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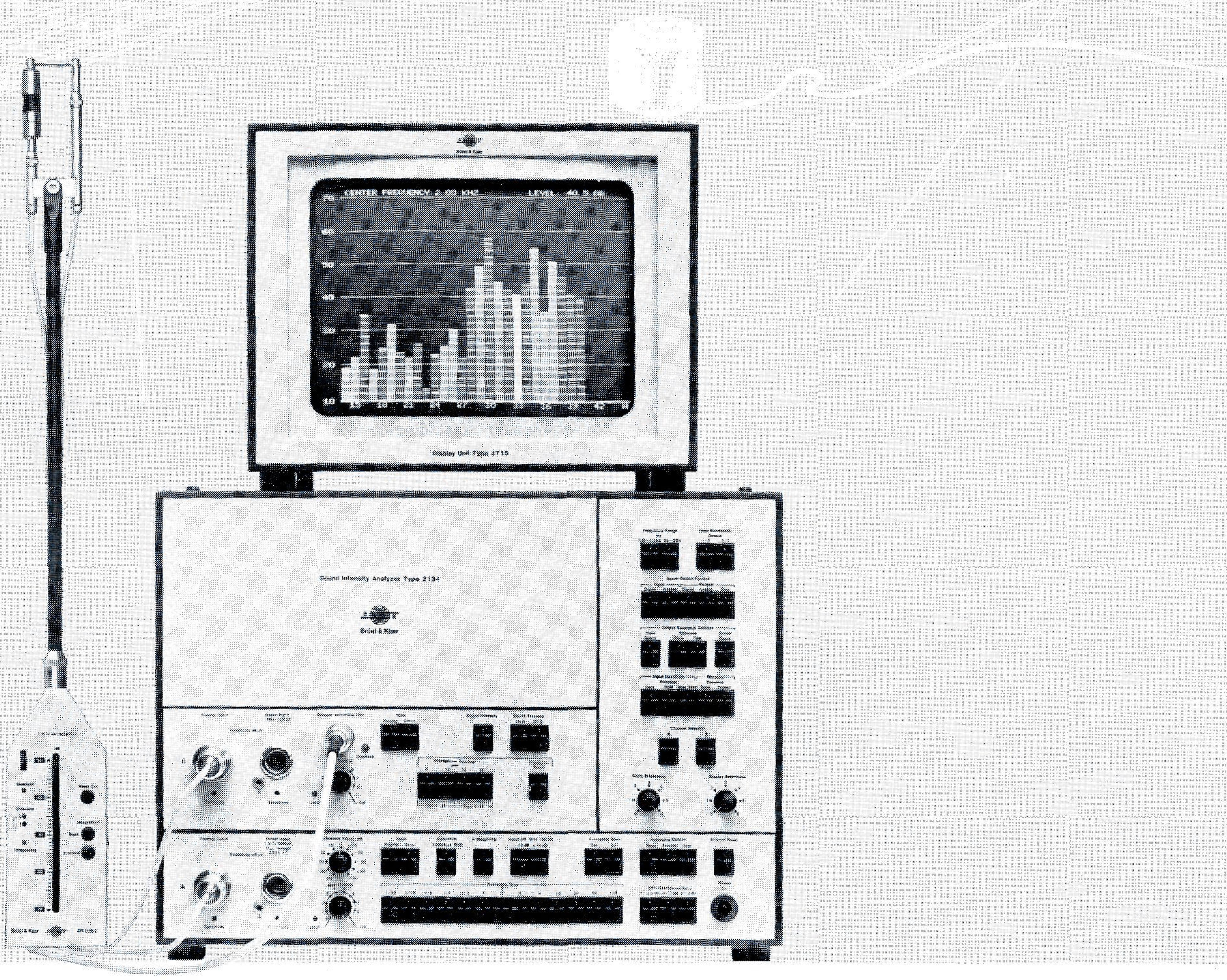
Sound power determination in highly reactive environments using sound intensity measurements



Sound power determination in highly reactive environments using sound intensity measurements

S. Gade, K.B. Ginn, O. Roth
& M. Brock
Brüel & Kjær

Introduction

The advent of real-time analysis using digital filtering techniques for signal processing has been a major breakthrough for the precision with which acoustic intensity measurements can be performed using the two microphone method.

