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CALIBRATION AND INHERENT ERRORS OF A TWO HYDROPHONE SOUND INTENSITY MEASUREMENT SYSTEM

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1. INTRODUCTION

The most commonly measured characteristic of a point in a sound field is the acoustic pressure. A microphone or hydrophone placed in a sound field will produce an electrical signal proportional to the local instantaneous pressure which can then be processed to extract a limited amount of information about that sound field. Other acoustic quantities can be derived from measurements of acoustic pressure but require some ideal acoustic condition to prevail. A particular example of this is the determination of sound power radiated by a noise source: measurements of acoustic pressure at a point in a free field environment, away from the near-field of the source, can be directly related to the magnitude of the sound intensity vector at that point, and sound intensity integrated over a closed surface enclosing a source will give the total sound power radiated by that source. Alternatively, sound power can be calculated from measurements of sound pressure due to a noise source radiating into a highly reverberant environment. If sound intensity could be measured directly then the dependence upon idealised acoustic environments would be greatly reduced.

Pressure measurements made in the near field of a complex noise source can only yield a limited amount of information about that source, particularly as regards the flow of acoustic energy away from or into a particular region of the source; simple pressure measurements will not distinguish between radiation or absorption. Direct measurement of sound intensity in the near field of a complex source would enable the source to be investigated and characterised in terms of the flow of acoustic energy out of and into that source.

The ability to measure sound intensity has been identified as a useful tool in the study of noise radiation from ships with regard to total sound power radiated into air and water, and with regard to the ship's hull as a complex noise source. This paper discusses the design criteria, errors and calibration of the "two microphone (hydrophone)" method of sound intensity measurement for these applications, with particular reference to the "in-water" case using available instrumentation (i.e. B&K 8103 hydrophones and 2626 charge amplifiers).

2. MEASUREMENT PRINCIPLES

The instantaneous sound intensity is defined to be the product of the instantaneous sound pressure and the instantaneous particle velocity. The instantaneous particle velocity is a vector, therefore intensity is also a vector. Intensity is a measure of the magnitude and direction of the sound energy flux at a point in a sound field at a particular instant in time; the time average of this quantity is a measure of the net sound energy (per unit area) transported through that point.

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To measure sound intensity instantaneous sound pressure and instantaneous particle velocity need to be measured with preservation of their relative phase. The pressure can be simply measured with a hydrophone but measuring the particle velocity satisfactorily is a problem. One solution to this problem (1) is to use the signals from two closely spaced hydrophones from which one can derive instantaneous pressure and particle velocity at a notional point mid-way between the two transducers. In the frequency domain it can be shown that time-averaged sound intensity as a function of frequency is related to the imaginary part of the cross-spectrum of two hydrophone signals (2).

$$I_e(f) = \frac{Q_{12}(f)}{\omega\rho h} \tag{2.1}$$

Where $Q_{12}(f)$ = imaginary part of X-spectrum between P_1 and P_2

ρ = density of medium

h = hydrophone spacing

ω = angular frequency

$I_e(f)$ = time averaged estimate of intensity for frequency f

This relationship is very convenient as it indicates that measurements of sound intensity can be made with the use of two hydrophones (or microphones) and a suitable two-channel frequency analyser.

The advantages of the above techniques are apparent simplicity and that they rely entirely upon pressure measurements, so once the system is calibrated for pressure response (sensitivity and phase) then it is calibrated for intensity (provided the density of the medium and the hydrophone spacing are known). There are also a number of disadvantages and inherent errors and these will be reviewed in the next section.

3. REVIEW OF ERRORS

3.1. Introduction It is very difficult to write about errors for the general case. In order to derive analytical formulae to describe errors then some specific type of field must be assumed. The simplest field will be that due to a propagating plane wave, so this is the case used for most of the examples presented below. Derivations and more detailed discussion of these errors can be found in the references indicated after each sub-title.

3.2. Finite Approximation Error (3,4)

The error in intensity estimation is:

$$\frac{I_e}{I_t} = \frac{\sin(kh)}{(kh)} \tag{3.1}$$

Where: I_t = true intensity

k = wavenumber

This implies an increasing under-estimation of intensity with increasing frequency. For a known maximum acceptable error and upper frequency limit, an optimum transducer spacing can be calculated. It must be remembered that Equation 3.1. only applies to a plane wave and is therefore not strictly indicative of the error in other field types.

