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HYDROPHONE CALIBRATION BY THE SUBSTITUTION METHOD USING PSEUDO-GAUSSIAN WHITE NOISE

D.R.E.A. Technical Memorandum 76/B

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HYDROPHONE CALIBRATION BY THE SUBSTITUTION METHOD USING PSEUDO-GAUSSIAN WHITE NOISE

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ABSTRACT

A computer-based procedure has been developed for calibrating hydrophones by the substitution method using a pseudo-gaussian white noise signal. The technique has been shown to be a viable alternative to the more conventional CW and pulsed CW substitution methods. Owing to the wideband nature of the noise signal, the effects of boundary conditions are reduced considerably. Software routines for a Honeywell H-316 minicomputer are used to generate the noise signal, perform the analog-to-digital sampling and carry out the calibration computations. This method is particularly useful for low frequency wideband calibration and would allow measurement to less than one Hertz.

SOMMAIRE

On a élaboré une procédure automatisée d'étalonnage des hydrophones par méthode de substitution employant un pseudo-bruit blanc. Cette technique s'est avérée être une solution de rechange viable aux méthodes de substitution plus classiques employant des ondes entretenues et des ondes entretenues pulsées. Puisqu'il s'agit d'un signal de bruit à large bande, les effets des conditions de limite sont considérablement diminués. On se sert du logiciel d'un mini-ordinateur Honneywell H-316 pour produire le signal de bruit, effectuer l'échantillonnage analogique-numérique et faire les calculs d'étalonnage. Cette méthode est particulièrement utile pour l'étalonnage basse fréquence à large bande et elle permettrait de mesurer à une fréquence inférieure à un (1) hertz.

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1. INTRODUCTION

A hydrophone calibration method using a wideband random noise signal in a reverberant tank was described by McMorrow, Wallace and Coop in 1953.[1] Accuracy and resolution were limited by the readout and processing techniques available at that time. Technological advances have allowed these limitations to be largely overcome and a computer-based procedure has been implemented that uses a pseudo-gaussian white noise signal in the substitution method[2] of calibration. A minicomputer system is used to generate the noise signal, perform the analog-to-digital sampling and carry out the calibration computations via the FFT technique.

This report first outlines the substitution method and compares the relative merits of the conventional CW or pulsed CW signals with the noise signal. Restrictions on the characteristics of the hydrophones are also discussed. The calibration equipment and procedure are then described with details of the noise generation algorithm and signal conditioning requirements. Finally, examples of the use of the calibration procedure are presented.

2. COMPARISON OF SIGNALS IN THE SUBSTITUTION METHOD

The simplest and most frequently used calibration technique is the substitution or comparison method[2,3], in which the response of a hydrophone, referred to as the unknown, is obtained by comparing its output signal to that of a standard hydrophone placed in the same sound field. Conventionally, the sound field is derived from a CW or pulsed CW source which is stepped in frequency over the band of interest.

Accurate open water calibrations normally require both free-field and far-field conditions.[2,3] The far-field requirement can be met by choosing a sufficiently large projector-to-hydrophone separation. In general, however, free-field conditions can be approximated only in large homogeneous bodies of water where the distance to any boundary or sound scattering object can be made very large compared to the projector-to-hydrophone separation. In acoustic tanks with CW signals, the far-field requirement usually precludes the very close separations necessary for practical free-field conditions. Furthermore, unless the tank is highly anechoic, standing waves are set up causing large variations in sound field intensity over small distances.

At the higher frequencies, pulsed CW or tone burst signals are used to achieve practical free-field conditions.[2] The time separation between the signal arriving at the hydrophone directly from the projector and the first signal arriving by another path must be long enough to contain a few cycles at the measurement frequency. The required number of cycles depends on the Q of any resonances in the measurement system. This places a definite lower frequency limit on the pulsed CW method.

An alternative signal that overcomes some of the limitations of CW and pulsed CW signals is gaussian white noise. The use of computer-generated pseudo-gaussian noise ensures that an identical signal spectrum is presented to both the standard and unknown hydrophones. The frequency spectra are analyzed, using the FFT technique to assemble the various frequency components in bands or bins. The effects of multiple reflections within the tank tend to be smeared out since any pair of signal paths can produce both constructive and destructive interference within a frequency bin. The dual to the frequency smearing effect is the smearing of the spatial variations of the sound field in the tank. The bin width or frequency resolution should be narrow enough to allow definition of the hydrophone characteristics but not so narrow that the signal level is overly sensitive to hydrophone positioning.

Because the sound may be arriving at the hydrophone position from many different directions, the hydrophones, both standard and unknown, should be omnidirectional. If the tank is fairly anechoic then the predominant sound path will be directly from the projector to the hydrophone and some directivity may be acceptable. Nevertheless, the results of noise calibrations on directive hydrophones must be interpreted with care. Another restriction on the hydrophones is one of size. The hydrophone dimensions should be very small compared to the tank dimensions to ensure that the sound field in the tank is essentially independent of the presence of the hydrophone. Otherwise, both the standard and unknown should be of the same size, shape and orientation so as to exert a similar influence on the sound field.

