Proceedings of the Institute of Acoustics

THE AUTOMATION OF THE THREE-TRANSDUCER RECIPROCITY CALIBRATION METHOD

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INTRODUCTION

The School of Electronic and Electrical Engineering, University of Birmingham, is frequently asked to perform acoustic measurements which require the use of an accurately calibrated reference hydrophone. These measurements include beamplots of commercial transducers, the validation of acoustic emission levels from mechanical equipment and the calibration of reference hydrophones for other organisations.

Reference hydrophones are known to age, and are therefore re-calibrated at six-monthly intervals, to monitor changes in sensitivity and to highlight any major variations introduced by rough handling. The three-transducer reciprocity method of calibration is an absolute method only requiring the accurate measurement of a number of voltages and currents. However, it is extremely laborious and time consuming.

This paper describes the automation of the three-transducer reciprocity method of calibrating underwater transducers and the precautions taken to reduce the errors introduced by the transient response of the transducer when calibrated in a small tank using pulsed signals.

THE THREE-TRANSDUCER CALIBRATION MEASUREMENT

The reciprocity principle was considered by Rayleigh [1] for use in air acoustics and later used by MacLean [2] for calibrating underwater transducers. A variety of reciprocity calibration techniques and the problems associated with them are described in the classic text by Bobber [3].

The three-transducer reciprocity method uses three transducers T1, T2 and T3, as shown in figure 1. The method utilizes the measured current flowing in the transducer when used as a projector, I_{T1}, I_{T2} and I_{T3}, and the voltage received on the transducers E_{T1}, E_{T2} and E_{T3}. One of the transducers should be reciprocal, a requirement that is difficult to prove. However, the usual test is to use two transducers of different constructions in alternate transmit and receiving arrangements. If the following is proved then the transducers can be considered to be reciprocal.

THREE-TRANSDUCER RECIPROCITY CALIBRATION

$$\frac{E_{T2}}{I_{T1}} = \frac{E_{T1}}{I_{T2}}$$

The transducer to be calibrated is T1, the reciprocal transducer is T2, and a third transducer, T3, is used only as a projector. The receiver sensitivity, M1, of transducer T1 is given by:

$$M1 = \sqrt{\left(\frac{2}{(\rho f)}\right)\frac{(E_{T21}.E_{T31})}{(E_{T32}.I_{T2})}}$$

where

$M1$ is the receiving sensitivity of transducer T1

ρ is the density of medium in which the transducers are calibrated

f is the operating frequency

E_{T21} is the voltage received on T1 when transmitting on T2

E_{T31} is the voltage received on T1 when transmitting on T3

E_{T32} is the voltage received on T2 when transmitting on T3

I_{T2} is the transmit current measured in T2

This equation is a modified form of the reciprocity calibration equation, where all the ranges between transducers are 1m and the sensitivity is quoted with respect to a range of 1m.

The calibration process requires a measurement of the current flowing in the reciprocal transducer whilst transmitting. This measurement may be made by means of the potential developed across a series resistor, a current transformer or by the indirect method of measuring the impedance and terminal voltage of the transducer. Care should be taken to ensure that the current measurement does not alter the potentials on the transducer connections with respect to the water surrounding the transducer.

The current measurements taken to obtain the results described in this paper were made by measuring the impedance of the transducer, Z, at the same drive levels as used for the other measurements. The impedance measurement instrument used a continuous excitation, and it would therefore be expected that a reflected impedance error would be introduced as a result of the standing waves set up in the measurement tank. However, it can be shown that these errors are small compared with the overall variations encountered during the calibration process. The receiver sensitivity of transducer T1 obtained by measuring the impedance of the reciprocal transducer is given by:

$$M1 = \sqrt{\left(\frac{2}{(\rho f)}\right)\frac{(E_{T21} . E_{T31} . Z_{T2})}{(E_{T32} . E_{T2})}}$$

where
Z_{T2} is the impedance of transducer T2
E_{T2} is the terminal voltage of transducer T2 when used as a projector

The calibration process requires four voltage measurements plus an impedance measurement for each of three different spatial combinations of transducers. The traditional method of re-positioning transducers and re-connecting measuring instruments is extremely laborious and time consuming. To calculate the sensitivity and the associated statistical parameters for a dozen frequency points would take several days. This paper describes the equipment used to reduce this measurement period to a few hours.

POSSIBLE SOURCES OF ERROR

There is a large number of possible sources of error that affect the accuracy of the calibration of an underwater transducer. Transducers are sensitive to temperature changes, rough handling, corrosion, water ingress, gas bubbles, drive power levels and pressure changes due to movement. The effects of each of these parameters should be minimised.