3.3. Proximity Effect (3,4) Although included here under a separate heading this error is essentially the finite approximation error derived for specific fields other than a plane wave, viz. the near field of monopole, dipole and quadrupole sources. In these cases the phase angle between the two hydrophone signals will be the same as that in a plane wave, but the magnitude of the pressure varies with distance from the centre of the point source.

3.4. Phase Mis-Match Error (3,4) The measurement of sound intensity by this technique depends upon accurately sensing the phase between the pressures exciting the two transducers. If there is any difference in the sensing characteristics of the measurement channels which results in a distortion of the phase angle an error will result. For a plane wave and small angles:

$$\frac{I_e}{I_t} = 1 \pm \frac{\phi}{kh} \qquad (3.2)$$

Where ϕ = phase mis-match between measurement channels

From this, for constant ϕ, the error will increasingly over or under estimate intensity for decreasing frequency and will imply a low frequency limit for measurement for a known maximum acceptable error.

More usually ϕ will be some function of frequency and will introduce some error at all frequencies of interest. However, there will often be some low frequency cut-off in the measurement channels (e.g. high pass filter in a B&K 2626 charge amplifier) which will introduce significant phase mis-match roughly proportional to an individual channel phase shift and therefore a quite definite lower limiting frequency. Equations 3.1 and 3.2 show that two-hydrophone intensity measurements are inherently frequency band limited: changing the transducer spacing will simply move this band up or down the spectrum. Later sections of this paper describe methods of expanding this frequency band by means of calibrating out phase mis-match in the system.

3.5. Diffraction (5) At and above frequencies where wavelength is of a similar magnitude to transducer dimensions, the acoustic field may be significantly altered by the physical presence of the transducers. Reference (5) discusses these effects for intensity measurements in air using half-inch microphones. In water wavelengths are longer than in air for a wave of particular frequency and the transducers (Bruel and Kjaer 8103 Hydrophones) are less than half an inch in diameter. Scaling the results of Reference (5) shows that significant diffraction effects are not expected below 20 kHz.

3.6. Spatial Sampling (6) In general, the intensity of a sound field will vary continuously through space. Practical measurements will consist of intensity estimated at discrete points in the field. Errors will result if insufficient measurement points are used to describe the spatial variation of the field. The above two references discuss how the Nyquist sampling theorem can be applied to spatial sampling with use of a spatial Fourier transform. The only way to determine the minimum number of points required to describe a particular surface in a field is to measure at many points and estimate how much reduction is possible. The spatial variation of the field will depend upon the nature of the source e.g. in the near field of vibrating plate the field will vary with the wavelength in the plate.

3.7. Rounding Error (4) For two closely spaced microphones the output signals will usually be very nearly in phase implying that the real part of their cross spectrum will be large compared to the imaginary part. This imaginary part will usually be the result of calculating the difference between two much larger numbers (from complex multiplication or division) and therefore is subject to rounding errors due to a finite number of significant figures imposed by digital computer calculations. This is a particular hazard when using dedicated dual channel FFT analysers for this type measurement as often precision is sacrificed in favour of a fast processing time.

3.8. Statistical Errors (7) For random signals an error dependent upon the number of averages used to determine intensity and the coherence between the two hydrophone signals is formulated as:

$$\frac{\sigma(I)}{I_t} \approx \left(\frac{1-\gamma^2}{2n\gamma^2}\right)^{\frac{1}{2}} \frac{1}{\theta} \tag{3.3}$$

Where γ^2 = coherence
n = number of averages
θ = phase angle between hydrophone signals
σ = standard deviation

In general θ will be small and γ^2 very close to 1.0 such that n is "reasonable" (say, 50) for a tolerable error. Care must be taken with the use of equation 3.3 for values of γ^2 close to unity, small values of θ, signal types other than Gaussian random and in the presence of bias errors.

