MEASURING DEEP-OCEAN MACHINERY NOISE (AT DEPTHS IN EXCESS OF I KILOMETRE)

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1 INTRODUCTION

Subsea noise monitoring has a long history, with particular relevance to military activity, and environmental concerns. However, there is an increasing need to be able to survey the distribution of noise associated with industrial activity. For example, acoustic positioning and telemetry systems can be adversely affected by unwanted noise and it is important to be able to locate and analyse such noise to minimise the risks of system failure.

The exploitation of marine resources, such as oil, routinely requires equipment to be deployed to water depths in excess of 1000m, withstanding water pressures greater than 100bar (10 MPa or 1450 psi). The role of the human diver has been superceded in the majority of such developments by the remotely operated vehicle (ROV). Video links allow the pilot to control the ROV from his desk on the mother vessel. Many work class ROVs now have a depth rating of 3000m, with some able to descend to the abyssal floor at 5 - 6km. Acoustic systems used for navigation, include scanning sonars to identify structures at short range and transponder systems to allow the ROV to be positioned with respect to the vessel or an array of seabed beacons.

2 USING ROBOTIC VEHICLES TO MAKE NOISE SURVEYS

The Oceaneering "Magnum 49" ROV, being launched in its cage with a Sonardyne type 8031 hydrophone (at 60°), and a directional "Compatt" transponder (held vertically).

ROV systems - two stage deployment

The ROV (Remotely Operated Vehicle) shown is contained within a steel cage, hung from a heavy duty "umbilical" cable, from which it emerges when at the desired depths. The almost neutrally buoyant ROV then moves away from the cage towards the operation site. A lighter second cable, the ROV "tether", is paid out by the tether management system (TMS) within the cage. The ROV is thus unimpeded by the drag of the main umbilical.

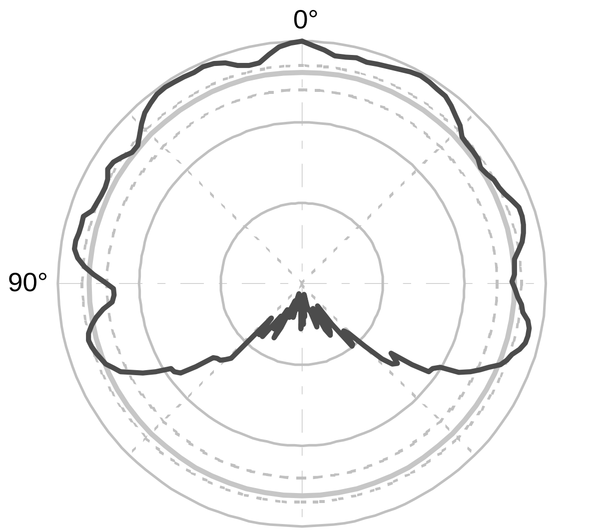
Hydraulic power is used by work class ROVs which are equipped with robotic arms, used to construct the underwater plant and pipelines associated with subsea oil recovery. In many cases the thrusters used to propel the vehicle are also hydraulic. ROV performance is limited by the hydrodynamic drag on the tether, and high power levels are required to overcome this, and to be able to lift heavy objects into place. This can create acoustic interference.

2.2 Use of a noise shield to overcome ROV self noise

Long range acoustic systems are vulnerable to noise near the receiver. Hydraulic pumps and control systems create significant ultrasonic noise, which can reduce the range of acoustic positioning systems. This ROV self noise is therefore of concern to subsea surveyors and construction contractors. Its effects are quite localised, and of little significance at more than a few hundred metres from the ROV, but the local distribution of sources on the vehicle need to known if the use of acoustics is to be optimised.

It is thus surprising that the typical noisy ROV can itself to be measure noise, but this is again possible when the sources of self noise are understood. A shielded hydrophone can be used to retain sensitivity over a wide "field of view" in front of the ROV whilst minimising the sensitivity to self noise. Sonardyne manufacture a 3000m rated noise shield for use with the "RovNav" system transducers, to improve the performance of Long BaseLine (LBL) ROV navigation. The RovNav transducer receives signals from the seabed transponders which form an array covering the field of operation. The size of the operational area will then be affected by ROV self noise.

