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NONLINEARITY OF CYLINDRICAL HYDROPHONES USED FOR THE MEASUREMENT OF PARAMETRIC ARRAYS

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ABSTRACT

Although the subject of nonlinearity in piezoelectric materials used for transmission at high drive levels is now being considered, little attention has been given to the possibility of nonlinear effects on reception. This is because hydrophones are more than adequately linear when used for conventional reception. However, the investigation of parametric arrays, where the aim is to observe a difference frequency signal, generated in the propagation medium, in the presence of two relatively high level primary signals, may place much more stringent requirements on hydrophone linearity and thus be a very sensitive test of any such nonlinearity.

In experimental studies of parametric sources operating at primary frequencies of about 100 kHz and 1 MHz we have observed significant intermodulation occurring in a number of cylindrical hydrophones. These effects are most noticeable where the difference frequency pressure is small compared with the primary pressure, as is the case in the transducer nearfield where most of these measurements were performed. This nonlinearity also becomes more significant as the difference frequency and, hence, conversion efficiency of the parametric source is reduced. The problem may be overcome by making measurements at an increased range where spherical spreading and attenuation reduce the relatively high levels of the primary signals.

The presence of such a nonlinearity, provided it is at least comparable with the real signal level, can be identified by the resulting characteristic beam profile and investigated by use of an acoustic filter that reduces the primary pressure levels incident on the hydrophone.

INTRODUCTION

The parametric array is an acoustic source of radiation that utilises non-linear propagation of sound through water. Usually two high intensity collinear primary beams at frequencies $f_1 = f_o + f_-/2$ and $f_2 = f_o - f_-/2$ are transmitted and the intermodulation signal at the difference frequency f_-, generated as a result of the propagation, is utilised. Its advantages include the narrow beam width and the wide range over thich f_- may be simply swept by altering the primary frequencies f_1 and f_2. Since Westervelt (1, 2) investigated the basic theory the technique has been greatly developed and widely applied, with the state of the art being summarised in a recent conference in this series (3).

The study of parametric sources requires careful experimentation as the parametric output can easily be obscured by other nonlinear behaviour, either in the transmitting transducer or the receiving system (4,5). Possibly the least considered of these extra sources is the fact that the hydrophone itself may be nonlinear and thus generate a local signal at the difference frequency (5). This behaviour will be most important in the nearfield of the transducer where the primary frequency pressures incident on the hydrophone are at their largest compared with the parametrically generated signal. Beyond this near-field region any hydrophone generated component will decrease more rapidly than the true parametric output due to spherical spreading and absorption of the primary waves. Thus measurements are most safely made outside the nearfield region.

This, however, may not be possible or desirable. For example the preliminary testing of sources for sub-bottom profiling applications may have to be performed in tank facilities of limited size. Alternatively laboratory applications may specifically require experiments to be performed in the near-field where the parametric beam cross section is smallest and the true parametric output largest. Examples of this type of application include the acoustic testing of specimens of limited size, and rough surface scattering studies.

Experimentally we have found the nonlinear response of hydrophones to be significant in both types of situation with resulting complications in a wide range of experiments. As a consequence of this experience we have made some preliminary investigations of the phenomena and obtained quantitative data for a number of individual hydrophones. The ideal outcome of such a programme of work would be guidelines for the choice of hydrophones for a given experiment.

THEORETICAL CONSIDERATIONS

Prior to poling, the ceramics used in the construction of most hydrophones show only a square law relationship between the applied electric field and ceramic strain. In order to make the ceramic useful for transduction it must be poled during manufacture by the application of a high electric field, so that the resulting response is approximately linear. Thus, although the relationship between strain and electric field may be assumed to be linear for most circumstances it is fundamentally nonlinear. For a hydrophone this fundamental ceramic nonlinearity will combine with the stress-strain behaviour of the construction used to produce an overall nonlinear response. Clearly this may be very complex so we will consider the behaviour from a phenomena-logical approach. A full description of the ceramic nonlinearity would require consideration of the equation of state with second order terms added. Although considerable attention has been given to nonlinearity in transmitting applications (6), where the nonlinearity can become very significant, little has been given to the inverse problem for high mechanical drive levels.