3. CALIBRATION SYSTEM AND PROCEDURE

A block diagram of the noise calibration system is shown in Figure 1. The system is centered around a Honeywell H-316 minicomputer, which is used to control the calibration process, perform calculations and produce hard-copy results. The upper sampling frequency of 18.4 kHz is limited by the speed of the A/D converter and the associated software - this limits the calibrations to frequencies up to about 9.0 kHz.

A wideband moving coil projector such as the USRD Type J-11 or J-9 is used as the projector. The standard hydrophone is normally a 2.5 cm diameter ceramic sphere which has a constant sensitivity of -99.5 dB re 1 volt/μbar below 9.2 kHz.

A standard hydrophone is first mounted in a suitable position in the acoustic tank and a pseudo-gaussian noise signal is projected into the water. After a short delay to allow the field to become stationary, the time response of the standard output is sampled and the FFT technique is used to compute its power spectrum. A number of independent noise records are projected, the hydrophone output sampled, and power spectra computed; the results are averaged to give a mean power spectral density PS for the standard output. The standard hydrophone is then replaced by the unknown hydrophone and the above procedure is repeated, using identical noise records, to give a mean power spectral density PX for the unknown.

The sensitivity of the unknown hydrophone MX is computed from the following

$$MX = PX - PS + MS - G \qquad (1)$$

where all quantities are in decibels, MS is the sensitivity of the standard relative to 1 volt/μbar and G is the net system gain of the unknown over the standard. Equation (1) is evaluated at a set of discrete frequencies determined by the sampling rate of the hydrophones' outputs and by the number of FFT sample points.

The FFT technique comprises the computation of the complex discrete Fourier transform of a time sequence of samples, and therefore contains both amplitude and phase information. In the present implementation the phase information is discarded and only the magnitude or power spectral density is used. Should magnitude and phase calibrations be required in the future, it may be possible to use this phase information in a revised computational procedure.

4. GENERATION OF NOISE SIGNAL

The necessary wideband noise signal is obtained by passing software-generated pseudo-gaussian numbers through a digital-to-analog converter, the output of which is filtered, amplified and projected into the acoustic tank. The gaussian numbers are output at a rate equal to that used to sample the response of the hydrophone by the analog-to-digital converter.

Strictly speaking it is not necessary to impose a gaussian amplitude distribution on the transmitted signal. While other, possibly simpler signals might also satisfy, the gaussian signal provided very acceptable results.

A typical calibration requires a large number of independent records, say 100, each having 1024 points. To allow time for the sound field to reach a stationary state, up to 512 numbers are output before the hydrophone's response is sampled. Therefore, the generator should have a period in excess of 150,000.

The gaussian number generator described by Conolly[4] was chosen because of its long period and simplicity of implementation - keeping in mind that the word length of the H-316 minicomputer is 16 bits. First, a table of uniformly distributed random integers $X_{i,1} (1 \leq i \leq N)$, drawn from a population in the range 0 to 32767, is used to initialize the generator. Then new sequences (index j) are formed recursively as follows:

$$X_{i,j+1} = X_{i,j} + X_{i+1,j} - Y \ , \qquad (2)$$

for $\quad i=1,2,\ldots,N-1$

and $\quad X_{N,j+1} = X_{N,j} + X_{1,j+1} - Y \ ,$

where $\quad 3 \leq N \leq 12$, and $1 \leq j \leq M$.

The quantity M is any positive integer greater than 1 and generally not greater than the period of the generator. Also,

$$Y = \begin{cases} 32768 & \text{if } X_{i,j} + X_{i+1,j} \geq 32768 \\ & (i=1,\ldots,N-1) \\ & \text{or } X_{N,j} + X_{1,j+1} \geq 32768 \\ 0 & \text{otherwise.} \end{cases}$$

Finally, gaussian numbers G_j are formed by summing the uniformly distributed integers $X_{i,j}$ and scaling thus:

$$G_j = [\frac{1}{32N} \sum_{i=1}^{N} X_{i,j}] - 512 \; . \qquad (3)$$

The numbers so formed lie in the range of the 10-bit digital-to-analog converter; that is, between -512 to +511 inclusively with zero mean.

In the above-mentioned random number generator, the amplitude distribution becomes more gaussian as the value of N increases. Distributions for two values of N are shown in Figure 2. The generator period and standard deviation are given in Table I for several values of N. A typical power spectral density for a single record is shown in the lower curve of Figure 3; the result of averaging over 100 records is illustrated by the upper curve. The rolloff at the upper end of the frequency band is due to the low-pass filter used to prevent aliasing, as explained in the next section. The use of gaussian white noise averaged over several records ensures that all frequency components are present at approximately the same level.