One of the principal applications of sound intensity measurements is the determination of sound power radiated by sound sources [1,2]. In theory some of the advantages of using intensity rather than sound pressure measurements for determining sound power are:

1. No restriction upon the sound field which implies that the measurements can be performed in any room.
2. Measurements can be performed in the near field as well as in the far field.
3. No restriction upon the shape and size of the enclosing measurement surface.
4. The method excludes any influence from stationary, contaminating sound fields.

This note deals with some of the limitations of the points mentioned above, for measurements made with a practical sound intensity analysing system.

Active and reactive sound fields

A sound field may be considered to consist of two parts: an active part in which the sound pressure and particle velocity are in phase and a reactive part (i.e. diffuse part) in which the sound pressure and particle velocity are in quadrature. It is the active field which transports sound energy whereas the reactive field stores sound energy. The more energy that is stored relative to that transported, the more reactive the field is said to be. Later in this note a straightforward practical measure of the degree of reactivity of a sound field will be described.

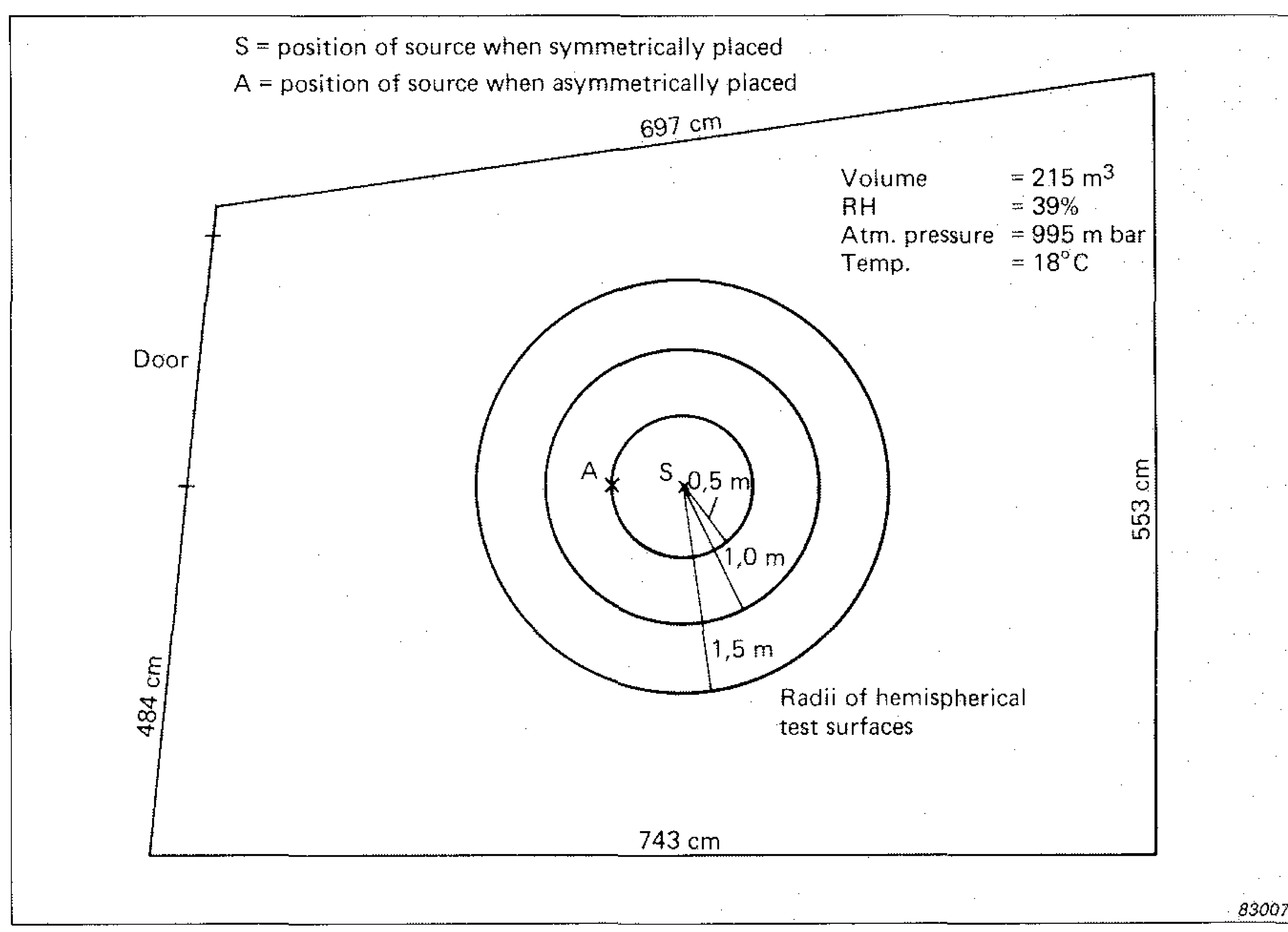


Fig. 1. ***Plan of reverberation room showing the test source positions and the radii of the test hemispheres.*** **"S" indicates the position of the source when situated at the centre of the hemispherical test surfaces. "A" indicates the positions of the source when placed off-centre relative to the test surfaces. The positions of the sound intensity probe on the test hemispheres are defined in Fig.2.**