We will simply consider the hydrophone as a 4 terminal network transforming from a mechanical port to an electric port. The presence of intermodulation on the output indicates that the transfer from pressure P(t) to output voltage V(t) is nonlinear with a significant second order component so that

$$V(t) = \alpha(\omega)P(t) + \beta(\omega)P^2(t)$$

where $\alpha(\omega)$ and $\beta(\omega)$ are frequency dependant transfer characteristics of the hydrophone. The normal, first order sensitivity $M(\omega_o)$ is defined by

$$M(\omega_o) = 20 \log |\alpha(\omega_o)|$$

while a new second order sensitivity $M'(\omega_o)$ may be defined by

$$M'(\omega_o) = 20 \log |\beta(\omega_o)| ,$$

where $M'(\omega_o)$ will be measured for peak signals and quoted in terms of dB relative to 1 volt per μPa^2. Normally $\beta \ll \alpha$ so that deviations from linearity will be small for a single frequency wave.

We will consider the incident pressure $P(t)$ to be the sum of two primary waves at angular frequencies ω_1 and ω_2, where $\omega_1 = \omega_o + \omega_-/2$ and $\omega_2 = \omega_o - \omega/2$, with pressure amplitudes P_1 and P_2 so that

$$P(t) = P_1 \cos\omega_1 t + P_2 \cos\omega_2 t .$$

If $\omega_- \ll \omega_o$ we may assume that $\alpha(\omega)$ and $\beta(\omega)$ take their values at ω_o, that is $\alpha(\omega_o)$ and $\beta(\omega_o)$, so that the hydrophone output is given by

$$V(t) = \frac{\beta(\omega_o)}{2}\left(P_1^2 + P_2^2\right) + \beta(\omega_o) P_1 P_2 \cos\omega_- t$$

$$+ \alpha(\omega_o)(P_1 \cos\omega_1 t + P_2 \cos\omega_2 t)$$

$$+ \text{terms in } 2\omega_1 , \quad 2\omega_2 \text{ and } \omega_1 + \omega_2 .$$

The difference frequency may be isolated by filtering, enabling its amplitude v_h to be measured in the presence of much higher signals. Hence the second order sensitivity is given by

$$M'(\omega_o) = 20 \log \frac{v_h}{P_1 P_2} \quad \text{where} \quad v_h = |\beta(\omega_o) P_1 P_2| .$$

The second order sensitivity $M'(\omega_o)$ is not the most suitable parameter for comparing the performance of hydrophones for parametric reception as it does not take into account the hydrophone sensitivity $M(\omega_-)$ at the difference frequency ω_- which determines the voltage v_ω produced across the hydrophone by the waterborne, parametric output P_-. For given P_1, P_2 and P_- the best hydrophone will be that which produces the smallest ratio v_h/v_ω. Now

$$20 \log \left(\frac{v_h}{v_\omega}\right) = 20 \log \left| \frac{\beta(\omega_o) P_1 P_2}{\alpha(\omega_-) P_-} \right| = R + 20 \log \left| \frac{P_1 P_2}{P_-} \right|$$

where $$R(\omega_o, \omega_-) = 20 \log \left| \frac{\beta(\omega_o)}{\alpha(\omega_-)} \right| = M'(\omega_o) - M(\omega_-)$$

This new parameter R will be used as a hydrophone figure of merit for parametric reception.

EXPERIMENTAL OBSERVATIONS

Observations were made on a number of cylindrical hydrophones using 3 different primary frequency transducers operating at 102 kHz, 455 kHz and 920 kHz. Each transducer was driven by a two frequency tone burst resulting from the modulation of a carrier frequency f_o by a tone burst with frequency equal to half that of the required difference frequency f_-. In each case the hydrophone output was passed through a passive low pass filter that gave at least 60 dB attenuation of the primaries to ensure that intermodulation in the receiving electronics was not important. The filters used were themselves checked and found to have an intermodulation ratio of better than −110 dB relative to 1 V per V^2 measured at the input, which was again not significant. The output signal after suitable amplification and bandpass filtering was either displayed directly on an oscilloscope or passed through a transient recorder and signal averager to improve the signal to noise ratio. The hydrophones tested were mainly of the Brüel & Kjær 8103 miniature type with a damped resonance at about 120 kHz, although some others were used, including laboratory mounted cylinders enclosed in epoxy.