5. SIGNAL CONDITIONING

The maximum frequency component that can possibly be used in the digital computations is equal to the Nyquist frequency or one-half the sampling frequency. Frequency components above the Nyquist frequency will cause aliasing, which may give rise to erroneous results unless they are suppressed. As a result some signal conditioning is required.

When driven by the gaussian number generator, the digital-to-analog converter outputs a sequence of rectangular pulses of varying amplitude. Such a signal has large components at frequencies well above the maximum frequency of interest. Low-pass filtering is used to reduce the levels of the undesirable high frequencies in the projector driving signal. The cut-off frequency of the filter is set just below the Nyquist frequency.

The signal observed at the output terminals may contain undesirable high and low frequencies from sources other than the projector as well as 60 Hz components due to power line interference. Therefore, the signal is normally passed through a bandpass filter before it is sampled by the analog-to-digital converter. The upper cut-off frequency is set equal to the highest frequency of interest which should be below the Nyquist frequency. The lower cut-off frequency is normally determined by the amount of low frequency rejection required.

6. EXAMPLES

First, a standard hydrophone (2.5 cm diameter sphere) was calibrated against itself by the substitution method using the pseudo-gaussian noise signal with a sampling rate of 18.4 kHz and a resolution of 18 Hz. Based on Equation (1) and on the assumption that the value of MS is fixed, the computed value of MX should be a straight line across the entire frequency band - with a value equal to that of MS. Indeed, this result is obtained, as shown by the solid line in Figure 4, if the position of the hydrophone is not changed during the calibration. The effect of changing the hydrophone position by approximately 3 cm is shown by the dashed curve in Figure 4; the attendant changes in the acoustic field are indicated by the departures from a straight line at the higher frequencies, especially beyond 1500 Hertz. This result emphasizes the necessity for accurate positioning of the hydrophones, although the sensitivity to hydrophone positioning can be reduced by broadening the frequency resolution.

Figure 5 shows the calibration results for a 5.1 cm diameter spherical hydrophone using the pseudo-gaussian noise signal (dashed curve) and a pulsed CW signal (solid curve). The agreement is very good in the overlapping frequency range from 1.0 to 9.2 kHz. Below 1 kHz, however, calibration results are obtainable with the pseudo-gaussian signal but would not be valid with the pulsed CW waveform.

A resonant bender transducer (Edo Western Model 248-4.5) that is nearly omnidirectional was calibrated by the two methods, pseudo-gaussian noise and pulsed CW. The results, presented in Figure 6, show agreement within ±1 dB over most of the frequency range. The greater discrepancy at higher frequencies could be due to the increasing directivity of the transducer and to the difficulty in matching the positions of the standard and unknown when they are of widely differing size and shape.

The noise method can be used to detect certain faults in hydrophones. For example, a bubble of air in a hydrophone boot was simulated by attaching a plastic bubble of about 0.2 cm^3 to the outside of an omnidirectional hydrophone. The calibration results with and without the bubble are shown in Figure 7. The bubble resonance is clearly evident at about 650 Hz.

The calibration curve of Figure 5 is replotted in Figure 8 down to 20 Hz. The calibration was carried out in two sections: the upper section with a sampling rate of 18.4 kHz and resolution of 144 Hz and the lower section with sampling rate 2 kHz and resolution 7.8 Hz. Hum interference is readily identified by the dip near 60 Hz but this does not preclude a valid calibration at other frequencies.

7. CONCLUSIONS

Pseudo-gaussian noise is an attractive alternative to conventional CW signals in the substitution method of hydrophone calibration. It allows for automatic wideband calibration at medium-to-low frequencies under free-field conditions and in the case of tank measurements, the noise technique is far less sensitive to interference from boundary reflections.

The pseudo-gaussian noise method is especially useful for calibration at low frequencies down to one Hertz or less - being limited only by the sound generation equipment. The pulsed CW and noise methods are complementary in the sense that they can be used together to obtain ultra wideband hydrophone calibrations in an open acoustic tank.

TABLE I. CHARACTERISTICS OF PSEUDO-GAUSSIAN NUMBER GENERATOR

Sequence Length, N	5	6	7	12
Period	344064	172032	2080768	4444160
Standard Deviation	132	121	112	85

