 0.5 m.

The experimental setup is shown in Figure 3. The data were taken by slowly rotating the transducer assembly and recording the echoes as the transducer beams swept by the net. In this way it was possible to see the echo signals, even though in many instances they were not much above the background noise level. The data sheets (polar plots of the scanning transducer signals) are included in the appendix.

The target size calculation is printed on the data sheets included in the appendix. As an example of the calculation process, the information from the second page of the appendix is reprinted here.

\[
\begin{align*}
\text{FREQUENCY} &= 150.0 \text{ KHz} \\
V &= 33.5 \quad -R 0.0 \quad +T 168.5 \quad \text{LEVEL} = 194.0 \\
\text{OUTPUT} &= 13.0 \quad -G 40.0 \quad -S -197.8 \quad +R 0.0 \quad \text{SL} = 144.8 \quad \text{DBW} \\
T S \text{ AT } 150.0 \text{ KHz} &= -49.2 \text{ DB}
\end{align*}
\]
Figure 3. Experimental setup for target strength measurements. The acoustic transducer had a relatively narrow beam (−20°) at 150-200 kHz. The range, r, was 1 m for the net, line, and float experiments. The line supporting the float had a target strength about 20 dB lower than that of the float, so that its contribution was negligible and could be ignored during measurements of float target strength. For single line measurements, the narrowbeam acoustic transducers operated at 230 kHz, and r was 0.5 m in order to achieve a signal-to-noise ratio adequate to measure target strengths as low as -70 dB. For the float line, net, and float measurements, water depth, d, was 2 m. For the thin line measurements, d was 0.67 m.
The first line gives the frequency. The second line is the transmitting calculation. It says, in effect,

A transmitting transducer with a transmitting response, $T_v$, of 160.5 dB re 1 $\mu$Pa per volt of drive at a range of 1 m, being driven with a voltage of 33.5 dBV, will produce a level, at a range of 1 m ($R = 0.0$ means 1 m), of 194.0 dB (160.5 + 33.5) re 1 $\mu$Pa, which is the level impinging on the net.

The transmitting equation, in decibels, is

$$T_v + V - R = \text{level}. \quad (9)$$

The third line is the receiving calculation. It says,

If, for a receiving transducer with a receiving sensitivity, $S$, of -197.8 dBV re an incoming level of 1 $\mu$Pa, the signal received, after amplification of 40.0 dB (G 40.0 dB), has an output level of -13.0 dBV (OUTPUT -13.0), it follows that the incoming signal level (SL) at a range of 1 m must have been 144.8 dB re 1 $\mu$Pa.

The receiving equation, in decibels, is

$$SL - R + S + G = O, \quad (10a)$$

or

$$O - G - S + R = SL, \quad (10b)$$

where the "output" level is abbreviated "O". The fourth line is the resulting target strength.

If the net was ensonified with a level of 194.0 dB (re 1 $\mu$Pa), and the echo returned to the source (referenced to 1 m) has a level of only 144.8 dB (re 1 $\mu$Pa), then the loss due to the net is 49.2 dB, so the target strength, $TS$, is -49.2 dB.

The $TS$ calculation, then, is

$$\text{level(in)} + TS = \text{SL(out)}, \quad (11a)$$

or

$$\text{Target Strength (TS)} = \text{Received Signal Level (SL)} - \text{Transmitted Level (LEVEL)}. \quad (11b)$$

The high-frequency narrowbeam transducers were also used to scan the nylon net mesh (both solid and hollow monofilament) at a range of 0.5 m. These data (also included in the appendix) show a significant structure which was not evident in the broader beam, lower frequency tests, where the net structure was averaged out.
In order to test a hypothesis that the observed small-scale structure was due to the knots in the net, a single vertical monofilament line was suspended in the APL-UW acoustic tank and scanned at 230 kHz. A “figure 8” knot was then tied in this line. The observed target size increased approx. 4 dB. (Note: This knot had about half the bulk of the standard net knot.)