The initial observations made with the 920 kHz primary transducer for 100 kHz difference frequency gave no indication of the problem to come since the parametric output is relatively large for the step down ratio f_o/f_- involved. The beam cross section at a range of 63 cm for example (figure 1a) shows the characteristic parametric form of an inverted V with no side lobes. Lowering the difference frequency to 40 kHz (figure 1b) appears to make little difference, apart from the expected widening of the pattern, although the sides of the section do appear slightly concave. By 10 kHz, however, the beam is clearly distorted with a narrow, hydrophone generated, peak superimposed on the relatively wide parametric beam. For 5 kHz, as shown in figure 1d, the true parametric output is even lower and the hydrophone contribution dominates with only about 10% of the output signal on axis results from the array. The central part of the beam now follows the shape of the primary pressure squared as is indicated by the superimposed circles on the plot. The hydrophone nonlinearity clearly becomes more significant as the true parametric output decreases with increasing step down ratio. Although this extra signal is obvious from sections at lower frequencies, the hydrophone component may significantly increase axial pressure levels by 2 or 3 dB without making outstanding changes to beam profiles. The axial pressure levels, assuming the hydrophone to be linear, deviate increasingly from the theoretical predictions as the difference frequency is lowered, until the axial variation finally follows the primary variation squared.

Since the hydrophone generated signal is proportional to the local product of the primary pressures the relative importance of this source may be reduced by increasing the observation range where this is possible. This is illustrated in figure 2 which shows the relative improvement obtained by increasing the range R, from 63 cm to 121 cm for a transducer with last nearfield maximum at 39 cm.

For the purposes of hydrophone comparison a number of techniques may be used. A simple comparison may be made by observing the different form of the beam sections obtained when observing the same parametric array. In figure 3 the sections recorded with a Brüel and Kjær 8103 and laboratory constructed hydrophone are compared, the difference in performance being obvious. From these plots the figure of merit R may be estimated to differ by 14 dB for the two hydrophones under identical circumstances indicating the advantages that can be obtained by a suitable choice of hydrophone.

In order to obtain quantitative estimates of $M'(\omega_o)$ and $R(\omega_o,\omega_-)$ it is necessary to separate out the components v_h and v_ω of the hydrophone output. This may be achieved by reducing the difference frequency to the point where v_ω is neglible, so that the whole hydrophone output arises from its own nonlinearity. An alternative method, used in this work, is to prevent the primary signals from reaching the hydrophone by use of an acoustic low pass filter that has a significantly higher transmission loss at the primaries than the difference frequency. The acoustic filter consisted of a sheet of cork filled butyl rubber with a transmission loss differential of at least 15 dB. Measurements made with and without the filter immediately in front of the hydrophone enabled v_h to be reliably estimated provided the transmission loss differential was accurately known. The process is illustrated in figure 4 which shows beam profiles with and without the acoustic filter present. Using this technique, it is possible, and important, to check on the relative phases of the hydrophone and parametric signals. This method also automatically allows for extraneous difference frequency radiation transmitted directly from the transducer.

With the acoustic filter it was possible to investigate the precise relationship of the hydrophone generated signal to the primary frequency pressure. Although the basic relationship was in general a square law, some hydrophones showed an increase in $M'(\omega_o)$ at higher drive levels. In one case this deviation was related to the pulse repetition frequency used and therefore presumed to result from heating effects in the hydrophone at the high primary levels used. When measurements were made at sufficiently low pulse repetition rates the hydrophone generated component v_h was proportional to the square of the mean primary frequency output as shown in figure 5.

Measurements for a single 8103 hydrophone (Table 1) showed that for a primary frequency of 455 kHz the second order sensitivity, although not constant, changes only slowly with difference frequency. It is not clear whether this variation results from changes in $\beta(\omega)$ with or from systematic errors in the experimental procedure. In Table 2 the nonlinear coefficients of four nominally identical hydrophones are compared under identical circumstances, the figure of merit R varying by 4 dB between them. In contrast three laboratory mounted cylinders showed variations in $M'(\omega_o)$ and $R(\omega_o,\omega_-)$ of up to 10 dB under identical situations. The nonlinear coefficients appeared to be independant of the orientation of the hydrophone about its axis of symmetry.