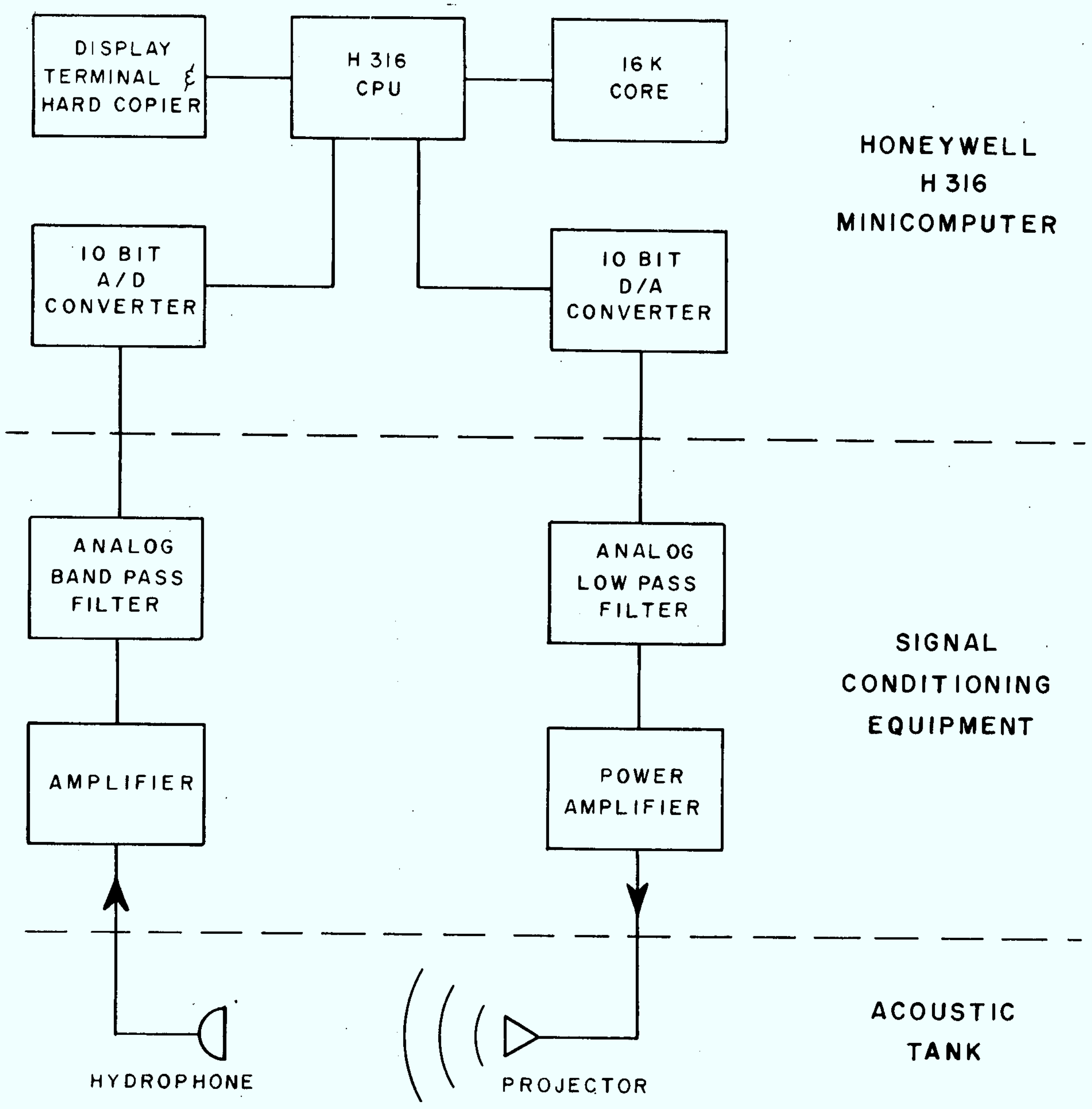

FIG. 1 BLOCK DIAGRAM OF PSEUDO-GAUSSIAN NOISE CALIBRATION SYSTEM

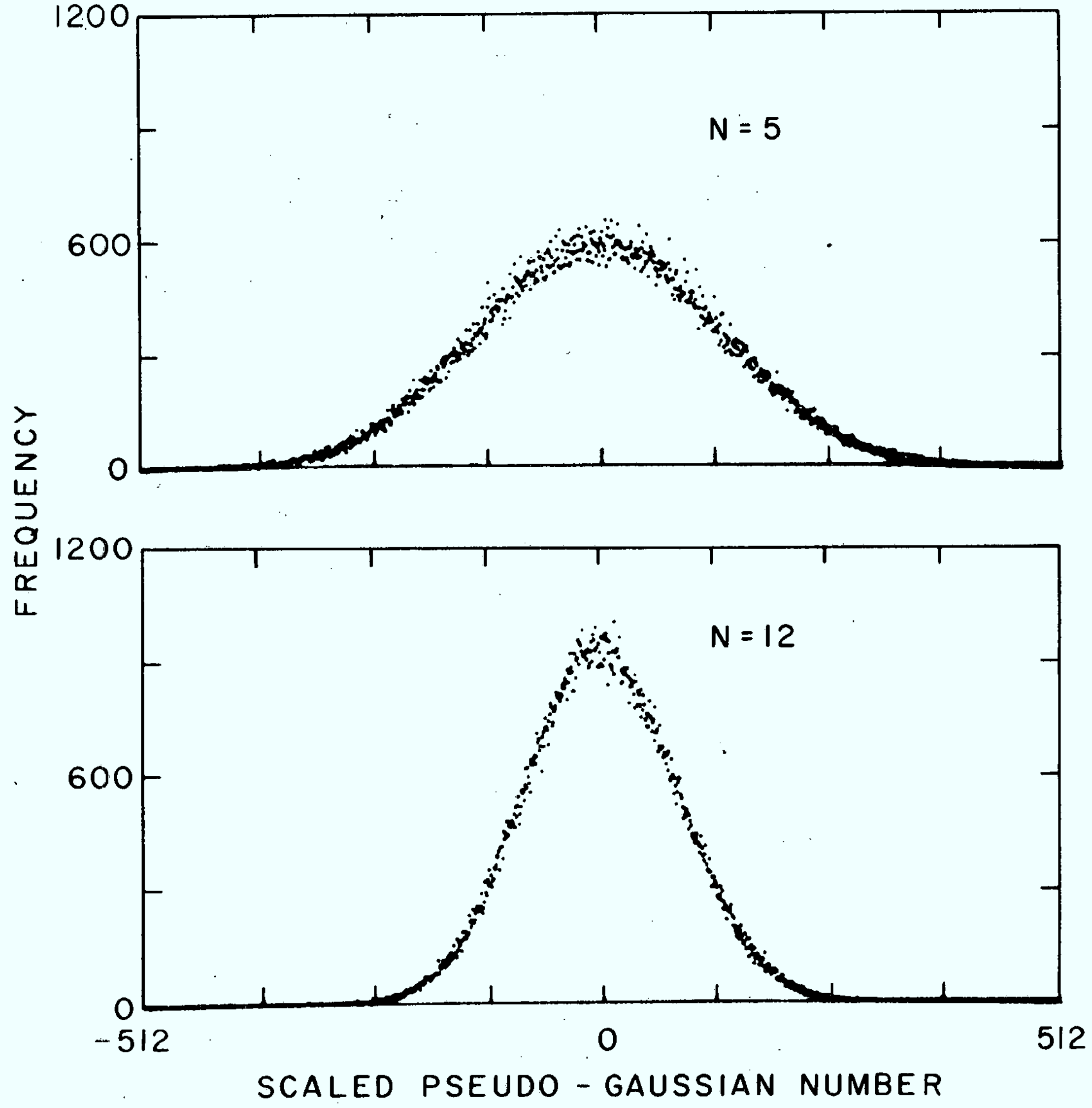

FIG. 2 DISTRIBUTIONS OF 200000 SOFTWARE-GENERATED PSEUDO-GAUSSIAN NUMBERS FOR N=5 AND N=12

