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# DIGITAL AUTOMATIC MEASUREMENTS OF UNDERWATER SOUND TRANSDUCERS

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## INTRODUCTION

In the process of developing, producing and using underwater sound transducers, it is necessary to perform frequent measurements, such as calibration, test and evaluation. Measurement techniques are constantly improved, along with the progress of science and technology, particularly electronic technology. In the 1940's and 1950's, the essential characteristics of transducers, such as impedance locus, response curves and directivity patterns, *etc.*, were determined by measuring, calculating and plotting point by point, and all operation relied on the hands and eyes of an operator. Obviously this process was tedious and errors occurred easily. From the end of the 1950's or the beginning of the 1960's, the analogous automatic measurements for essential characteristics of underwater sound transducers were realised. A typical example of this is described by R.J. Bobber in the literature (1). The analogous automatic measurements reduced the measuring time greatly, although in some cases they were not very precise. From the early 1970's, the digital automatic measurement methods based on computers were under development (2), (3). As a result, the measurement technique for transducers began striding towards advanced digital automatisation.

Recently, an automatic measuring system, in which a computer is used as a centre controller and processor and a two channel Transfer Function Analyser (TFA) as a measuring unit, has been set up in the Hangzhou Underwater Acoustics Institute (HUAI). Programmable measurements for essential characteristics of underwater sound transducers under the condition of sinwave have been successfully performed. This paper mainly describes the programmable measurement methods for impedance (or admittance), transmitting response and receiving sensitivity, *etc.*

## AUTOMATIC MEASUREMENT OF IMPEDANCE

Previously, impedances were usually measured point by point and under the condition of low driving level with complex impedance (admittance) bridges. Consequently it took much time, and the values obtained from measurement at low power level cannot be extrapolated to high power conditions for projectors. Afterwards, an analogous automatic measuring method based on resolving a voltage (or current) vector into real and imaginary parts was established according to procedures outlined in the literature (4). An impedance (admittance) diagram can be plotted automatically on a recorder. Under certain conditions, this method may also be used at high power level. However, it is necessary to keep the driving current or voltage of the transducer constant during measurement of the impedance or admittance diagram. Consequently, the power is rigorously required to have a constant voltage or current output, otherwise considerable errors may occur.

In the new system at HUAI, measurements of complex ratios of samples of driving voltage to current of transducers are carried out by means of a TRA, and control and data processing are carried out on a minicomputer.

Figure 1 shows an arrangement for the measurements. The output signal of a digital sweep generator is amplified by a power amplifier, then drives an unknown transducer T. $V_T$ is the complex driving voltage at the transducer terminals, and $I_T$ is the complex current flowing through it. The complex voltage sample $U_V = V_T.K$ is obtained by an attenuator whose attenuation coefficient is K and whose phase distortion is negligible (phase shift $< 1°$) and is fed into the first channel (ch.1) of the TFA. The complex current sample $U_I = I_T.C_I$ is obtained by a current transformer whose sensitivity is $C_I$ and whose phase shift and inserting resistance are negligible and is fed into the second channel (ch.2) of the TFA. The following measurements are then carried out by the TFA: $|U_V|$ and $|U_I|$, real component of $U_I/U_V$, *i.e.*,

$$a = \left|\frac{I_T}{V_T}\right| \cdot \frac{C_I}{K} \cdot \cos\theta \tag{1}$$

and imaginary component of $U_I/U_V$, *i.e.*,

$$b = \left|\frac{I_T}{V_T}\right| \frac{C_I}{K} \sin\theta \tag{2}$$

where $\theta$ is a phase angle of $U_I$ with reference to $U_V$ and approximately equals that of $I_T$ with reference to $V_T$.