The shield is seen in the photograph as a pyramidal shape, mounted at an angle, with the small hydrophone at its apex in a guard. This shape provides shielding over a roughly ± 45 ° conical direction, whilst maintaining a sensitivity over most of the remaining extended hemisphere.



Freq: 28·7kHz (Sonardyne Channel 10)
Circles at 10dB intervals re maximum response.
Broken circles at -3dB and -6dB.
D.I. at 0°: 3·8dB. Blue circle: D.I. = 0dB
N.R. Index between 135° abd 225°: 20.3dB

In the polar response shown here, the 0° direction indicates the pyramid axis, opposite the shielded direction of 180°. The response shown has been integrated in two ways. The average over all directions (assuming an axisymmetric response) is shown by the blue circle. The response at 0° is larger by the directivity index (DI) for this direction.

The average over the ±45° shielded cone (135° - 225°), is less by a 20.3 dB ratio. This noise reduction ratio (NR) provides a measure of the performance of the shield when properly aligned.

The shielding is frequency dependent, with the best results obtained at the higher frequencies. However the response over the unshielded directions remains substantially unaffected by this design, with minimal interference generated by the energy reflected from the shield. Additional anti-vibration features are used in the base to avoid flanking transmission.

3 DEVELOPMENT OF A DEEP OCEAN NOISE HYDROPHONE

3.1 A decade of near surface noise surveys

Sonardyne have conducted surveys of underwater noise down to 180m depth for well over 10 years. These are provided as a service to clients to help assess the inevitable compromises involved in their operations. Thruster noise, particularly on dynamically positioned (DP) vessels has been the most important issue, but many ROV noise surveys have also been made, both in open water, underneath ROV support vessels, and within the confines of ROV test tanks. The open water tests provide a more representative environment, but their costs are often higher, unless they can be combined with other work.

The type 7773 noise hydrophone system uses a hand operated cable drum with 200m of 7 core cable. This supplies DC power and returns the hydrophone signal, suitably amplified. In addition a calibration signal is generated by the surface equipment and passed down, through the hydrophone and back up the signal path. The wide band calibration signal has a nearly "white" spectral distribution over 5 - 100 kHz. It provides an essential continuity check through the vulnerable underwater cable, which can easily be damaged in deployment, especially when the hydrophone is mounted on an ROV, rather than being deployed separately.

3.2 Techniques for deep ocean noise monitoring

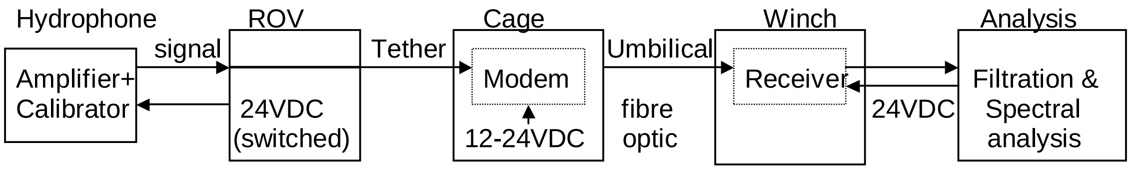
When the depths are too great for the type 7773 cable system to be used, other options need to be considered. Independent battery operated data logging systems can be used, from which data is retrieved when the instrument is recovered. However, the delay in getting the results limits the productivity, and requires a rigid plan with no scope to respond to the findings.
Real time information can be telemetered acoustically, but the data rates limit the bandwidth of the signal, so an optical fibre system was used. Deep ROVs routinely use fibre optic communications through their umbilical cables, and optical signal distances of many kilometres can be achieved with very little attenuation, especially in mono-mode fibres.

3.3 The fibre optic link and choice of modulation system

Whilst fibre optic transmission provides excellent bandwidth, the dynamic range and linearity is limited. This limitation can be overcome using a frequency modulation of the optical signal. A voltage to frequency converter is used to drive a laser diode which emits infrared light pulses compatible with monomode optic fibre, fitted in an industry standard type FC receptacle.

This scheme requires the use of a spare terminated fibre within the ROV umbilical. Whilst umbilicals typically have many such fibres, only one may be in use, with the signals being multiplexed. Multiplexing schemes are often proprietary, with no common standard, so the "hot spare" fibre, already terminated, provides a well defined independent link. Where necessary (as on the Magnum) an adaptor can be used to connect to the alternative ST connector type.