Errors will be introduced by the finite input impedance of the measuring instruments, which will therefore not measure the received voltage under open circuit conditions. This can be corrected by measuring the impedance of the transducer and the measuring instrument and then estimating the open circuit voltage necessary to cause the measured value.

Traditionally, the three transducers would be mounted in a linear manner. This would involve the removal of one transducer, and the replacement by another, to maintain the same field conditions. Such large-scale movements have been avoided by mounting the transducers on a triangular frame with the addition of three rotators to maintain the correct spatial alignment.

THREE-TRANSDUCER RECIPROCITY CALIBRATION

The three transducers should not be placed in close proximity, because the presence of one transducer can influence the sensitivity of a neighbouring transducer. This effect can also be described in terms of the transducers not being within a true free-field condition. As the transducers are to be calibrated within a tank, pulsed calibration techniques must be used to establish an equivalent free-field condition. The use of pulsed excitation generates additional problems with respect to the effects of the transient response of the transducer and of the accurate measurement of the energy contained within a broad-band pulse.

A poor signal-to-noise ratio at the receiver will lead to large errors in the measured sensitivity. This is a particular problem at low frequencies where the efficiency of the transmitting transducer will be very low.

The effects introduced by using pulsed calibration techniques and as a result of a low signal-to-noise ratio can be minimised by using a narrow-band receiver with a bandwidth matched to that of the transmitted pulse. For example, with the transducers mounted on a triangular frame and separated by a distance of 1m, a multi-path signal via a second transducer would have to travel a distance of 2m. This indicates that a pulse length in the water should be less than 1m, which is equivalent to a duration of 667μs when the velocity of propagation is $1500ms^{-1}$. The spatial arrangement limits the pulse duration, and therefore the frequency increments between uncorrelated calibration measurements are limited to 1500Hz for the arrangement described in this paper.

The received signal is obtained from the amplitude spectral density

$$E_T(\omega) = \sqrt{E(\omega)E(\omega)^*}$$

where $E(\omega)$ is given by the Fourier Transform

$$E(\omega) = \int_{t1}^{t2} W(t).E(t).\exp(-j\omega t) \quad dt$$

where
$W(t)$ is a temporal weighting function
$E(t)$ is the received signal
ω is the operating frequency in radians s^{-1}

A discrete version is evaluated with the observation time being equal to the additional propagation period of the first multi-path signal. The weighting function $W(t)$ is chosen as an optimal window function, to provide a flat-top to the frequency domain cell within the constraints of the limited observation period. This process provides a signal-to-noise ratio improvement of the order of 20dB for the arrangement described.

To reduce the variance of the measured amplitude, an ensemble average is taken of the amplitude spectral density results. The signal-to-noise ratio improvement as a result of the average would be expected to be of the order of $1.5\log_2 N$, where N is the number of averages. A total of twenty averages were used for the results presented in this paper, this corresponds to an improvement of about 6.5dB. The total improvement in the signal-to-noise ratio obtained by the receiver is therefore of the order of 26dB. To obtain a sensitivity measurement with a repeatability of the order of 0.1dB a signal-to-noise ratio at the output of the receiver of +40dB is required. Therefore, signal-to-noise ratios of the order of +14dB at the transducer are sufficient to meet this criterion.

MICROPROCESSOR SYSTEM

The measurement rig is shown in figure 1. The three transducers are mounted on a triangular frame, as described earlier, with an inter-transducer spacing of one metre. The transducers are mounted on flooded, glass-reinforced tubes, to provide a rigid mounting structure with an acoustic impedance as similar to that of water as possible. The hollow tubes permit the cable of the hydrophone to be threaded axially through the transducer mount. Each hydrophone has a rotation mechanism associated with it, so that the same angular portion of the transducer is used at all times with respect to the other transducers.

Figure 2 shows the equipment which is used to perform the calibration measurements. A microprocessor controlled switching matrix is used to route the signals from the three transducers to an impedance bridge, a pulsed transmitter and a Fourier Transform receiver. This unit also controls the three rotators to ensure that the transducers are pointing in the correct direction for each measurement. A front panel control is also provided on this switching matrix so that manual measurements may be made. All the component parts of the measurement system are linked together via an IEEE488 interface to a host computer which performs the routing, controlling and sensitivity calibration calculations.

RESULTS

Figure 3 shows the results of calibrating a one-inch ball hydrophone in increments of 1kHz from 10kHz to 100kHz. This transducer shows a variation in received sensitivities of between -194.7 dB re 1 μPa and -204 dB re 1 μPa. This transducer has been calibrated many times before and the circular markers show the results obtained at the National Physics Laboratory, India [4] and other independent measurements made a Birmingham for the same transducer. These calibrations were made over a period of several years, using the impedance measurement technique with a broad-bandwidth receiver.