Under the control of a computer, the generator automatically sweeps according to preset sweep parameters, and the digital data correspond to all preset frequency values f and higher measurement values are transferred through an interface to an internal storage in the computer, or other external memory, such as a disc. Then the computer optionally makes the computations of conductance G(f) and susceptance B(f), or resistance $R_p(f)$ and capacitance $C_p(f)$ in the parallel equivalent circuit, resistance $R_s(f)$ and reactance $X_s(f)$ in the series equivalent circuit and input electrical power $P_e(f)$ according to the following corresponding expressions:

$$G(f) = a(f).\frac{K}{C_I} \tag{3}$$

$$B(f) = b(f).\frac{K}{C_I} \tag{4}$$

$$R_p(f) = \frac{1}{a(f)} \cdot \frac{C_I}{K} \tag{5}$$

$$C_p(f) = b(f).\frac{K}{C_I 2\pi f} \tag{6}$$

$$R_s(f) = \frac{a(f)}{a^2(f) + b^2(f)} \cdot \frac{C_I}{K} \tag{7}$$

$$X_S(f) = \frac{-b(f)}{a^2(f) + b^2(f)} \frac{C_I}{K} \tag{8}$$

$$P_e(f) = \frac{a(f) \cdot |U_V(f)|^2}{2KC_I} = \frac{|U_I(f)|^2}{2KC_I} \cdot \frac{a(f)}{a^2(f) + b^2(f)} \tag{9}$$

The computation results are printed out by means of a printer and/or plotted on a X-Y recorder. When an admittance or impedance diagram is plotted, there are two forms which can be freely selected by BASIC program. For instance, Figure 2 shows the admittance characteristics of a piezoelectric transducer which is plotted as the parallel values of G and B as a function of frequency. It may also be presented as an equal-scale plot of G *versus* B with frequency as the parameter in Figure 3.

Using this method, the charge in impedance characteristics of a transducer at high power can be measured effectively. For example, Figure 4 shows the impedance loci of a magnetostrictive transducer plotted automatically at two driving currents. It can be seen from this that electromagnetic loss increases and projection resistance reduces, which is due, perhaps, to the appearance of the acoustic cavitation in water, with increase in driving power.

Appendix A shows the BASIC program flow chart for measuring admittance and impedance of transducers.

AUTOMATIC MEASUREMENTS OF TRANSMITTING RESPONSE AND RECEIVING SENSITIVITY

Before, in order to measure the transmitting response and receiving sensitivity at many frequencies, or over a wide frequency range, analogous automatic recording was carried out by means of systems similar to that described in ref. 1. However, the recorded data are not very precise and when hydrophones are absolutely calibrated using the reciprocity technique, it is still necessary to measure and calculate point by point. For the time being, it is quite possible to improve the former measurement technique with the aid of a computer and other digital instruments.

Let us consider a pair of projectors and hydrophones mounted in a free field with their principle axes in line and directed towards each other, as shown in Figure 5. The distance between their acoustic centres is d meter. When the projector is driven at voltage $V_T$ (corresponding current $I_T$) the hydrophone produces an open circuit voltage $e_o$. Obviously, the transducer pair, including the sound transfer part, may be regarded as a four-terminal network. What is interesting in the calibration of transducers usually is the ratio of $e_o/V_T$, or $e_o/I_T$, representing the transfer characteristic of the network, instead of values of $V_T$ (or $I_T$) and $e_o$. If the separation distance d satisfies the far-field conditions and with si and $M_o$ representing the transmitting response to the current of the projector and free-field voltage sensitivity of the hydrophone respectively, we have the following relation:

$$\frac{e_o}{I_T} = SiM_o/d \tag{10}$$

According to the IEC standard (5), the ratio $e_o/I_T = |Z_{TO}|$ is referred to as a transfer impedance magnitude of this transducer pair.

Three transfer impedance magnitudes $|Z_{PH}|$, $|Z_{TH}|$ and $|Z_{PT}|$ may be obtained by three combinations of three transducers (projector P, transducer T and hydrophone H) in the above manner. Then, when transducer T satisfies reciprocity conditions, the sensitivity $M_H$ and $M_T$ of H and T and the transmitting response to current $S_T$ and $S_P$ of T and P may be calculated according to the well-known formulae.