The 8031 provides deep modulation of a 2MHz carrier frequency, to occupy most of a 4MHz bandwidth. The same chip can be configured to demodulate the output of the receiver PIN diode, and thus reconstruct the analogue signal for analysis at the surface. The block diagram shows the remotely switched 24VDC supply to the hydrophone supplied by the ROV. This initiated a 100 second calibration phase, after which the system reverted to listen mode.



3.4 The tether and surface cabling

The proven line drivers of the type 7773 were used to drive a screened twisted pair in the tether of the Magnum 49. The ROV had an available electrical high pressure connector to which the hydrophone cable was linked. It was found convenient to wait until the main winch was stationary before connecting the fibre optic system receiver at the surface, avoiding any need for the signal to be passed through the fibre optic rotary joint (FORJ). Whilst tests had shown the system had sufficient optical attenuation budget to cope with the typical losses a FORJ may impose, this feature has yet to be tried in service. A screened twisted pair was then used to connect the optical receiver module to the demodulator and filter system at the analysis station.

3.5 Analysis at the surface

An HP 35560A analyser is used to deliver on site results across the full 5-100 kHz band on paper and to log them to disc. In addition to any spectral peaks, the noise is integrated over defined bands, such as the Sonardyne MF band , 18 - 36 kHz. A set of filters and true RMS meter provide additional information on real time amplitude fluctuations.

This band noise level can be used to predict the range from which a known signal can be received at the ROV. Such calculations require a knowledge of the polar responses of the instruments. The transponder shown has a directional transducer, to assist it communicating with the vessel on the surface. An Ultrashort baseline (USBL) transducer array, mounted in a transceiver on a pole deployed below the vessel, can then determine the range and direction of the transponder and the ROV.

The video link is important when surveying underwater structures, but is often limited in range to about 10m. The high frequency (over 500kHz) scanning sonar systems will extend the range out to 100m or more. This is usually sufficient for an ROV on a fixed installation. Where greater range is required as when surveying a new site, or placing the initial structures, medium frequency (5-100 kHz) acoustic positioning systems are used. Such systems make use of transponders such as the Compatt (Computing and telemetry transponder) seen in Fig 1. These are usually attached, with flotation, to a releasable seabed weight, but can also be used to position the ROV in relation to the vessel above. The noise measured in this band by the 8031 system is used to plan the optimal distribution of such equipment.

The pilot's control panel shown here includes the video monitors and the scanning sonar display. Equipment in this trial was set up just to the left of the picture, on the desk of Mike Brett , the ROV supervisor seen on the right.

3.6 The maximum operational range

The relevant sonar equation is relatively simple if both hydrophone and transponder have a uniform response over the likely signal directions, and if the transponder, when in service, is mounted at the noise measurement point.

$$PL = SL - 20 \log R - \alpha R > NL + DT$$

The minimum detectable signal sound pressure level (PL), at the position of the hydrophone is then determined by the noise level (NL) measured. Both these are usually given in decibels referred to root mean square (RMS) pressure (dB re 1μPa, or dB//μPa). The RMS averaging procedure used here is taken over a 30 separately logged records each of which is analysed by a Fast Fourier transform (FFT). Each gives a contribution to an average spectrum, which is then integrated over the band to give the RMS noise level.

The detection threshold (DT) is the signal to noise ratio required for reliable detection. DT > 5dB is required when white noise covers the MF band (18-36kHz) for the transponder shown.

For a specified source level (SL) the maximum range R can then be calculated. If the source level is specified in dB referred to 1 microPascal · metre (dB//μPa·m) then the range is also given in metres.

As an example if the source level is 198 dB//µPa·m and the noise level is 130 dB//µPa over the octave band, the maximum acceptable transmission loss (TL) is 63 dB. This corresponds to a range of about 1km vertically at frequencies around 20kHz (attenuation α of about 3dB/km).

The additional corrections for directional transponders will not be considered here.

4 HYDROPHONE CALIBRATION

The transducer used in the 8031 system is a spherical omnidirectional type 7859, developed for the Sonardyne EHF band (50-110 kHz) Compatt transponder.