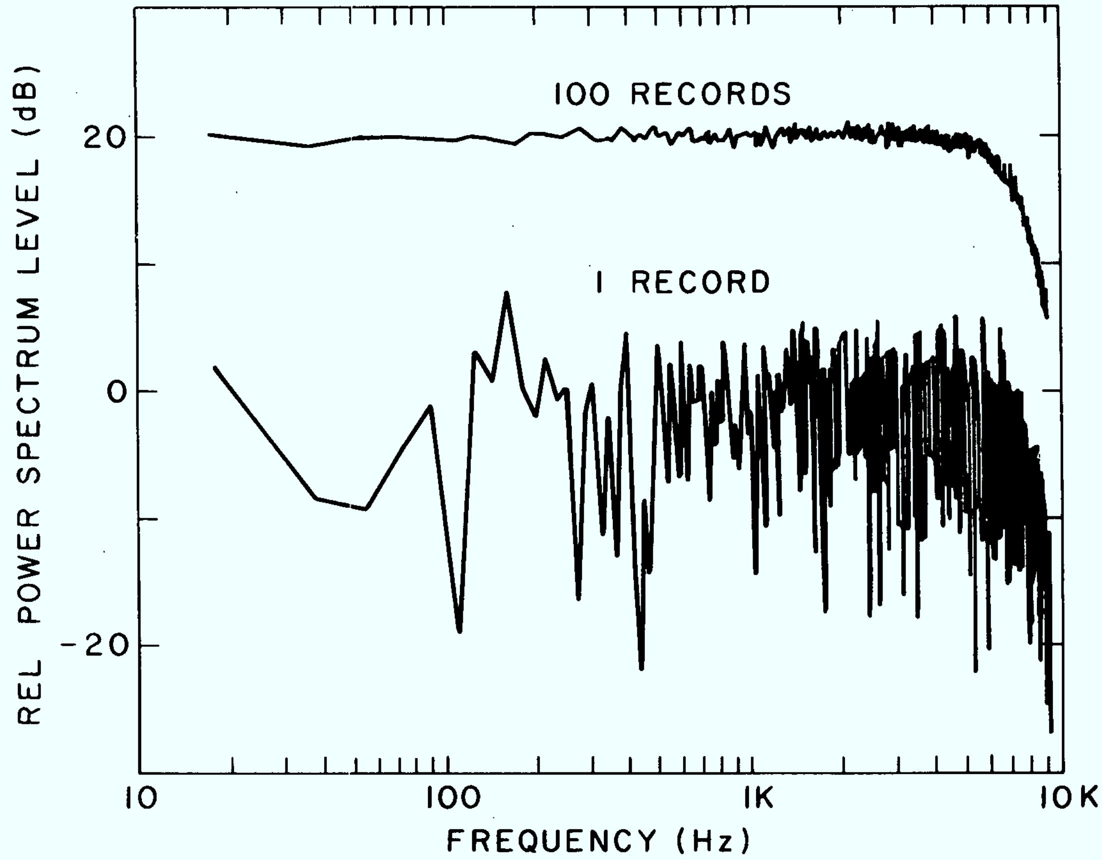

FIG. 3 POWER SPECTRUM LEVELS FOR PSEUDO-GAUSSIAN NOISE SEQUENCES WITH N=12. MEASURED SPECTRA ARE SHOWN FOR ONE RECORD OF 1024 VOLTAGE LEVELS AND 100 RECORDS USING AN OUTPUT AND SAMPLE RATE OF 18.4 KHZ