First of all, therefore, the measurements of transfer impedance magnitudes of transducer pairs are carried out by TFA under the control of the computer. Figure 6 shows an arrangement for the measurements. The output signal of the digital sweep generator is first amplified by a power amplifier and then drives a projector P. Let a current Ip flow through the projector P. The current sampling voltage $U_I = I_P.C_I$ at output terminals of a current transformer is fed into ch.1 of the TFA. Simultaneously, the open circuit voltage $e_H$ at the output terminals of the hydrophone H is fed into ch.2. Then let the TFA measure a ratio $e_H/U_I$ in dB:

$$A = 20\log\frac{e_H}{I_P C_I} = 20\log|Z_{PH}| - 20\log C_I \qquad (11)$$

If the generator makes a sweep from frequency $f_1$ to $f_2$ with increment $\Delta f$, N+1 data of expression (11) may be obtained, where $N = (f_2-f_1)/\Delta f$. Let the data be stored in the computer or other external memory as an array $A_i$ (i = 0,1,2..N). Therefore, corresponding to three combinations of P-H, P-T and T-H, three arrays $A_{1,i}$, $A_{2,i}$ and $A_{3,i}$ are obtained respectively. The computer can then calculate free-field voltage sensitivity levels and transmitting response levels to current at various frequencies according to the following expressions:

$$M_HL(f_i) = \tfrac{1}{2}(A_{1,i}-A_{2,i}+A_{3,i}) + 10\log J_S + 10\log d + 10\log C_I - 120 \qquad (12)$$

$$M_TL(f_i) = \tfrac{1}{2}(A_{2,i}-A_{1,i}+A_{3,i}) + 10\log J_S + 10\log d + 10\log C_I - 120 \qquad (13)$$

$$S_TL(f_i) = \tfrac{1}{2}(A_{2,i}-A_{1,i}+A_{3,i}) - 10\log J_S + 10\log d + 10\log C_I + 120 \qquad (14)$$

$$S_PL(f_i) = \tfrac{1}{2}(A_{1,i}-A_{3,i}+A_{2,i}) - 10\log J_S + 10\log d + 10\log C_I + 120 \qquad (15)$$

where $f_i = f_1 + i\Delta f$, i = 0,1,2,...N, $J_S$ is a spherical reciprocity constant.

The BASIC program flow chart for reciprocity calibration is shown in Appendix B. In order to set subscripts of arrays in sequence and the program to switch automatically to calculation steps, a pointer variable Q is set prior to measurement steps. An "input stipulated key" is used for awaiting the combination changes and mounting the transducers. After completion of all the steps, *i.e.*, when $Q \geqslant 4$, the program is switched to calculation steps. The calculation results are shown on the terminal and printed on a printer. Finally, plotting steps are performed if the frequency characteristic plots are required.

It is known that underwater sound transducers, except standard hydrophones and projectors, are usually calibrated by comparison with a calibrated standard hydrophone. Therefore, to establish the computer aided comparison calibration procedures is, in a sense, more practical.

When sensitivity measurements are carried out, a projector P is separately combined with an unknown transducer X and standard hydrophone O, as shown in Figure 5. Using the above method, the measurements of arrays $A_{1,i}$ and $A_{2,i}$, corresponding to P-X and P-O respectively, are carried out. The computer then makes calculations according to the following expression, to obtain sensitivity levels at various frequencies:

$$M_X L(fi) = A_{1,i} - A_{2,i} + M_o L(fi) \qquad (16)$$

where $fi = f_1 + i\Delta f$, $i = 0,1,2,...N$. $M_o L(f)$ is the free-field voltage sensitivity level of the standard hydrophone which has been loaded.

To measure the transmitting response to current, it is merely necessary to measure an array $A_i$ by measurement circuit, as shown in Figure 5. Then let the computer make calculations according to the following expression, to obtain the transmitting response level to current at various frequencies:

$$S_I L(fi) = A_i + 20\log C_I - M_o L(fi) - 20\log d \qquad (17)$$

A measurement procedure similar to that of the transmitting response to current may be used to obtain the transmitting response to voltage of an unknown transducer, but the current sampling voltage must be replaced by the voltage sample $U_V = V_T.K$, and the expression is as follows:

$$S_V L(fi) = A_i + 20\log K - M_o L(fi) - 20\log d \qquad (18)$$

Appendix C shows the BASIC program flow chart for calibration with a standard hydrophone. As an example, Figure 7 shows the free-field voltage sensitivity of a spherical hydrophone as a function of frequency. Figure 8 shows the transmitting response level to current of a magnetostrictive transducer at $I_T = 0.5A$ as a function of frequency.