4. CALIBRATION TECHNIQUE

The only error discussed in Section 3 which can be reliably compensated for in the general case is that due to phase mis-match between the two measurement channels (8). All other errors can only be minimised by careful equipment selection and configuration. Figure 1 shows relevant parameters for describing any mis-match between the two measurement channels and the effect upon measurement. In general H_1 and H_2 cannot be easily determined individually because a contribution by H_1 and H_2 will be made by the input amplifiers and filters of the analyser. More easily measured is the ratio H_2/H_1 as this is simply the transfer function measured between the two electrical signals for a common pressure exciting both transducers (i.e. $P_1 = P_2$).

For intensity measurements we can calculate $e_1 e_2^*$ but we want to know $P_1 P_2^*$. The two quantities can be related:

$$P_1 P_2^* = \frac{e_1 e_2^*}{|H_2|^2} \cdot \frac{H_2}{H_1} \tag{4.1}$$

$|H_2|^2$ is simply a gain factor and H_2/H_1 can be determined experimentally prior to or after taking measurements.

There are two principle methods of determining H_2/H_1. From Figure 1:

$$\frac{e_2}{e_1} = \frac{H_2 P_2}{H_1 P_1} \tag{4.2}$$

Method 1 relies upon being able to place the transducers in a field such that $P_2 = P_1$ in which case Equation 4.2 reduces to:

$$\frac{e_2}{e_1} = \frac{H_2}{H_1} \tag{4.3}$$

It is not very easy to produce such a field, in general H_2/H_1 will have a magnitude very close to 1.0 and only small phase. The calibration field must be more accurate than the differences to be determined.

An alternative approach is not be expect $P_1 = P_2$ but to rely upon being able to replace each transducer with the other such that the condition shown in Figure 2 is fulfilled. From Figure 1:

$$TF1 = \frac{e_2}{e_1} = \frac{H_2 P_2}{H_1 P_1} \qquad (4.4)$$

From Figure 2:

$$TF2 = \frac{e_2}{e_1} = \frac{H_2 P_1}{H_1 P_2} \qquad (4.5)$$

Combining Equations 4.4 and 4.5:

$$(TF1 \; . \; TF2)^{1/2} = \frac{H_2}{H_1} \qquad (4.6)$$

Providing the two transducers are dimensionally identical and are mounted such that they can be interchanged accurately then Equation 4.6 is a good basis for a practical calibration method.

Equation 3.2 implies that if there is some phase mis-match then even when P_1 and P_2 are in phase (i.e. no sound intensity in the direction of measurement) then a finite intensity will be registered. This therefore sets some lower limit for the magnitude of intensity measurable to a particular accuracy in a field of particular acoustic pressure. The true and spurious intensities will either add or subtract depending on their relative orientation. This is a good way of looking at the quality of an intensity measurement system and a parameter can be defined as the intensity registered at 90° to the direction of propagation of a plane wave (i.e $P_1 = P_2$ and intensity should be zero) relative to the true intensity of the plane wave $\{\bar{P}_1^2/\rho c = \bar{P}_2^2/\rho c\}$

Expressed in decibels this parameter could be called "Intensibility" and can be determined as a function of frequency. Knowing intensibility, the spurious intensity is known in any field relative to the pressure of that field. Comparing spurious intensity and measured intensity an estimate of the validity of that measurement can be made (e.g. if a measured intensity approaches the predicted spurious intensity then the measurement is very suspect). An ideal system would have an intensibility of $-\infty$ dB; with current transducers, equipment and calibration technique the practical lower limit is about -40 dB. Whether or not a system of particular intensibility is acceptable is application dependent. Intensibility is conveniently related to the common mode transfer function between the two channels.

$$\text{Intensibility} = 10 \log_{10} \left[\text{Im} \left(\frac{H_2}{H_1} \right) \frac{1}{kh} \right] \qquad (4.7)$$

Note that this is the intensibility of a system before applying a H_2/H_1 calibration. After applying the calibration, the intensibility is rather better i.e. (less than before) and will only be greater than $-\infty$ dB if there are any differences in mis-match between the current measurement and the calibration test e.g. a temperature, wetting or statistical effect). Also note that intensibility is a function of transducer spacing.

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Intensibility is a good measure of comparative quality between intensity measurement systems. It is an effective indicator to measurement error in circumstances where phase error is dominant over other sources of error.