RESULTS

Comparison of Theory and Experiment

The results of the measurements are shown in Table I. The theoretical target strengths of the solid wires (steel and copper) are very close to the experimental values. The theoretical target strengths of the monofilament lines are significantly different, which probably reflects the fact that the physical characteristics of the monofilaments are somewhat different from the values cited in the reference works. Since the source of our particular samples is not known, and since we have no way of assessing the temperature and humidity changes, these differences probably reflect an incomplete knowledge of our sample. It is of more importance to note that, compared with solid monofilament, the target strength of the hollow monofilament theoretically decreased by 10 dB, and the experimental value decreased by 8 dB. The important feature is that the hollow monofilament has lost 8-10 dB in target strength. Hollow monofilament clearly does not improve net detectability for the porpoise; rather, it makes the net even more invisible than it had been previously with solid monofilament. Finally, the increase in target strength over solid nylon monofilament, by 8.5 dB, when going to metal-filled monofilament clearly reinforces the concept that the bulk characteristics of the thin line are controlling factors rather than the details.
Table I. Measured and theoretical target strengths, in decibels.

<table>
<thead>
<tr>
<th>Freq.</th>
<th>Float</th>
<th>Line (single)</th>
<th>Net (25 mm diam. hard sphere)</th>
<th>Net (unmod.)</th>
<th>Net (hollow)</th>
<th>Knot (solid line)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>-22.1</td>
<td>-42.1</td>
<td>-40.0</td>
<td>-49.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>170</td>
<td>-19.0</td>
<td>-38.0</td>
<td>-38.6</td>
<td>-46.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>-21.0</td>
<td>-36.0</td>
<td>-38.6</td>
<td>-49.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>230</td>
<td></td>
<td></td>
<td>-47 max</td>
<td></td>
<td>4 dB &gt;</td>
<td>4 dB &gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>to thin line</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-62 min</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Steel (0.5 mm)</th>
<th>Copper (0.25 mm)</th>
<th>Nylon (mono.)</th>
<th>Nylon (hollow) (0.5 mm/0.25 mm)</th>
<th>Plastic/Copper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory</td>
<td>-50.3</td>
<td>-62.2</td>
<td>-66.4</td>
<td>-76.4</td>
</tr>
<tr>
<td>230 kHz</td>
<td>-50</td>
<td>-62</td>
<td>-61</td>
<td>-69</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-52.5</td>
<td></td>
</tr>
</tbody>
</table>

Comparison of Float Echoes and Net Echoes.

Echoes from the floats were greater, by about 25 dB, than echoes from the unmodified net. The target strength of the floats, however, does not change with distance whereas, because of its spatial extent, the target strength of the net increases with distance. (Note Eq. 1.) The target strengths reported here have been normalized for a range of 1 m. For an increase of 25 dB in net target size, the distance would need to increase to approx. 300 m. However, at this range, the signal loss at 150 kHz would be about 140 dB (50 dB for spreading loss each way, 20 dB for attenuation each way, and -20 dB for the increase in net target size with range) — a virtually impossible situation for detection purposes.

At a range of 30 m, the net would have a target size of approx. -30 dB, and the float would still be -20 dB. Attenuation and spreading losses would be about 60 dB. The total signal loss for the net would be 90 dB, and that for the float, 80 dB. The lead weights would have about the same target strength as the net at this range. The lines are about 10 dB higher than the net at all ranges.

At a range of about 30 m, then, a porpoise approaching the net could no longer distinguish it from the floats bobbing on the surface and the lead lines suspended 10 m below the surface. At a range of 10 m, the floats have a target strength about 15 dB higher than that of the net. It should be specifically noted, furthermore, that the lower the frequency, the greater the disparity between float echoes (which are essentially frequency independent) and net echoes (which decrease as the cube of frequency, see Eq. 1).
Another important factor in this problem is the angle of the net with respect to the porpoise's line of (acoustic) sight. This is best seen in the 230 kHz measurements, where the maximum excursion of the returns drops off rapidly with angle, both for the solid and the hollow monofilament nets. This is because large "in-phase" echoes occur less frequently at nonperpendicular incidence and are not as likely to include as large a portion of the net as at perpendicular incidence. Because the net is continually moving in the ocean, both horizontally and vertically, the likelihood of a maximum target size return becomes extremely low. Thus, if the porpoise approaches the net perpendicularly, he may occasionally get a glimpse of something, but it will not reappear in succeeding pings. If the porpoise approaches the net at any significant angle, the average level will be slightly higher, but no random large returns will be observed.