## CONCLUSION AND DISCUSSION

Though the basic measurement principle and methods described above are well-known, the computer aided measurement technique, method for obtaining and processing data, and the way of providing results are superior to previous ones. In particular, the programmable conversational control by simple BASIC language enables the measurements to be quicker and more convenient. With respect to the desired time for providing a plot of frequency characteristics, the present technique is approximately similar to the analogous automatic one. But the former is better as far as the measurement accuracy is concerned. In addition, it is possible conveniently and quickly to measure the impedance, transmitting response and other characteristics of underwater sound projectors under high power.

The measurement error of impedance and admittance mainly depends on the accuracy of TFA itself and the voltage and current sampling error (including magnitude and phase). However, it can be seen by comparison between two impedance diagrams of the same transducer measured by the present method and by the precise bridge respectively, that they are consistent, particularly near the resonance frequency, as shown in Figure 3. The measurement error of transmitting response and sensitivity mainly depends on the deviation from the free acoustic field and the accuracy of TFA. In addition, we have to account for the calibration error of standard hydrophones, provided that a standard hydrophone is used. However, generally, the measurement error due to measurement devices is not important in comparison with the deviation of field and the calibration error of standard hydrophones. As shown in Figure 8, two measurements of the same transducer, measured in the same field and with the same standard hydrophone, using different techniques, are very consistent.

All the results shown in this paper wer obtained with continuous sinusoid signals in an anechoic tank. Clearly, this technique can also be used under conditions of tone pulse, but it is necessary to replace the TFA with that which is capable of pulse triggering sampling analysis.

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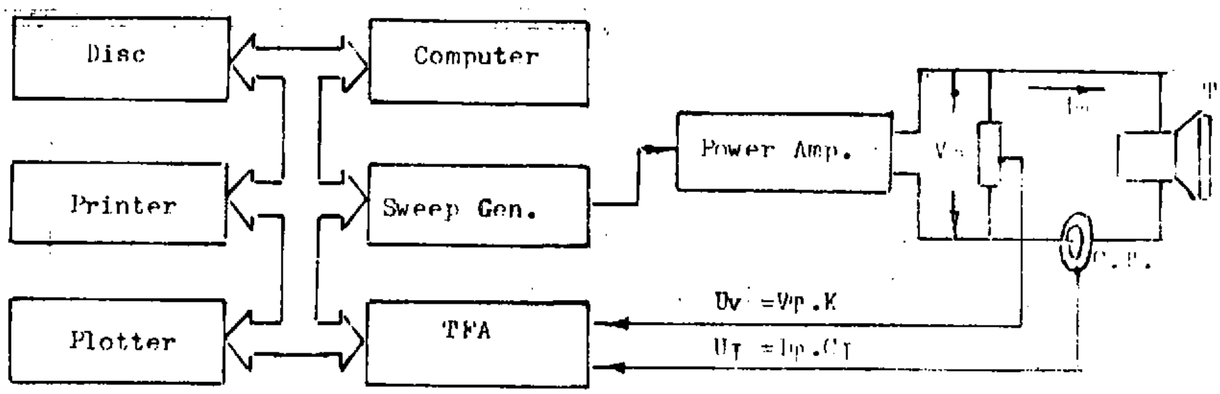