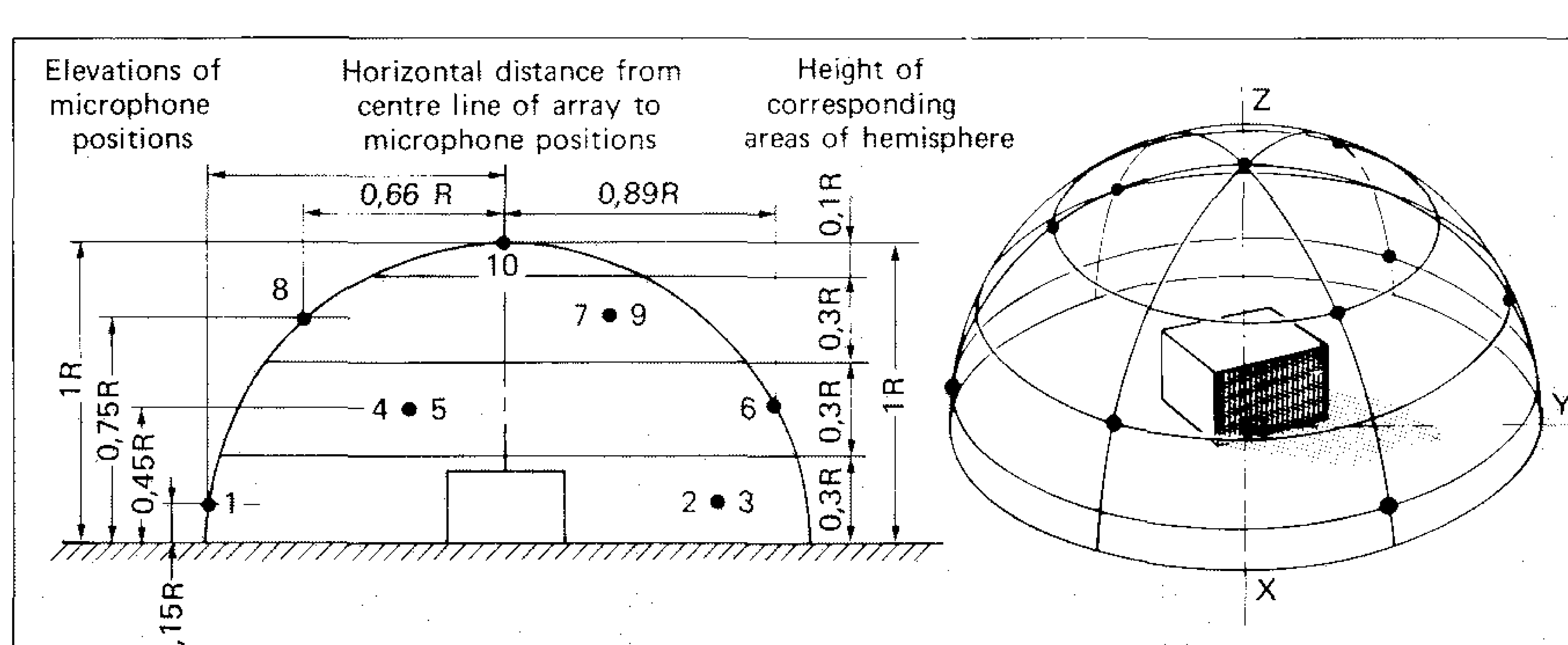


Fig. 2. As no standards yet exist for the determination of sound power using sound intensity measurements, the sound intensity probe was situated about the sound source at the microphone positions recommended by ISO 3745