To illustrate the problems of accurately calibrating an underwater transducer, the measurement rig was raised out of the water, a wetting agent was applied to the face of the transducers, and the calibration was then repeated. The results for the two calibration runs are shown in figure 4. It can be seen that there is good agreement across the majority of the frequency range. Figure 5 shows the difference between the two calibration runs. The mean of the difference between the two runs is 0.003dB and the standard deviation is 0.099dB. These results indicate the difficulty in attempting to repeatedly calibrate a transducer with consistent results.

Figure 6a shows the time-domain waveform recorded for a received signal consisting of a single cycle at a frequency of 10kHz. It can be seen that the signal is of the order of a few tens of microvolts in amplitude and that there is a significant noise component superimposed on the received signal. This unwanted component will occur as a result of the transient response of the transducer and as a result of the thermal and ambient acoustic noise levels. Figure 6b shows the equivalent frequency-domain representation of this signal. Three components are clearly visible: the wanted component at 10kHz, an unwanted component at 50kHz resulting from the emissions of a nearby display screen, and the coloured ambient noise spectra peaking at the resonant frequency of the transducer at a frequency of 76kHz. The value of received voltage used in the calibration is selected from a single frequency cell as indicated on the diagram. It can be seen that a conventional measurement utilizing a broad-band receiver would be subject to significant measurement errors under these conditions.

The results described in this paper are based on the assumption that the calibration process is a linear process. In order to calibrate at very low frequencies this assumption must be pushed to the limiting case of using a single cycle for the transmit pulse. An experimental verification of this is shown in figure 7 for a frequency of 10kHz. The calibration process is repeated for a number of cycles in the transmit waveform varying between one and eight. The calibration value changes by less than 0.1dB, except for a slight variation when using a single cycle, which corresponds to a signal-to-noise ratio at the transducer of less than 0dB.

CONCLUSIONS

This paper describes the automation of the three-transducer reciprocity calibration method and the application of modern signal processing techniques to permit measurements to be made at very low signal-to-noise ratios and at low frequencies.

Results have been presented for a number of transducers which highlight the problems of accurately calibrating transducers whilst obtaining consistent results. This system can now provide the facility to undertake a detailed study of the factors that influence the calibration accuracy of underwater transducers.

The results presented in this paper may indicate that the calibration of transducers can be considered by traditional linear systems theory and hence that transducers can be calibrated with waveforms other than that of continuous sinusoids. If this is true, then the next phase is to use broad-band signal processing techniques to calibrate a complete frequency range in a matter of seconds.

REFERENCES

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[3] R J BOBBER, 'Underwater Electroacoustic Measurements', Naval Research Laboratory, Washington, D.C. (1970)
[4] B V SMITH, 'Report to British Council on Visit to NPL, India' (1989)