Fig.1 Measuring arrangement for automatic measurement of impedances

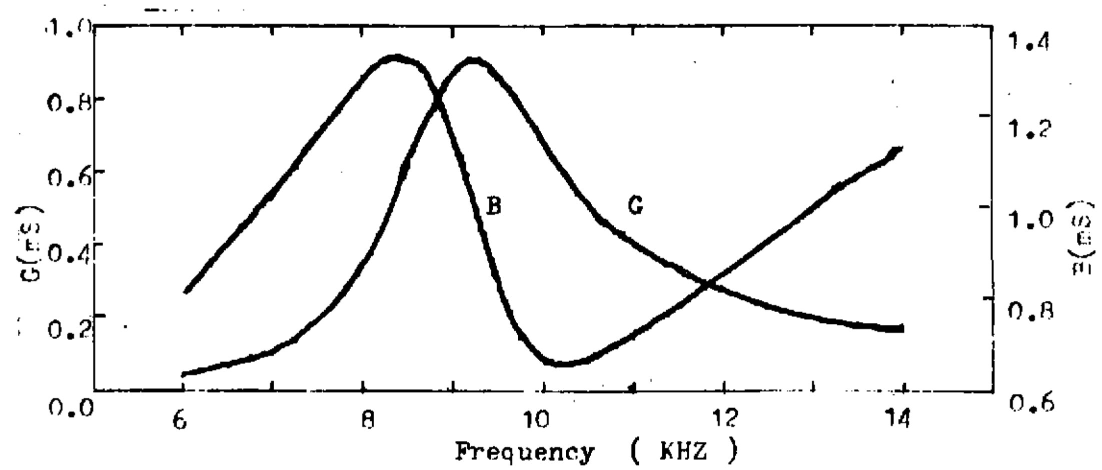



Fig.2 Admittance curve

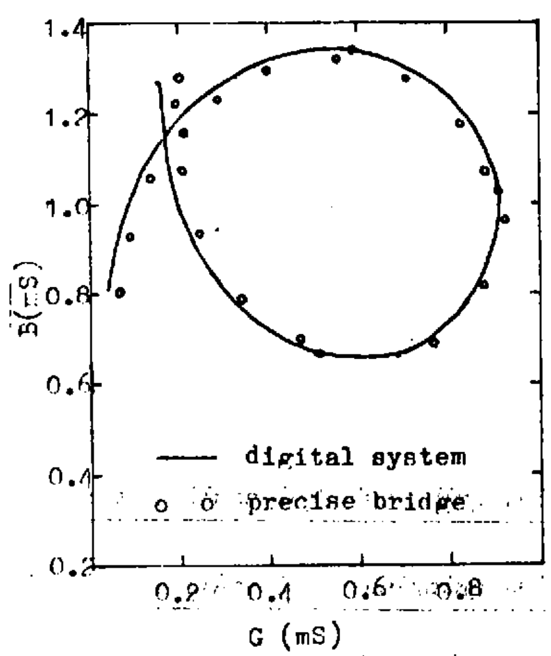



Fig.3 Admittance locus