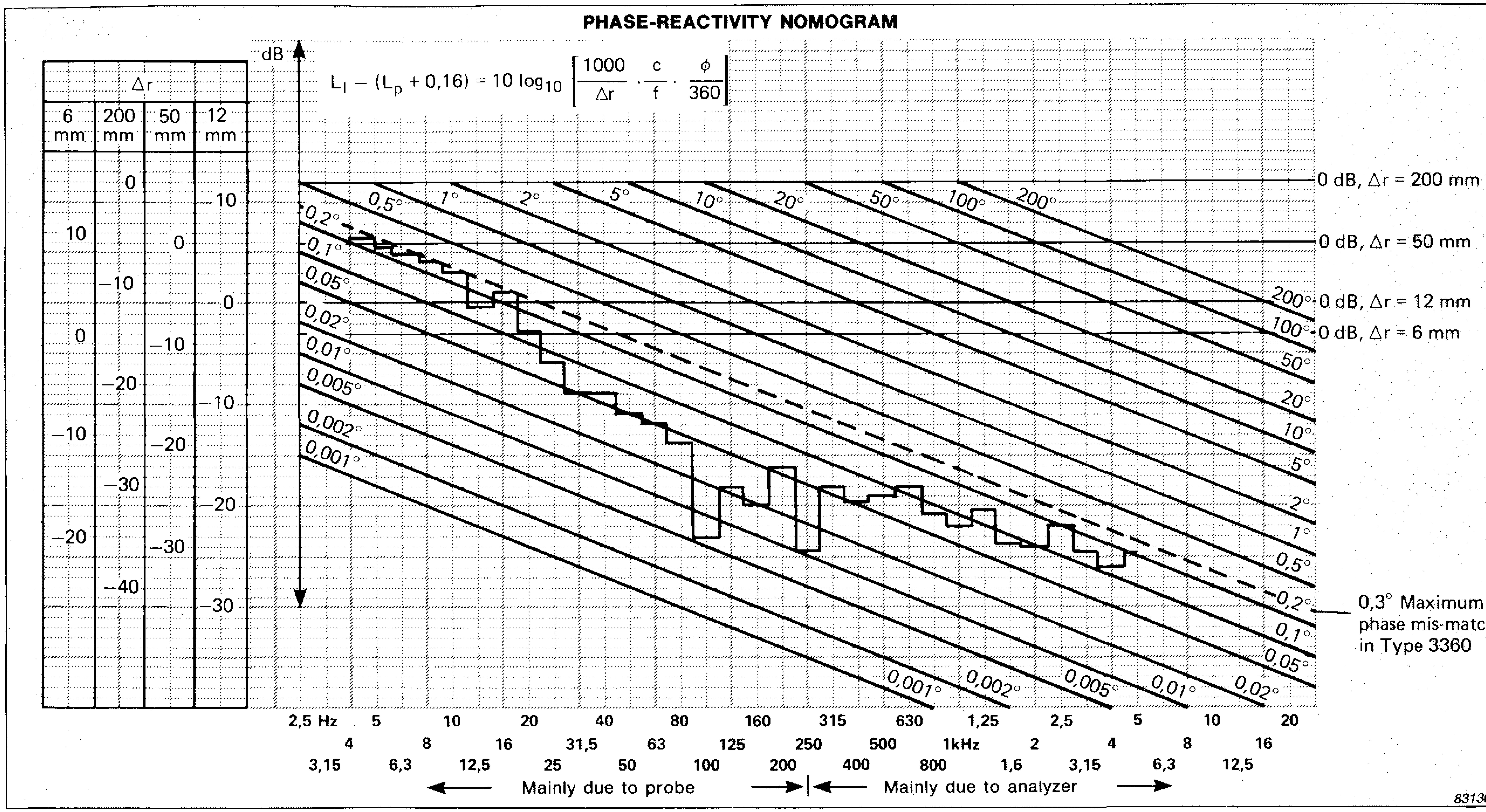


Fig.3. The phase-reactivity nomogram. The phase ϕ between the two microphone positions is shown as a function of frequency, spacer Δr and reactivity of the sound field. The approximation error which occurs at high frequency is not taken into account by this nomogram.

Note that for a free-field $L_I - L_p = 0$ and for a reactive field $L_I - L_p < 0$ dB.

To determine the influence that a phase mis-match of ϕ_a in the analyser and of ϕ_m in the probe will have on the measured intensity in a field of known reactivity and using a particular spacer:

1. Select the ordinate scale for the spacer employed.
2. Find the horizontal line corresponding to the measured reactivity.
3. At the point where the horizontal reactivity line crosses the vertical line corresponding to the frequency of interest, read off the phase of the sound field ϕ_f by interpolation between the sloping phase lines.
4. Calculate $\phi_f - \phi_a - \phi_m$ and $\phi_f + \phi_a + \phi_m$. These values are the limits of error in the measured phase at this frequency and from the ordinate axis the limits of error in dB can be found for the measured intensity.

Ideal sound intensity analyser

As an *ideal* intensity analyser would only respond to the active part of a sound field, such an instrument would indicate an intensity approaching $0\,W/m^2$ in a highly diffuse field, or expressed in another way, in a highly reactive field. On a logarithmic scale this reading would tend towards an infinitely low level in dB re $10^{-12}\,W/m^2$.

Practical sound intensity analyser

A practical sound intensity analyser could never display such a low intensity level. There will always remain some "residual" intensity level on the screen. It is this "residual" intensity level caused by the degree of phase-mismatch between the two channels of the instrument which sets the lower limit for the dynamic range of the instrument when it operates *in the intensity mode.*