THREE-TRANSDUCER RECIPROCITY CALIBRATION

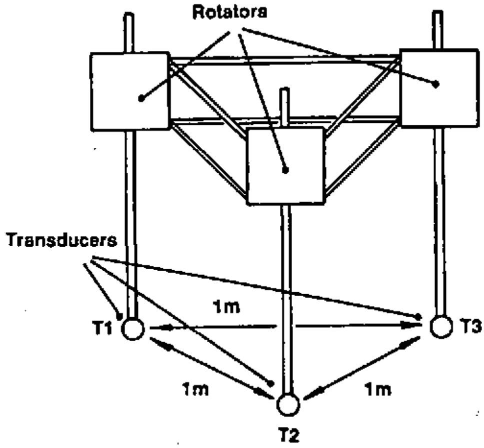

Figure 1 Three-Transducer Reciprocity Calibration Rig

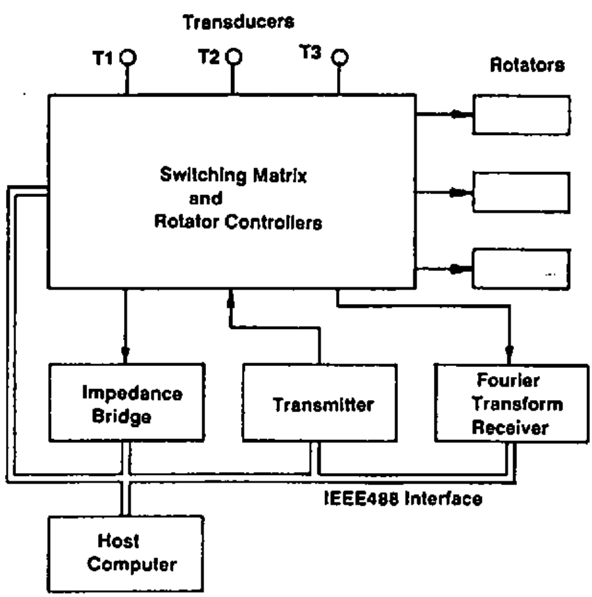

Figure 2 Calibration Equipment

THREE-TRANSDUCER RECIPROCITY CALIBRATION

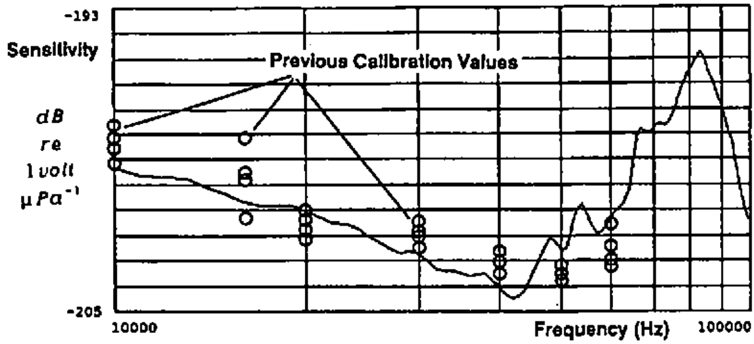

Figure 3 Receiver Sensitivity of a 1-Inch Ball Hydrophone

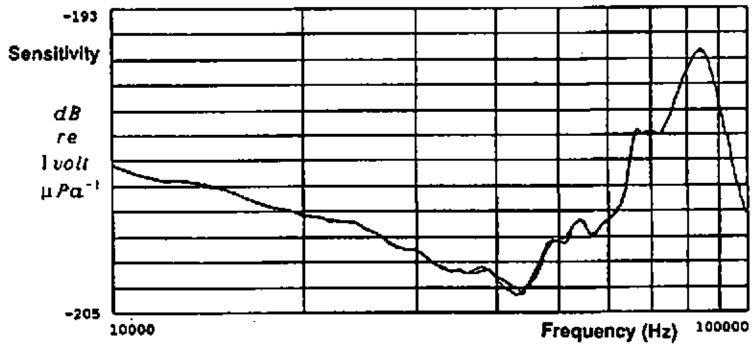

Figure 4 Two Calibration Measurements Taken 24 Hours Apart

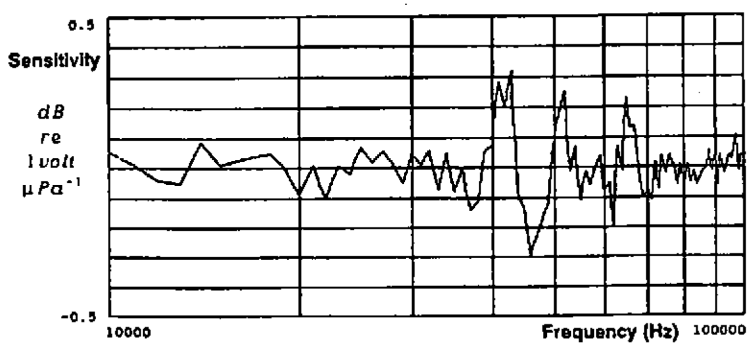

Figure 5 Difference between Two Calibration Measurements on same Transducer

THREE-TRANSDUCER RECIPROCITY CALIBRATION

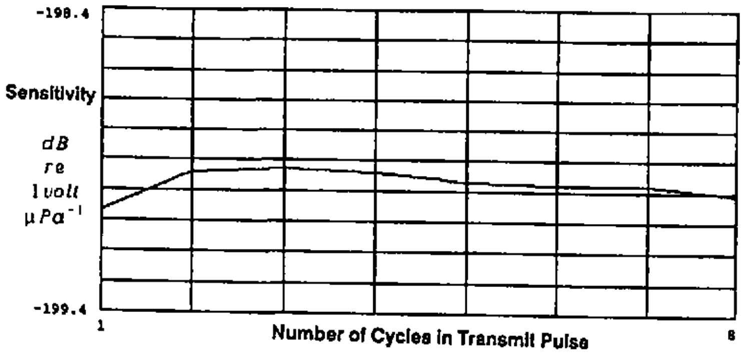

Figure 7 Sensitivity Variations with Number of Cycles in Transmit Pulse

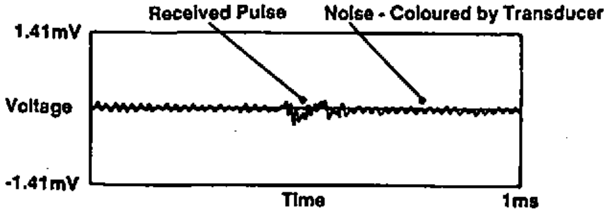

Figure 6a Time-Domain Waveform of Received Signal at 10kHz

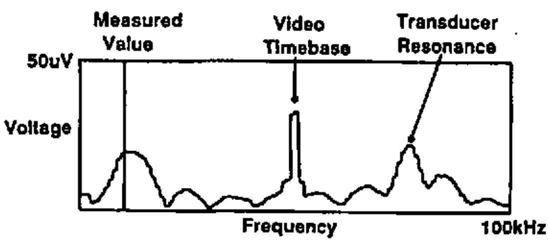

Figure 6b Frequency-Domain of Received Signal

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AUTOMATIC SINGLE CYCLE TRANSDUCER CALIBRATION

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1. THE LIMITATIONS OF TANK TESTING

Underwater transducers are usually calibrated in enclosed laboratory tanks for convenience. Precautions are then required to minimise the errors introduced by reverberation. Anechoic linings can be used to reduce the intensity of the sound returned from the walls, but there will still be errbrs, and the precautions necessary to eliminate the water surface echo are rather inconvenient. The alternative option is to used tone bursts spaced sufficiently to allow the reverberation to die away before the next measurement is made. Because many underwater systems deliver tone bursts for ranging and telemetry, this option is convenient and avoids the expense of large areas of anechoic lining. However, the time available for reverberation free measurements is small, typically a few milliseconds.The system described below has been developed to reduce the measurement period to one cycle, within the tone burst just before the first echo arrives. It is currently used to calibrate the transducers developed for the underwater navigation equipment made by Sonardyne.

The clear pulse time , after the signal first arrives at the hydrophone, but before the first echo starts to interfere, is limited by the tank dimensions, usually it's depth in particular. This limitation in the undistorted pulse length effectively limits the frequency of accurate calibration.

Underwater transmitters are normally resonant devices in order to provide an efficient source of high power. These transducers will have a mechanical Qm factor which is relatively high, ranging from say 3 to 10. This means that the waveform of the sound in the water will not respond instantly to the onset of the tone burst, but will exhibit an exponentially rising amplitude which asymptotically approaches the steady state value. There will then be an error in the measurement which