5. A PRACTICAL CALIBRATION SYSTEM AND SOME MEASUREMENTS

Figure 3 is a line drawing of a device for pressure excitation of two hydrophones over a wide frequency range. The two hydrophones are each held in a sleeve which enables a reasonable acoustic seal in the cavity yet an ease and accuracy in interchanging their positions to follow the calibration method explained in Section 4. The upper water chamber enables "wetting" of the hydrophones to be continuous even during position changing.

Two different sources are used for different frequency ranges. The piston source is good from 20 Hz to 5 kHz and the hydrophone source is good from 5 kHz to 25 kHz (and higher if required).

Inevitably the cavity does have acoustic resonances and at the minima in response between these resonances the acoustic pressure is too low to provide good coherent results, so certain frequency ranges in results need "interpolation". This situation would be improved if some damping could be introduced into the cavity.

Figure 4 shows H_2/H_1 for a pair of B&K 8103 hydrophones connected through a pair of B&K 2626 charge amplifiers to a Hewlett Packard 5420 signal analyser. Measurements below about 5 kHz are unreliable as below this frequency the hydrophone source is very inefficient and the coherence between the signals from the two hydrophones under test is not good. Figure 5 shows the intensibility calculated from this transfer function and shows that, without any phase calibration, the system is less than -15 dB intensibility over the range 5 kHz to 25 kHz for an 18mm separation in water. Irregularities in Figure 4 are most likely due to imperfections in the calibration technique rather than real channel differences.

6. DISCUSSION AND CONCLUSIONS

Section 3 of this paper highlights some of the many sources of error to which two-hydrophone intensity measurements are prone and indicates how these errors affect the choice of configuration for a particular measurement system. This section is a review and greater detail about the errors can be found in the texts indicated.

Sections 4 and 5 introduce a method by which any phase mis-match error can be calibrated out of a system and presents some example results. The piezoelectric hydrophones have a low frequency cut-off imposed electrically by the inherent capacitance and finite resistance. This cut-off frequency is * 0.02 Hz which implies good phase matching down to about 20 Hz; the lowest frequency of interest for machinery noise measurements.

A worthwhile exercise would be to experimentally prove that the hydrophones contribute insignificant phase mis-match. This would simplify calibration procedures and increase the accuracy of calibration. Such an experiment would be a direct comparison between common mode transfer function for the pressure driven transducers and measurement channels, and the electrically driven measurement channels alone: the pressure calibration will be subject to greater systematic errors than an electrical calibration. This would only work if charge sensitive preamplifiers are used, which are insensitive to transducer and cable capacitance. Voltage sensitive preamplifiers have a low frequency cut-off of typically 10 Hz to 20 Hz when used with capacitative transducers, and therefore cannot be electrically driven in an accurately representative manner (because the response is dependent upon all of the transducers' electrical properties).

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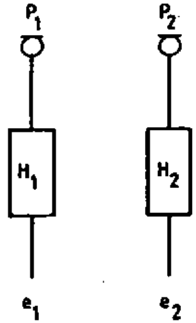