In Table 3 we present preliminary results for the variation with primary frequency of $M'(\omega_o)$ and $R(\omega_o,\omega_-)$ for a single 8103 hydrophone obtained by averaging over a number of measurements at low difference frequencies. The most obvious feature from these isolated measurements is that the nonlinearity decreases dramatically in magnitude as the primary frequency increases from 102 kHz to 920 kHz. The decrease M' of 36 dB for a 19 dB increase in primary frequency suggests that M' may vary as $1/\omega^2$, although considerably more data would be required to verify this. This primary frequency variation does, however, have considerable implications for the design of laboratory experiments working in the nearfield of the parametric array as far as the choice of operating frequency is concerned.

At the highest frequency the Brüel and Kjœr 8103 may well be approaching the absolute limit on its performance set by another second order phenomenon known as pseudo sound (4,8). This is the result of radiation pressure, which for the case of a modulated signal results in an alternating pressure at the difference frequency acting on the hydrophone. Although it is difficult to predict the magnitude of this effect on a cylindrical hydrophone we can estimate that it has an upper limit equivalent to a value of R of - 301 dB relative to 1 μPa/μPa. This value of R has been observed for one particular hydrophone indicating that the effective pseudo-sound level is at least as low as this.

CONCLUSION

We have found that nonlinearity of hydrophones can be a significant source of error in parametric array measurements. By detecting the intermodulation occurring in the hydrophone when subjected to two primary frequencies this effect may be quantified and hydrophones compared. The nonlinear behaviour does, however, seem to be complex and little can be concluded about how their performance may be improved. The use of an acoustic filter does provide a means of removing this effect from parametric measurements provided the results of truncating the parametric array are not detrimental to the experiment concerned.

During the preparation of this paper the authors' attention was drawn to similar work being performed at N.U.S.C. by Moffet and Blue (9).

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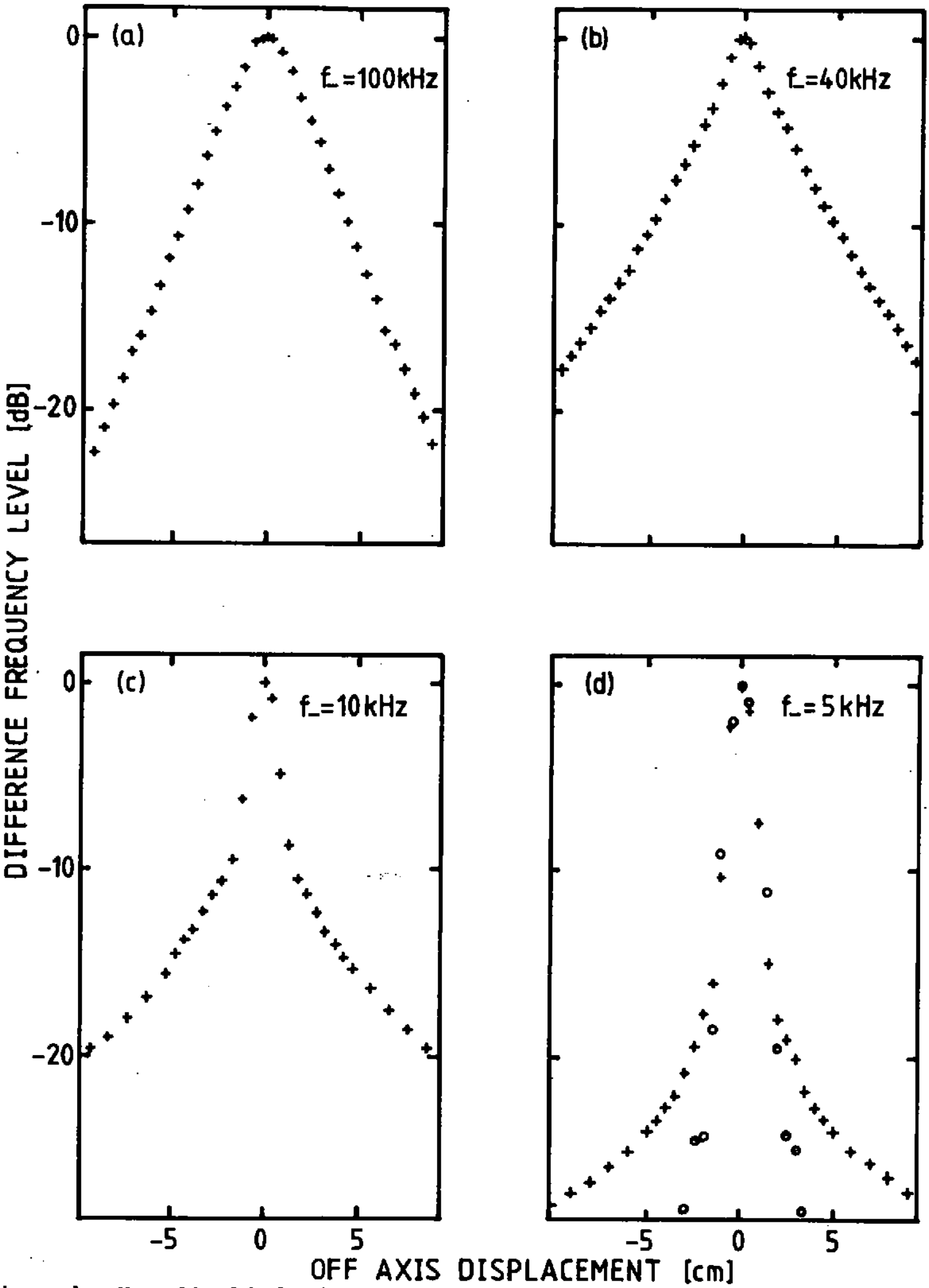