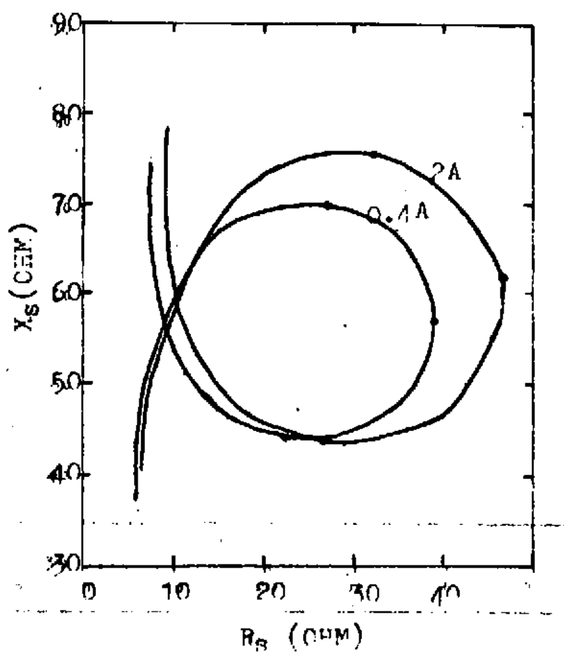



Fig.4 Impedance loci under different current

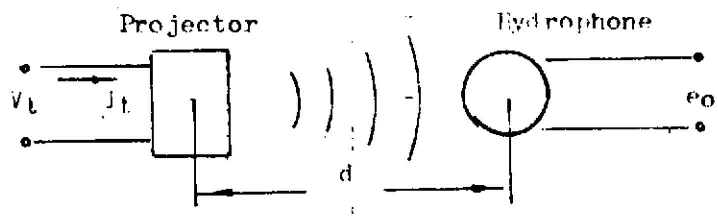



Fig.5 A transducer pair

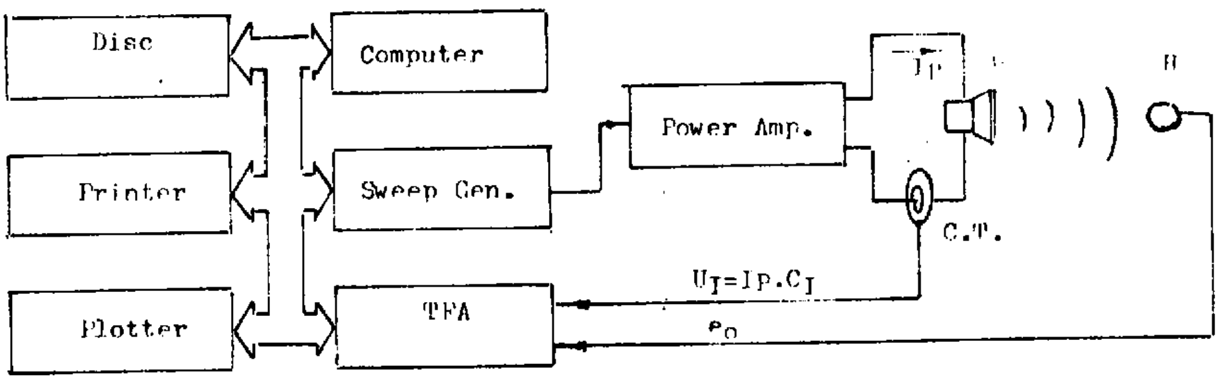