Figure 1.
Calibration parameters for equations 4.2 and 4.4

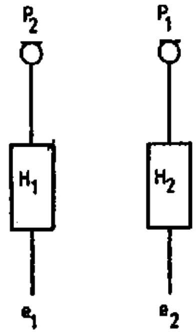


Figure 2.
Calibration parameters for equation 4.5

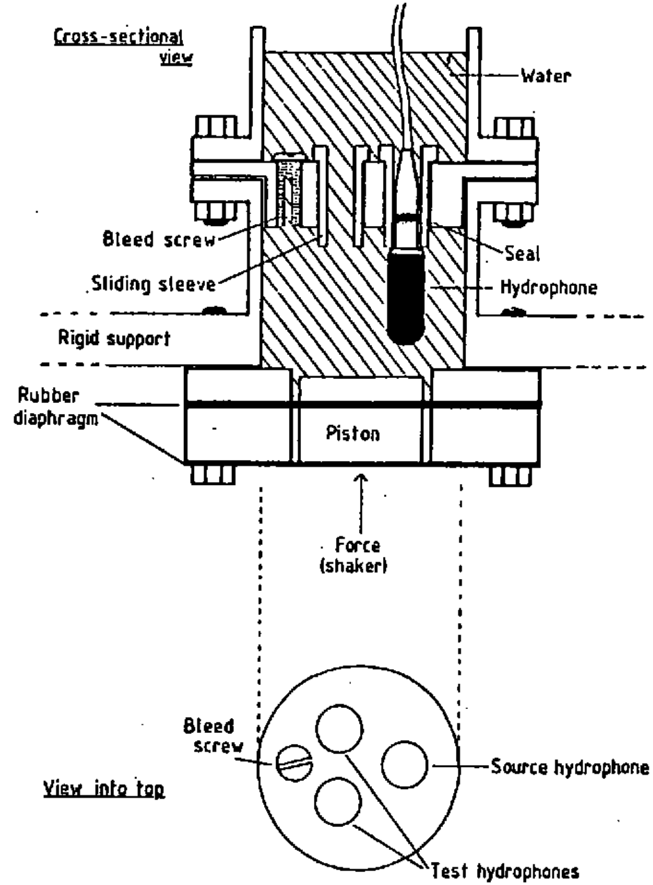


Fig. 3. 0.7 scale drawing of hydrophone calibration device.

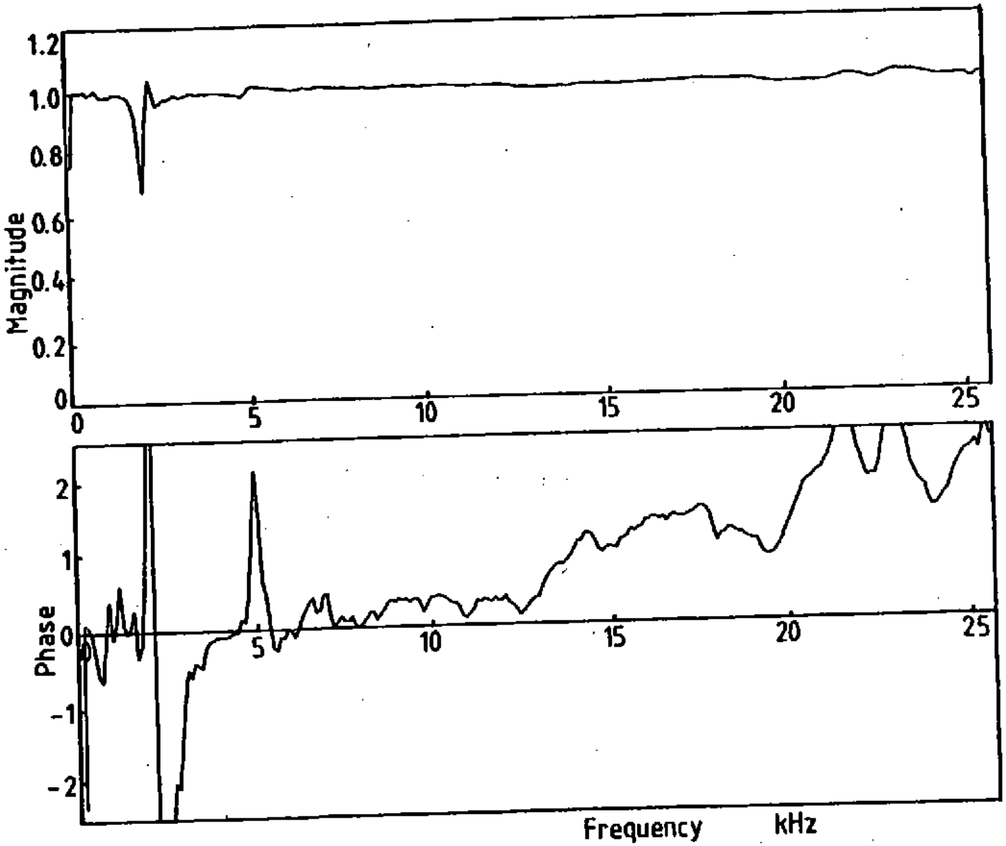


Figure 4.

Transfer function for common mode pressure excitation of hydrophones.