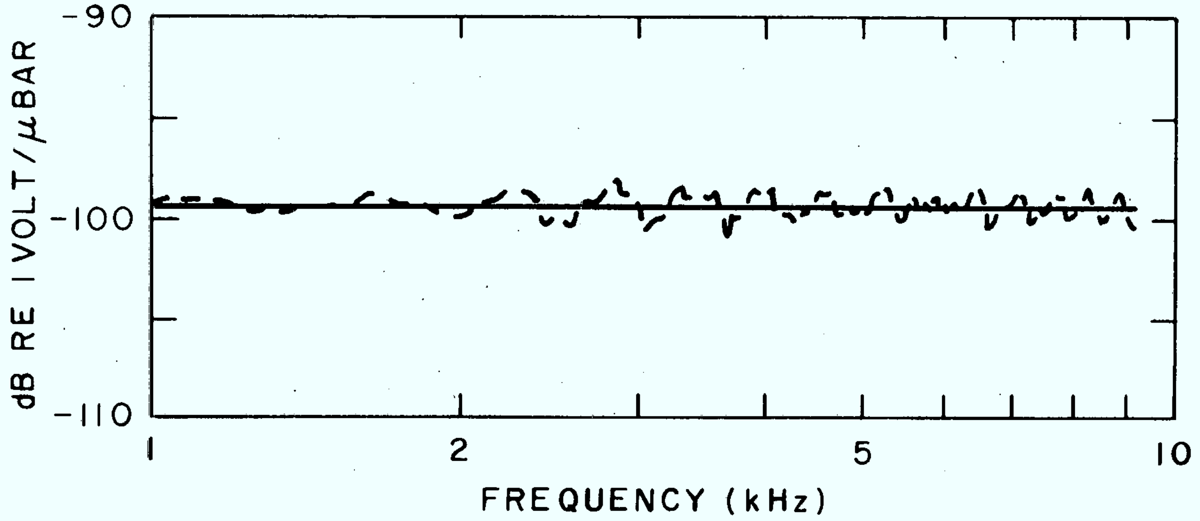

FIG. 4 SELF-CALIBRATION OF THE STANDARD HYDROPHONE WITH NO MOVEMENT (SOLID LINE) AND WITH A VERTICAL POSITIONING ERROR OF APPROXIMATELY 3 CM (DASHED LINE).