Fig.6 Measuring arrangement for automatic calibration

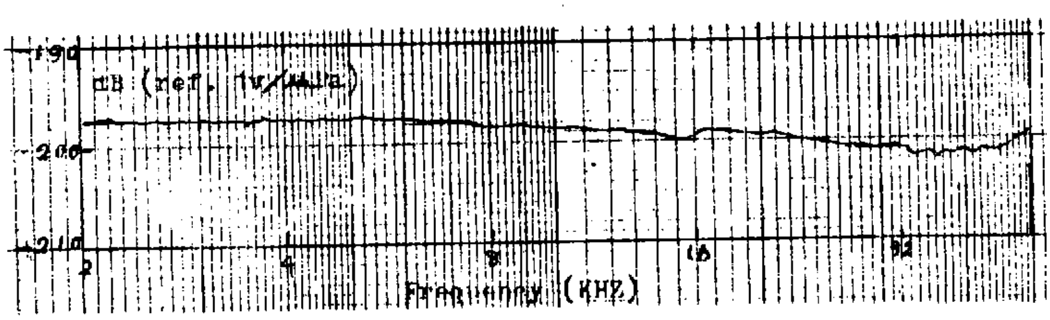



Fig.7 Sensitivity of a spherical hydrophone

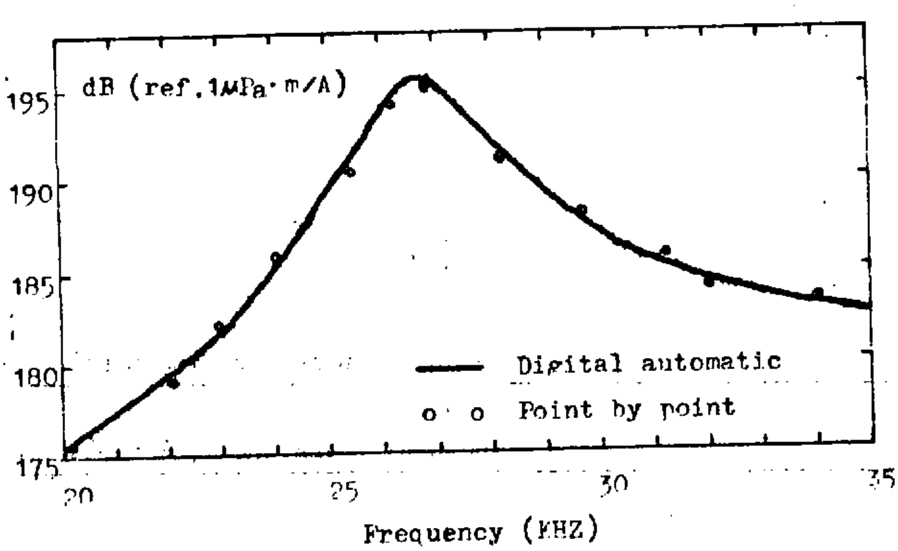
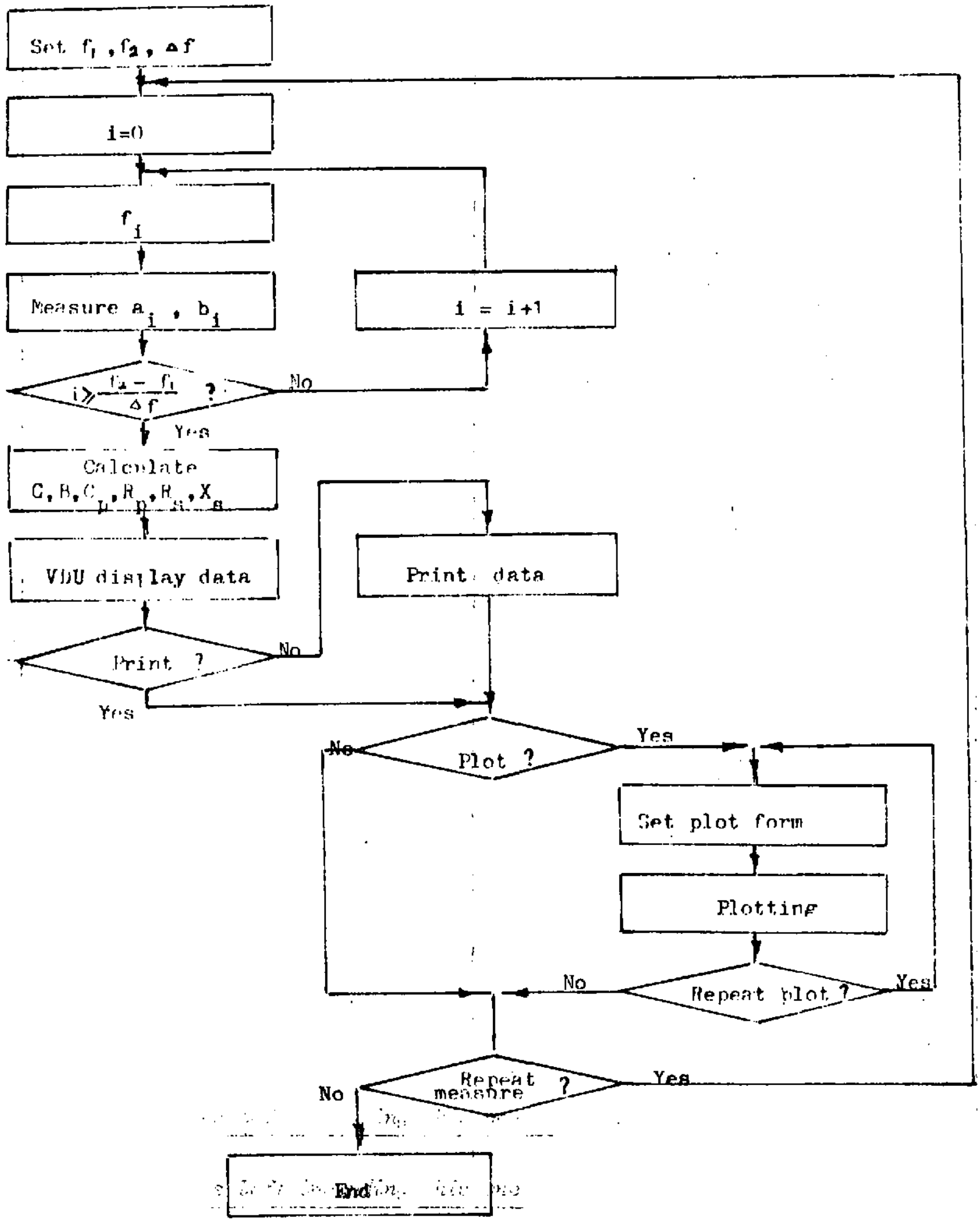