The frequency variation at ambient pressure was calibrated using a reverberant tank technique described in Ref #2. White noise was injected into the tank using a generator where electrically white noise is fed into a spherical transducer, parallel tuned to the lower frequency of the desired band, and flat to within 6dB over 4 octaves (5 - 80 kHz).

The device under test was then compared with the reference hydrophone immersed in the same reverberant field. This rapid test gave data for the average sensitivity over all directions, and distribution over all the frequencies of interest. There is little benefit in a more precise calibration in specified directions for usage where the direction is not well known. However, any major effect of pressure is of concern.

4.1 The effects of pressure on the transducer

The type 7859 was tested in 1996 to 3000psi (>200bar, 20MPa) to check both the survival pressure and the pressure effects on the sensitivity. The tests were intended to provide confidence that there were no major failures and that a sufficient sensitivity (particularly in transmission) was retained. However, the receive sensitivity data has proved useful here.

The large 10,000 psi rated pressure vessel at Southampton Oceanographic Centre were hired on 3 separate days. It had internal dimensions 0.95m ID and 1.2m deep, large enough to perform gated pulse two way reciprocity tests between two nominally identical transducers at a range of 0.44m. Very short (0.25 millisecond) signals were used for the measurements, which could be seen to be free from reverberation. The transducer response stabilised quickly, due to the good match to the water, and measurements could be made after 10 cycles.

can be used to find its receiver sensitivity M in units of V/Pa. M and S are related by Tests were made at both low and high power, of which only the low power are discussed here. High power tests were necessary to establish the source levels achievable at voltages above the linear region, where the transmit voltage response may be reduced. The voltage ratings of the connectors in the lid of the pressure pot limited the power which could be applied when there was no amplifier in the transducer housings.

4.2 Two way reciprocity

Standard hydrophones such as the B&K 8104 often used for tank testing are unsuitable for high pressures. However, by using passive housings (no amplifier), at low power, the EHF transducer can be calibrated both as a hydrophone and as a projector using the principle of reciprocity. This linkage between the projector and receiver sensitivities then only depends on the frequency and the properties of the water. In this analysis the two transducers are considered to be identical.

The current (amps) to the projector was measured by monitoring the voltage across a 10Ω resistor in series. This was used to find the current projector sensitivity S. The transducer can be considered as a "simple source" emitting spherically spreading waves. The rms acoustic pressure P is then inversely proportional to the range R, so that the product of pressure and range P·R is constant (Ref #2), and the units of projector sensitivity S are Pa.m/A. The voltage generated by the other transducer

$$M/S = 2\cdot\lambda / (\rho\cdot c) = 2 / (\rho.f) \qquad \text{Ref \#1 pp 164,168, 391}$$

Here ρ is the water density in kg/m^3, and f is the frequency in Hz.

Unitary analysis helps to provide confidence. The units of M/S are V·A/(Pa^2·m). The numerator V·A is equivalent to power in watts, or force times velocity (Newton·m/s), so the units can be reduced to N/(Pa^2·s). However Pa = N/m^2 = kg/(m·s^2), and if these terms are substituted, the units of M/S become m^3·s/kg, matching the units of 2/(ρ·f).

The predicted acoustic pressure at the hydrophone is then the projector sensitivity S multiplied by the current A and divided by the range R. The voltage V generated by the hydrophone is then found by multiplying by sensitivity M.

$$V = M\cdot S\cdot A/R \quad \text{or} \quad M\cdot S = V\cdot R / A$$

Again the units can be checked as V·m/A on both sides of the second equation. Both M and S can now be found

$$M^2 = 2\cdot V\cdot R/ A\cdot\rho\cdot f \qquad \& \qquad S^2 = V\cdot R\cdot\rho\cdot f /2\cdot A$$

This analysis assumes two identical transducers. In order to check this assumption, the connections were reversed, and the ratios of V/A compared. As seen in results below, they agreed to within 10%, (0.8dB) confirming their similarity.