depends on the pulse length and the time at which the measurement is made within the pulse.If a tolerable error is then defined, there will be a minimum pulse length which can be specified in cycles. High frequency transducers will require less time to reach an acceptable approximation to their steady state value. At lower frequencies, the limited pulse length will result in unacceptable errors, and this lower frequency limit will depend on the tank size.

AUTOMATIC SINGLE CYCLE TRANSDUCER CALIBRATION

2. AVERAGING TO REDUCE ERRORS

In practice, the lower frequency limit will be further restricted by the finite time taken to make a measurement. Even peak to peak measurements made by eye from an oscilloscope screen cannot use less than half a cycle, and effectively average over several cycles. Automatic measurements must be clearly defined, and a single cycle provides a straightforward criterion which can be implemented using available test equipment. To minimise the errors due to spurious noise an averaging system is required. There are several averaging options available, including

a) The mean of values from cycles in many successive tone bursts

b) The mean square voltage , $\overline{V^2}$, over many samples within a cycle

c) Making a Fourier integral over the cycle, at the fundamental frequency.

Whereas all these techniques will reduce the effects of noise and harmonics compared with the single peak to peak envelope measurement, only the last is completely effective. Unfortunately, it requires more computation than the mean square option(b), which has therefore been incorporated into the current procedures to avoid excessive delays. However, option (c) has been used successfully, and a combination of (a) and (b) is often applied.

3. SINGLE CYCLE R.M.S. MEASUREMENTS - ERROR IMPLICATIONS

Accurate single cycle root mean square measurements can be made with a digital oscilloscope capable of making the appropriate calculations. The cycle starts and finishes at a zero crossing (where the gradient is a maximum). It is important that as many samples as possible are made during the cycle. With a digitisation rate of 10 MHz, the number of samples, N, will exceed 100 for frequencies up to 100kHz. If the frequency was 100kHz exactly, and N = 100, there would be no error in measuring a true sine wave. For other adjacent frequencies there will be an error due to the averaging period not forming an exact whole cycle. However this fractional error will be less than $\cos(2\pi/N)/2\pi$, (or 0.03% if N=100), provided the sampling times are optimal. Any spurious noise spike will naturally be reduced by a factor of N. Any harmonic distortion will contribute the total rms power of all the higher harmonics, since each will have an integral number of cycles sampled and noise powers are additive for a linear system. However these errors are still less than those which can occur when peak to peak envelope size is measured.