Figure 1 Normalised hydrophone output for sections of a parametric array showing increased importance of hydrophone generation at low difference frequencies. (f_o = 920 kHz ; R = 63 cm) (a) f_- = 100 kHz ; (b) f_- = 40 kHz ; (c) f_- = 10 kHz ; (d) f_- = 5 kHz with square of primary variation for comparison (o).

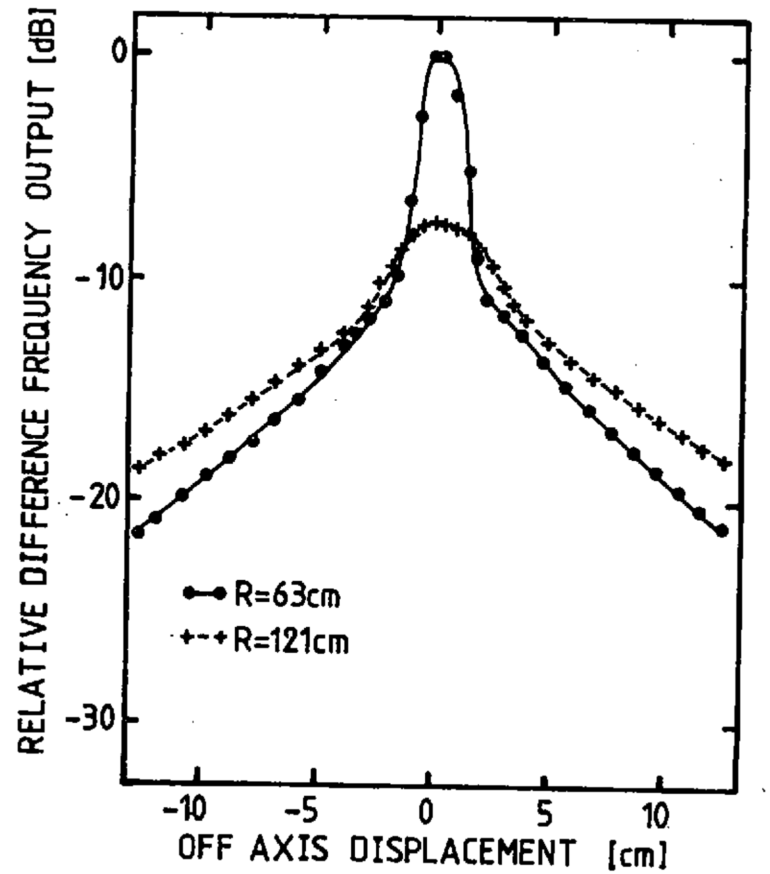

Figure 2 Hydrophone difference frequency output for sections of a parametric array made at 63 cm and 121 cm. (f_o = 920 kHz ; f_- = 10 kHz)