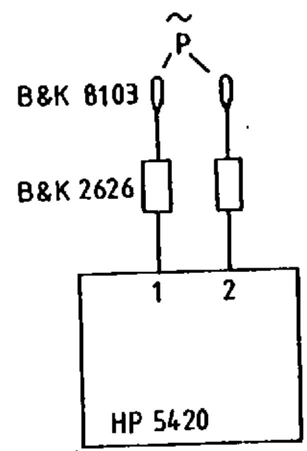
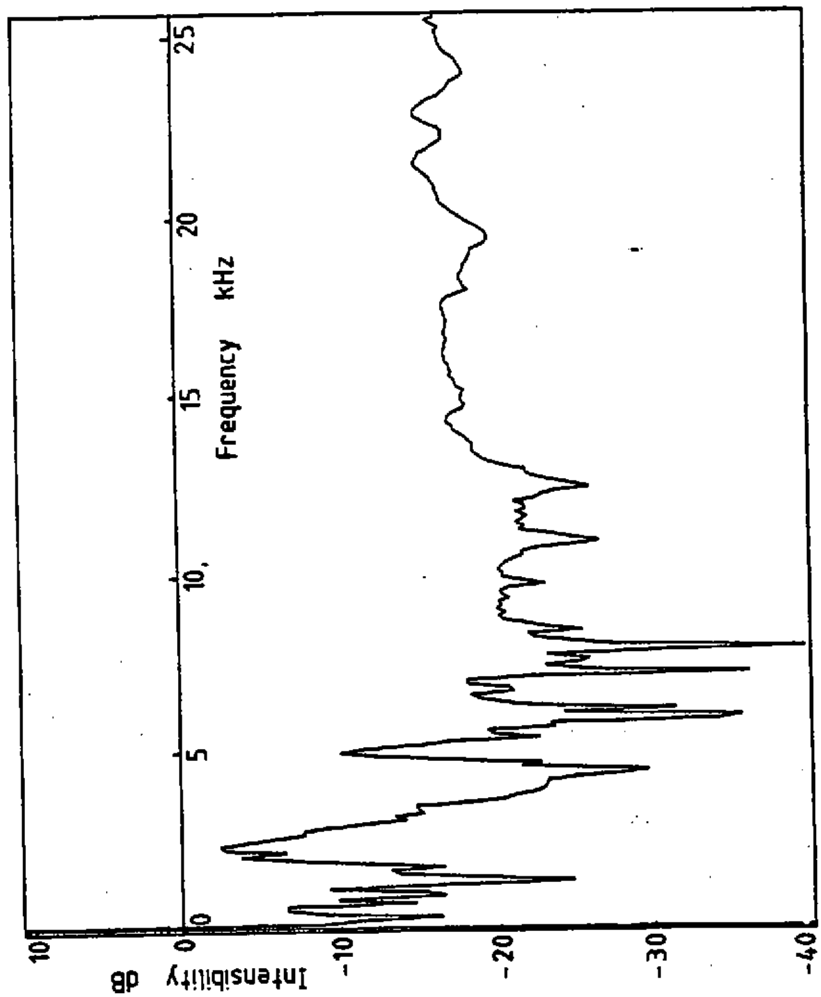


Figure 5.
Intensibility based upon figure 4 assumming 18mm separation in water.



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A COMPARISON OF PRONY AND NYQUIST SAMPLING FOR THE MEASUREMENT OF SHORT PULSES IN ACOUSTIC CALIBRATION

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SYNOPSIS

The need to simulate free field conditions in tanks and other confined spaces is introduced and the technique of using short pulses to achieve this is briefly discussed. The problems inherent in making actual measurements of these pulses are described.

The principles of the Prony (Coherent Sampling) system are explained and the techniques of oversampling, undersampling and compound sampling are described. The Prony system developed by Brown & Luckey of USRD is briefly described and the figures for the accuracy of the system, as measured by them, are quoted.

The limitations of the Prony System are explored, in particular the difficulties in measuring pulses from integrated systems, due to the need to synchronise the sampling device with the transmitted signal.

The principles of the Nyquist (Random Sampling) technique are explained and the relationships between sampling frequency, signal frequency, pulse length and accuracy are explored.

Some commercially available equipment is described with the relevant manufacturers' specifications.

A possible calibration system based on one of these devices is briefly described.

The conclusion is drawn that the very fast random sampling devices now available make the increased complexity of the Prony system largely redundant, except for certain specialised applications.