Errors in DC offset, a prevalent problem in low level digitisation, can be overcome by also calculating the mean value of the signal as measured. The hydrophone signal should have no DC component, and this mean value should therefore be zero. If not there must be a DC error δ. The measured mean value is then $\Sigma(x_n + \delta)/N$. If this is itself squared, and subtracted from the measured mean square value $\Sigma(x_n + \delta)^2/N$, the net result is the desired $\Sigma\, x_n^2/N$, bearing in mind that $\Sigma\, x_n$ is known to be zero.

Errors due to low frequency noise, such as 50Hz hum, will be largely eliminated with the DC offset errors. The more general case of broadband noise is more difficult to calculate but is not of great importance, as signal to noise levels in transducer calibration can be kept high by using adequate projector power, or by using appropriate filtering of frequencies outside the band of interest.

4. AUTOMATIC TEST ARRANGEMENT

The block diagram of the equipment used is shown in Fig 1. The tone burst is generated by a Sonardyne "ANT" (Acoustic Navigation Tester) which is sent commands from an IBM PC via an RS 232 serial line. This low level synthesised signal is amplified by a 150W push pull amplifier feeding a 10:1 step up transformer. This can give over 600V pk/pk sinusoidal drive to an underwater projector, which then generates a typical test source level of 180 dB//µPa.m. This is sufficient to provide an adequate signal from a calibrated omnidirectional B&K 8104 hydrophone, despite its rather low sensitivity (-205.9 dB//V/µPa). At the same time the level is well below the onset of transducer non linearity. A 100:1 voltage divider is incorporated into the amplifier case to facilitate the measurement of drive voltages.

The hydrophone can be directly connected to the HP54501A digital oscilloscope with negligible error due to loading by it's 16pf input capacity. A trigger signal is available from the ANT linked to the start of the synthesised waveform, so that a stable trace is obtained. Where necessary this will allow the waveform to be averaged over many tone bursts. Sequential measurements of drive waveform and hydrophone received waveforms provide data on their rms values, which are sent via an IEEE 488 bus to the PC. The Basic software changes channel sensitivities and time delays after the trigger, to fill the screen with the correct data. The operator can see exactly what is being measured and intervene if necessary. This overcomes a major disadvantage of many automatic systems ,in which the lack of real time information leads to "garbage" being printed, and thus acquiring a false appearance of infallibility.

AUTOMATIC SINGLE CYCLE TRANSDUCER CALIBRATION

The equipment shown in the block diagram is set up for polar plotting. In this case the transducer to be calibrated is mounted on a shaft connected to a submersible stepper motor. This motor is driven by signals provided by the DTR handshake line of the RS232 port on the PC. The non resonant transducer mounting frame used will accept a wide variety of housings, which can be conveniently attached by plastic tie-wraps; but in consequence it does not have facilities for holding the acoustic centre on the axis of rotation of the motor. There is thus an offset of the acoustic centre from the rotation axis, the effects of which are compensated by the software held in the PC. As well as the variation in signal level and true angle, the change in effective range with orientation means that the optimum timing for the measurement of the received waveform varies. In consequence the oscilloscope is reprogrammed as the orientation is changed to vary the delay before sampling the received waveform.

Additionally, when appropriate the ANT can be reprogrammed to change frequency, thus performing a set of measurements at each orientation. The data sent to the PC is then reconstructed to give a set (1, 4 or 9) of polar plots on one sheet as shown in Fig 3.

The graphic output shown is produced on an HP 7470 pen plotter on the IEEE 488 bus. Data from the oscilloscope is first stored on hard disc, and can also be output to the screen for quick inspection and printing.

5. SPREADSHEET FORMAT

Spreadsheet software has been found particularly useful in transducer design, where the optimum performance parameters can be found by adjustment of the design data displayed on the screen. Quite complex calculations such as resonant frequency of piston transducers, can be made within the spreadsheet software environment, by using look up tables and iteration by circular reference.

Calibration data has also been imported from the Basic control program using "comma separated value" (CSV) format. The data tables thus formed provide a useful reminder to enter additional information such as admittances and cable capacities. The software then automatically calculates transducer parameters such as

a) Equivalent parallel resistance and capacitance of the transducer without it's test cable (i.e. electrically unloaded)

b) Projector Source Level per Volt, dB//μPa.m/V and per watt dB//(μPa.m)^2/W.

AUTOMATIC SINGLE CYCLE TRANSDUCER CALIBRATION

These two projector sensitivities both provide useful information. The voltage sensitivity, S_v, can be plotted against frequency to show variations in source level when driven from a low impedance output stage. The power sensitivity, S_w, provides an indicator of system efficiency. The lifetime of underwater battery operated transponders is very dependent on achieving a high source level with minimum power. Note there are two possible units for the decibel reference level - $\mu Pa.m/\sqrt{W}$ or $(\mu Pa.m)^2/W$, dependent on the user's preferred formula

$$S_w = 20 \log (P.R/V/\sqrt{G}) = 10 \log (P^2.R^2/V^2/G)$$

Here P is the rms pressure at range R metres, V is the applied voltage and G the conductance in mho (Siemens).

c) Receiver sensitivity dB//V/µPa. This can be calculated for reciprocal transducers, making the appropriate adjustments for cable capacity.