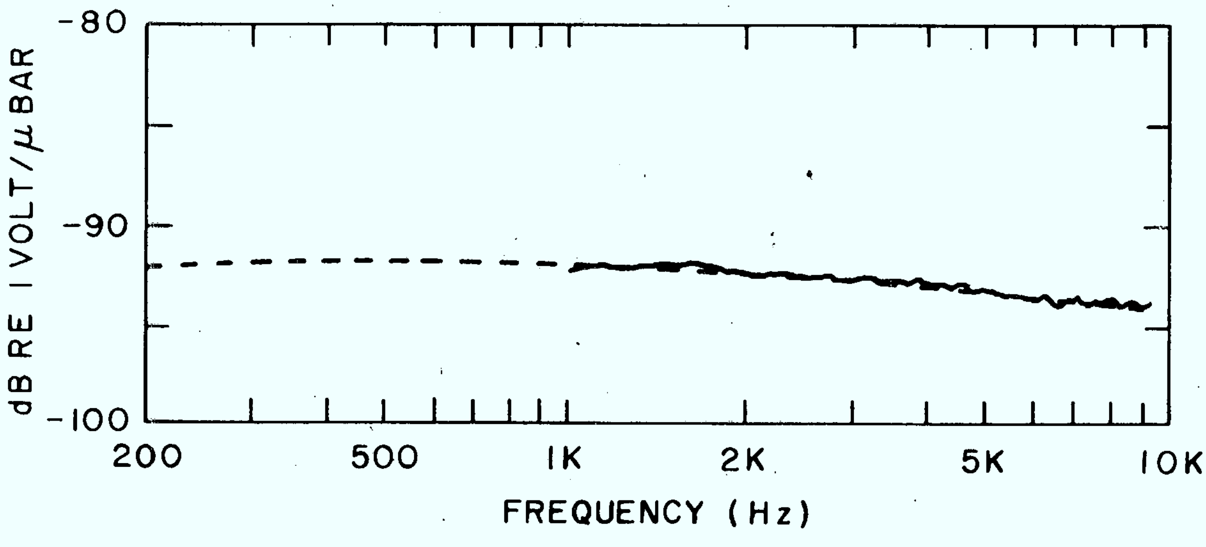

FIG. 5 SENSITIVITY OF A 5.1 CM-DIAMETER SPHERICAL HYDROPHONE BY THE PULSED CW METHOD (SOLID LINE) AND BY THE PSEUDO-GAUSSIAN NOISE METHOD (DASHED LINE)

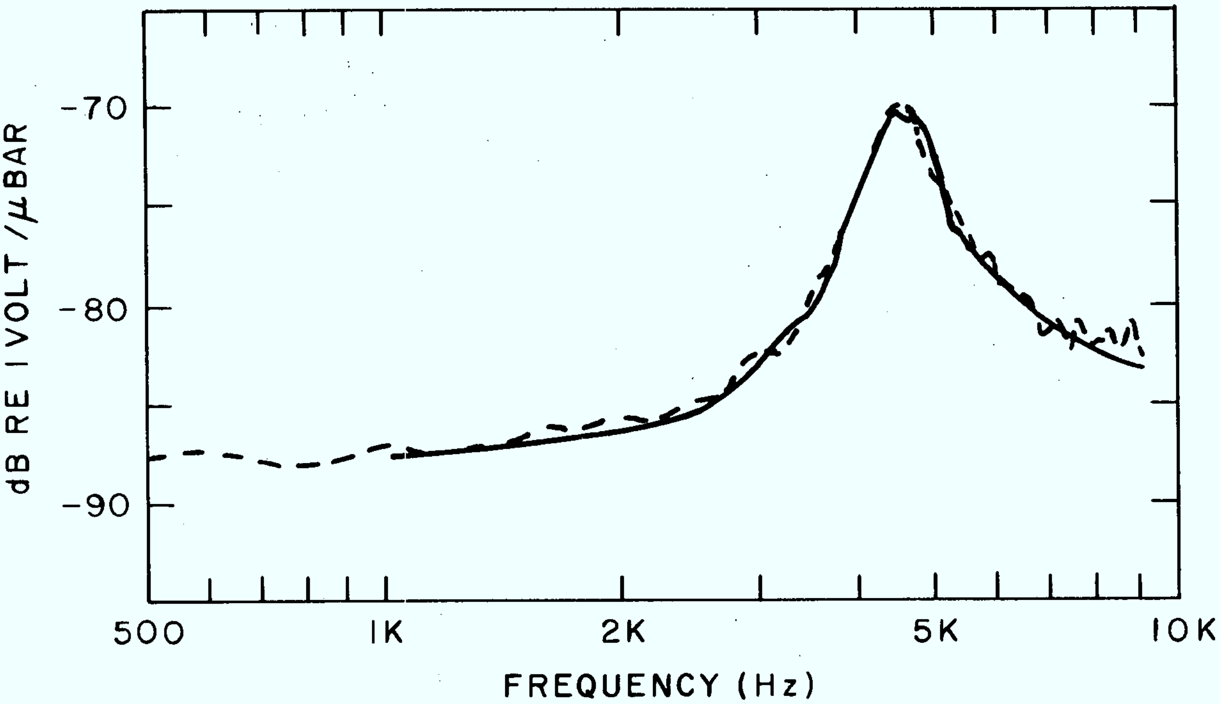

FIG. 6 SENSITIVITY OF AN EDO WESTERN MODEL 248-4.5 RESONANT BENDER TRANSDUCER BY THE PULSED CW METHOD (SOLID LINE) AND BY THE PSEUDO-GAUSSIAN NOISE METHOD (DASHED LINE)