Fig.8 Constant current transmitting response

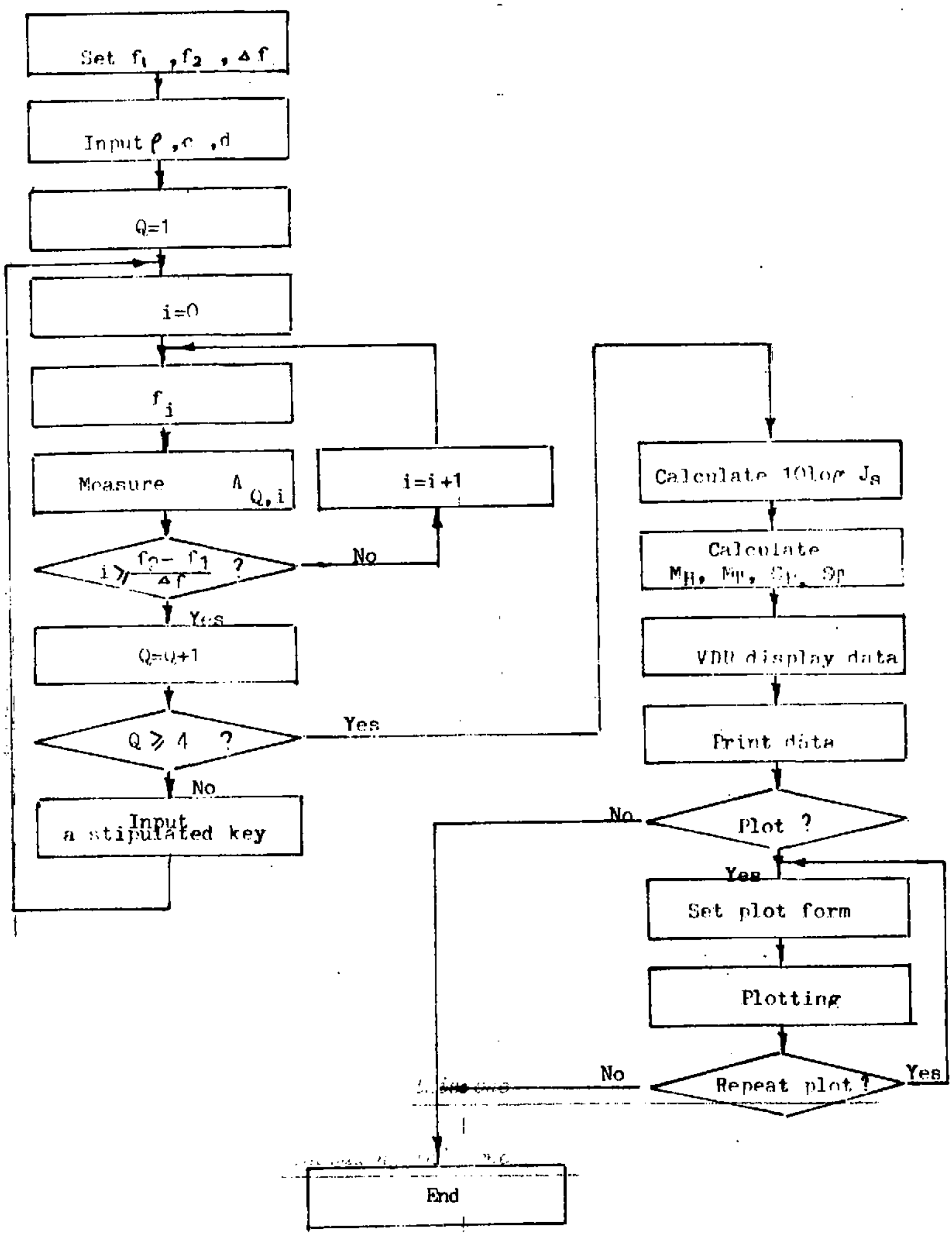
## Appendix A

Program flow chart for measuring admittance or impedance



Appendix B

Program flow chart for reciprocity calibration



Appendix C

Program flow chart for the calibration with a standard hydrophone