Fig 2 shows the data table. This is "Sheet 1", which puts data for a single orientation onto an A4 size sheet.

The second half of the table not shown here, extends the calculations to cover other orientations and to make use of the interactive scope of the spreadsheet. Directivity index data from polar plots is used to calculate the electroacoustic efficiency. This is left as an option because of the time taken to polar plot every frequency. Directional transducers have directivity indices which usually vary predictably with frequency and interpolations are thus valid. In contrast, the achievement of hemispherical or omnidirectional responses needs to be checked at closely spaced frequencies to avoid the narrow nulls which can occur due to interference from housings and guards.

The software is also set up to facilitate trial matching schemes. The relatively large electrical Q_e (Susceptance B/ Conductance G) of omnidirectional tube transducers in particular, means that the energy stored in the transducer is much larger than that projected per cycle. This energy can be recovered and restored with the opposite polarity by a suitable matching inductor. This matching thus improves the efficiency of the system as a whole. However the optimum inductor is frequency dependent and compromise choices are required. The software helps the designer to make these choices by calculating the consequences and displaying them in tabular or graphical form.

6.POWER MEASUREMENT

The use of low level conductance data is only appropriate to linear transducers. Where the transducer is driven into a nonlinear region, G is not a constant. Measurements have been made of the power consumed by the transducer by simultaneous measurement of voltage and current. From this the total power can be calculated by averaging the VI product over the whole cycle. This can be done at power levels where linearity cannot be assumed. The resultant data, including B and G, is then available for spreadsheet calculations. However, the measurement of high voltages without introducing phase shifts has proved difficult and is still a limitation on accuracy. A careful design of guarded potential divider has recently been made to control the small stray capacities which give rise to phase errors. Future calibrations should be able to measure the electrical performance and matching requirements of transducers at high power outputs.

7.ACKNOWLEDGEMENTS

The development of these techniques owes a great deal to the invaluable discussions with the staff of Sonardyne.The work was funded by Sonardyne, and the author is grateful for the opportunity to publish these results and the data on Sonardyne's LF transducer.
Many of the ideas were generated, and much of the work was done, by students from the electrical engineering dept of Surrey University, especially Nick Bowdler, the current industrial year student.

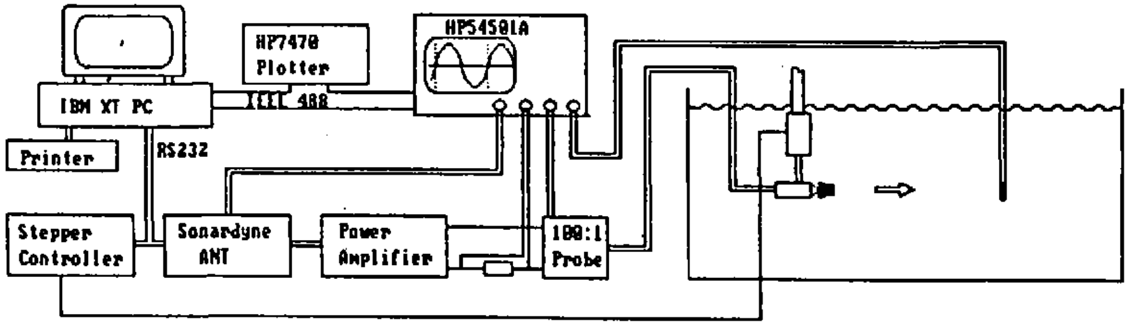

Fig 1

--Sheet 1--

Sonardyne Calibration software B&K128 File 7300-11a Transducer 7300 S/N 43177-11

Date: 27-02-90 Tested as projector with cable 250 pF: Data for transducer with 0 pF cable
Project: using B&K hydrophone #2(1122971 : in parallel, otherwise unloaded electrically
Customer: Eastport at range 1 metre : Parallel RC eq.:Projector Source :Receiver :