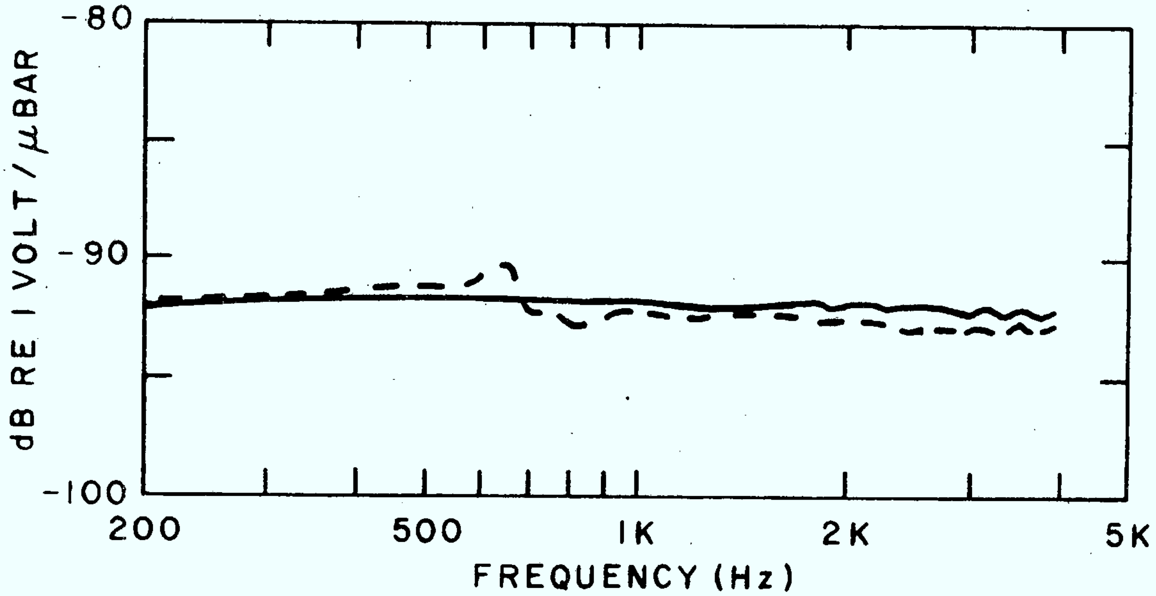

FIG. 7 EFFECT OF AN AIR BUBBLE ATTACHED TO A CYLINDRICAL HYDROPHONE. THE SOLID CURVE SHOWS THE NORMAL HYDROPHONE SENSITIVITY WHILE THE DASHED CURVE WAS OBTAINED WITH A 0.2 CM^3 AIR BUBBLE ON ITS OUTER SURFACE

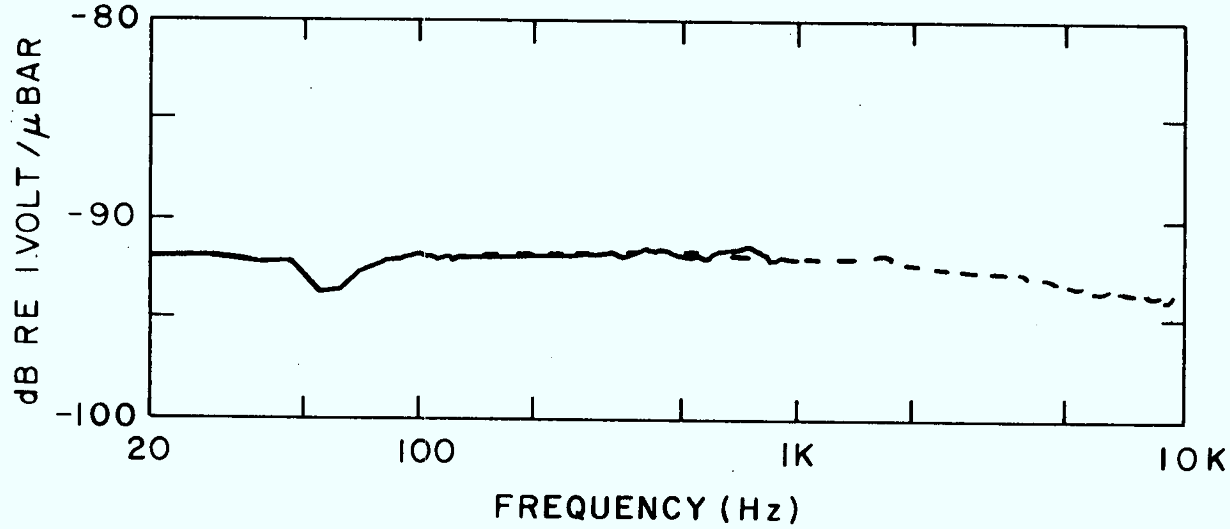

FIG. 8 WIDEBAND CALIBRATION OF A 5.1 CM-DIAMETER SPHERICAL HYDROPHONE BY THE PSEUDO-GAUSSIAN NOISE METHOD. THE DASHED CURVE WAS OBTAINED WITH A SAMPLE RATE OF 18.4 KHZ, A RECORD LENGTH OF 128 POINTS AND 100 AVERAGES. THE CORRESPONDING PARAMETERS FOR THE SOLID CURVE WERE 2 KHZ, 256 POINTS AND 100 AVERAGES. THE DIP NEAR 60 HZ IS DUE TO HUM INTERFERENCE

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