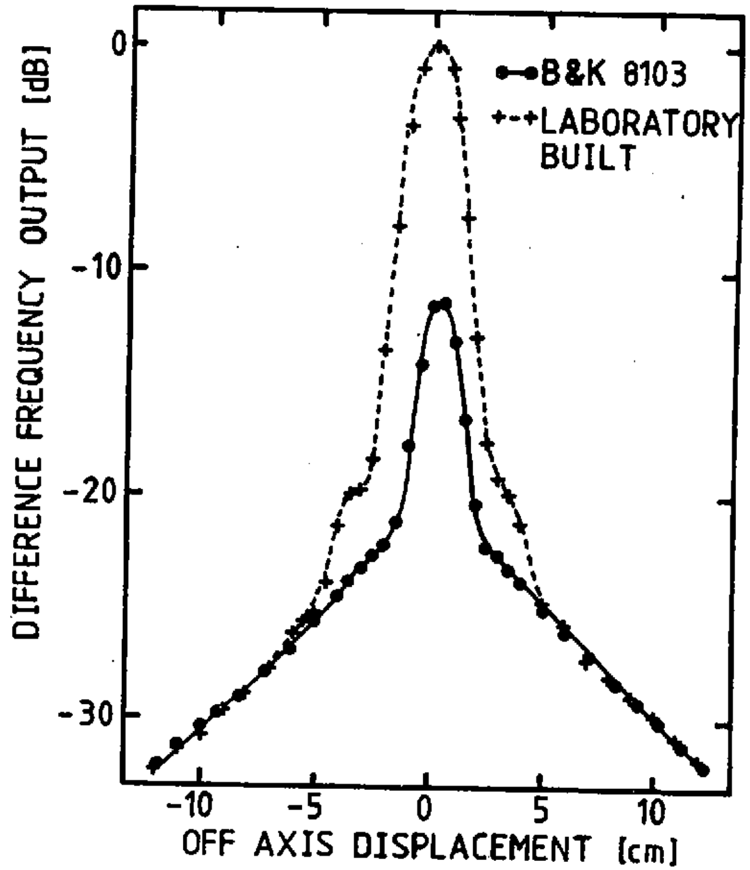

Figure 3 Comparison of hydrophone outputs on the same section of a parametric array showing difference in hydrophone generation.
(f_o = 920 kHz ; f_- = 10 kHz ; R = 63 cm)