F (kHz):	Vin(V):	Vout(mV):	G (umho):	B (umho):	B&K Sens :	Rp (ohm):	Cp (nF):	Level dB//uPa@1m @1VoltRMS:	@1WattRMS:	Receiver Sensitivity dB//V/uPa:
7	147.903	12.8844	78	641	-205.9	12821	14.32	124.7	165.8	-182.2
8	150.558	22.6191	164	633	-205.9	6098	12.34	129.4	167.3	-178.8
9	149.879	23.4394	94	664	-205.9	10638	11.49	129.8	170.1	-179.6
10	150.098	20.486	82	750	-205.9	12195	11.69	128.6	169.5	-182.8
11	151.363	21.2403	94	859	-205.9	10638	12.18	128.8	169.1	-184.6
12	152.541	20.363	148	914	-206	6757	11.87	128.5	166.8	-186.2
13	153.425	23.9906	188	992	-206	5319	11.89	129.9	167.2	-186.3
14	152.645	31.2068	227	977	-206.5	4405	10.86	132.7	169.1	-184
15	155.725	33.7467	164	969	-206.5	6098	10.03	133.2	171.1	-183.9
16	159.624	30.3468	148	1055	-206.8	6757	10.24	132.4	170.7	-186
17	157.089	30.8846	86	1148	-206.8	11628	10.5	132.7	173.4	-186.9
18	159.464	32.7656	78	1250	-206.9	12821	10.87	133.2	174.3	-107.7
19	159.049	19.6871	164	1227	-206.9	6098	10.03	128.8	166.7	-192.4
20	163.803	14.0852	36	1383	-206.7	27778	10.76	125.4	169.8	-197.2

Fig 2

AUTOMATIC SINGLE CYCLE TRANSDUCER CALIBRATION

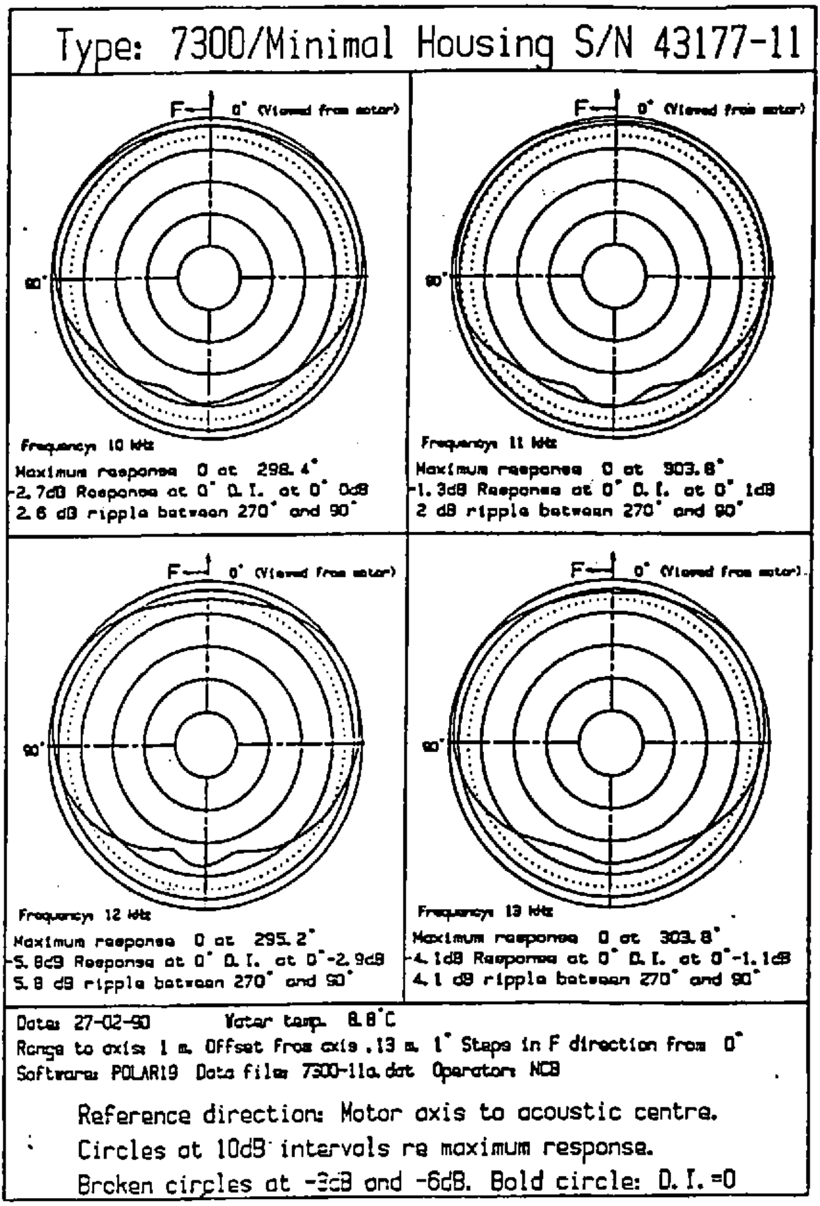

Fig 3