Salmon of the size taken by the high seas fishery have a target strength ranging from -50 dB (tail aspect) to -25 dB (side aspect), about the size of the floats. Entrapped in the net, beam-aspect fish would appear as isolated objects to be pursued (if they are recognized as fish) or to be avoided. In either case, at close range, their echoes would be larger than the net echoes by perhaps 10 dB, causing the porpoise to lose sight (acoustically speaking) of the net in their vicinity.

Hollow Monofilament Echoes

Several things can affect the target strength of the hollow monofilament line:

1. The image of the air tube inside the monofilament is not the same size as the actual air tube, because of defocusing due to the refractive index of the nylon. This is probably not a very large factor since the line is small compared with the wavelength of the sound.

2. Because of their resonant properties, air bubbles can appear to be up to 1000 times greater in area than their actual physical size. Air tubes can behave similarly, but, because the tubes under discussion here are much longer than the wavelength of the incident sound, they would not resonate and hence would not exhibit the large target strengths of resonant bubbles.

3. The time for hollow monofilaments to fill with water is not known — they are rather tightly sealed at the knots — but air compressed to a small bubble in a knot may increase the target strength of the knot, which is already slightly increased simply due to the knot's larger size compared with the line.

4. The most critical feature affecting the use of hollow monofilament to increase the target strength of a net is the fact that, unless the air tube diameter is greater than 0.6 of the monofilament diameter, it actually decreases the target strength, because of its bulk characteristics.
CONCLUSION

The conclusion from all this, of course, is that the porpoise, while he may get some indications of the net's presence at longer ranges (>>30 m), will essentially see only the floats bobbing on the surface (with an occasional glimpse of the lead lines below) if he approaches nearer to the net than 10 m. The knots in the net will give him the best echoes, but the hollow monofilament is no better (both experiment and theory indicate it is several decibels worse) than the solid monofilament. It does appear, however, that the hollow monofilament knots are slightly better reflectors over wider angles than the solid monofilament knots. This suggests that it may be possible to construct a net with enhanced reflection capabilities at the knot intersections, which might significantly increase the porpoise's awareness of the net structure without (it is hoped) incurring a concomitant (or at least a significant) loss in fishing effectiveness. A more promising approach, however, and one that would better enhance the target strength of the net monofilament, consists of making the monofilament of a composite material either by including a wire core in a hollow monofilament or by filling the solid nylon monofilament with metal particles that, in the aggregate, would occupy about 20-25% of the total nylon volume. The monofilament bulk density would increase from 1.1 to about 3, the bulk compressibility would decrease from 0.7 to about 0.5, and $Z_m$ would increase about 10 dB — making the target strength of the net about the same as that of the net lines at all ranges. To the porpoise, this may make the net acoustically visible as a sparse mesh at short range, whereas at present the net will become acoustically transparent at short range.

REFERENCES

APPENDIX

Acoustic Polar Plots
Figure A1. Echoes from single strands at a frequency of 230 kHz and a range of 0.5 m.

- 0.5 mm music wire: TS = -50 dB
- 0.5 mm plastic with 0.25 mm copper core: TS = -52 dB
- 0.5 mm nylon monofilament: TS = -61 dB
- 0.25 mm copper wire: TS = -62 dB
- 0.5 mm plastic with 0.25 mm hollow core: TS = -69 dB
Figure A2. Net, 150 kHz, TS = -49.2 dB
Figure A3. Net, 170 kHz, TS = -46.6 dB
Figure A4.  Net, 200 kHz, TS = -49.6 dB
Figure A5. Float, 150 kHz, TS = -22.1 dB
Figure A6. Float, 170 kHz, TS = -19 dB
Figure A7.  Float, 200 kHz, TS = -21 dB
Figure A8. Line, 150 kHz, TS = -42.1 dB
Figure A9. Line, 170 kHz, TS = -38 dB
Figure A10. Line, 200 kHz, TS = -36 dB
Figure A11. Solid Net, 230 kHz, TS = -43 to -57 dB
Figure A12. Hollow Net, 230 kHz, TS = -47 to -62 dB