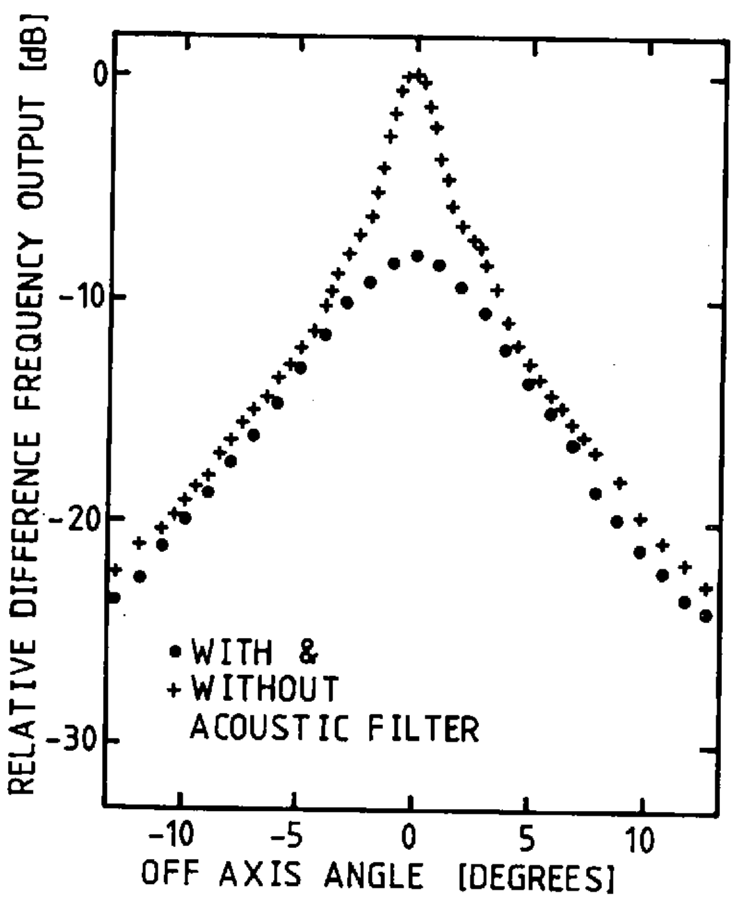

Figure 4 Hydrophone difference frequency output with (•) and without (+) acoustic filter immediately in front of hydrophone.
(f_o = 455 kHz ; f_- = 20 kHz).

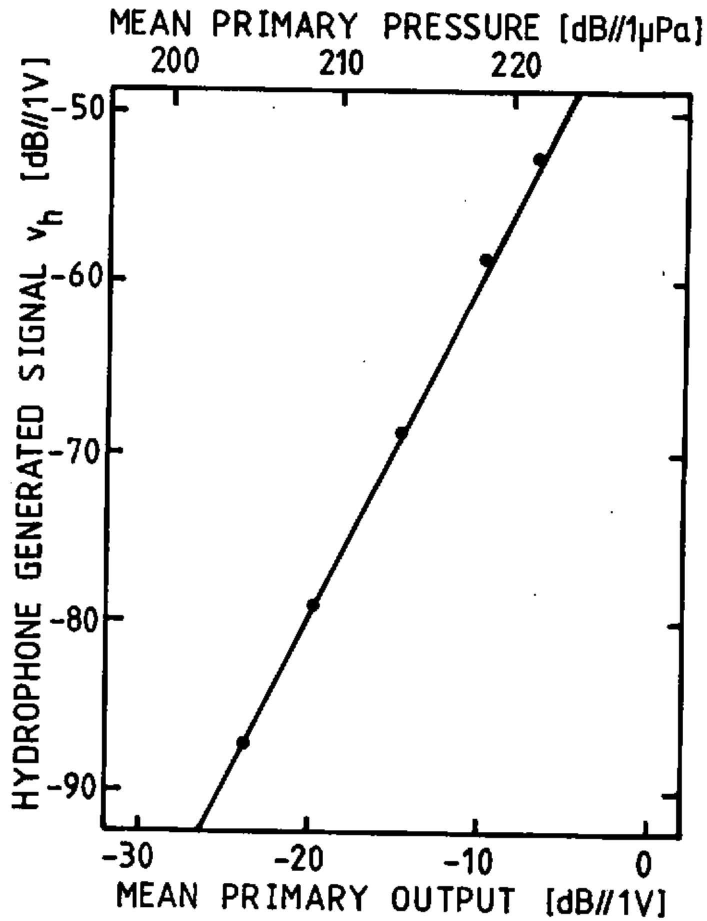

Figure 5 Square Law relationship between hydrophone generated signal at difference frequency and mean primary frequency output (mean primary pressure). (f_o = 455 kHz ; f_- = 20 kHz)

TABLE 1

Variation of hydrophone nonlinearity for a single B & K 8103 hydrophone with difference frequency for a carrier frequency of 455 kHz.

Difference Frequency f_- (kHz)	M' (dB rel. to 1 V/μPa^2)	R (dB rel. to 1 μPa/μPa^2)
5	-496	-285
10	-497	-286
20	-498	-286
30	-499	-287
40	-499	-287

TABLE 2

Comparison of the nonlinearity of 4 B & K 8103 hydrophones for f_o = 455 kHz and f_- = 20 kHz.

Hydrophone	M' (dB rel. to 1 V/μPa^2)	R (dB rel. to 1 μPa/μPa^2)
1	-496	-284
2	-497	-285
3	-499	-288
4	-498	-286

TABLE 3

Variation of hydrophone nonlinearity for a single B & K 8103 hydrophone with primary frequency.

Mean Primary Frequency (kHz)	M' (dB rel. to 1 V/μPa^2)	R (dB rel. to 1 μPa/μPa^2)
102	- 472	- 260
455	- 496	- 285
920	- 508	- 296