4.3 Test results

Summary test results are shown below. The columns show pressure and frequency, followed by the measured input amps and volts, and output volts. Results are in pairs designated “#1 to #2” and “#2 to #1” as the connections are reversed. Both linear and decibel results are shown. The hydrophone sensitivity results are a good indication of the variation with pressure. At 80 kHz they varied from 91.6 to 101.2 µV/Pa. The drop from the peak at 1000psi to 3000psi is believed to represent the effects of pressure generated stress on the ceramic. The lower results at 0 psi are more likely to be due to wetting problems in the somewhat oily water in the pot. The variations are not deemed to be significant in their effects on Compatt performance.

Direc'n	Freq'cy	Pressure	Input (pk/pk)		Output	Projector Sensitivity		Hydrophone Sensitivity	
	kHz	psi	amps	volts	Volts	Pa·m/V	dB//µPa·m/V	µV/Pa	dB//V/µPa
1 to 2	80	0	1.594	281.6	1.075	19.5	145.8	91.8	-200.7
2 to 1	80	0	1.453	284.8	1	17.75	145	92.7	-200.7
1 to 2	80	500	1.563	287	1.156	19.65	145.9	96.2	-200.3
2 to 1	80	500	1.484	293.8	1.156	18.7	145.4	98.7	-200.1
1 to 2	80	1000	1.531	288.8	1.219	19.84	146	99.8	-200
2 to 1	80	1000	1.460	296.6	1.203	18.8	145.5	101.2	-199.9
1 to 2	80	1500	1.563	295.3	1.203	19.48	145.8	98.1	-200.2

2 to 1	80	1500	1..5	301.6	1.187	18.56	145.4	99.5	-200
1 to 2	80	2000	1.578	300.2	1.156	18.88	145.5	95.7	-200.4
2 to 1	80	2000	1.531	306.4	1.141	18.1	145.2	96.5	-200.3
1 to 2	80	2500	1.609	308.3	1.119	18.26	145.2	93.2	-200.6
2 to 1	80	2500	1.578	314.5	1.1	17.58	144.9	93.3	-200.6
1 to 2	80	3000	1.641	318	1.106	17.77	145	91.8	-200.7
2 to 1	80	3000	1.609	325.8	1.081	16.98	144.6	91.6	-200.8
1 to 2	60	1000	2.781	489.2	0.65	9.98	140	62.4	-204.1
2 to 1	60	1000	2.828	489.2	0.662	10.16	140.1	62.5	-204.1
1 to 2	60	2000	2.594	493.1	0.618	9.33	139.4	63	-204
2 to 1	60	2000	2.594	483.3	0.618	9.52	139.6	63	-204
1 to 2	60	3000	2.25	481.7	0.487	7.9	138	60.1	-204.4
2 to 1	60	3000	2.234	478.6	0.487	7.92	138	60.3	-204.4
1 to 2	100	1000	1.516	435.9	0.487	9.25	139.3	56.7	-204.9
2 to 1	100	1000	1.531	432.8	0.475	9.24	139.3	55.7	-205.1
1 to 2	100	2000	1.516	441.6	0.487	9.13	139.2	56.7	-204.9
2 to 1	100	2000	1.531	437.2	0.494	9.33	139.4	56.8	-204.9
1 to 2	100	3000	1.516	448.9	0.494	9.04	139.1	57.1	-204.9
2 to 1	100	3000	1.516	447.3	0.506	9.19	139.3	57.8	-204.8

The hydrophone results at 60 kHz and 100 kHz are equally stable. However, the projector sensitivity at 60 kHz fell by 2 dB with respect to the 1000psi results. There was still good agreement between the forward and reverse paths.

The receive sensitivity at 60 kHz of 60 µV/Pa (-204 dB//V/µPa) varied less than 1dB over the pressure range 0 to 3000 psi (2km depth rating). This is despite a compressive stress of 143 MPa in the piezoelectric ceramic. This provides a good level of confidence for the deep ocean work, since the receive sensitivity will be flat below the 80 kHz resonant frequency if diffraction effects are ignored. Nevertheless a more comprehensive set of tests would be advisable if critical measurements were planned.

5. References

[1] Kinsler, Frey, Coppins & Saunders "Fundamentals of Acoustics", J.Wiley & Sons 1982.

[2] Hazelwood R.A., Robinson S.P. "Acoustic power calibration in reverberant tanks", Proc I.O.A. Vol 20 Pt 3 (1998)