Measurements

To test the performance of a practical intensity system, a series of measurements were performed in the most reactive environment available, namely a reverberation room of $215\,m^3$ with a reverberation time of 18 s at 100 Hz, falling to 10 s at 500 Hz and 5 s at 3150 Hz. According to ISO 3741 such a room may be used for sound power determinations using sound pressure measurements from 100 Hz to 10 kHz in third octave bands.

The sound power level L_W of a reference sound source was determined under various measurement conditions, using various methods. The results were compared with the reference values on the calibration chart of the sound source which were determined in third-octave bands from 100 Hz to 10 kHz using sound pressure levels measurements L_p in an anechoic room according to ISO 3745. The test sound source employed was a B & K Reference Sound Source Type 4204 as this source is extremely stable with time.

The measurements were performed using 10 measurement positions distributed as described in ISO Standard 3745 over the surface of hemisphere.

The measurements included:

1. Determination of L_W from L_p measurements according to ISO 3741 using: the Sound Intensity Analysing System Type 3360 operating in its sound pressure mode; the Building Acoustics Analyser Type 4418 which is pre-programmed for such measurements.
2. Determination of L_W from L_I measurements. The Sound Intensity Analysing System Type 3360 uses a finite difference approximation technique for calculating the intensity from pressure measurements from two closely spaced microphones. A microphone spacing Δr of 12 mm was used over hemispherical measurement surfaces of radii 0,5 m, 1,0 m, 1,5 m. In one measurement, the source was placed asymmetrically in the hemisphere at point A in Fig.1. Measurements were also performed with and without a prototype wind shield and also with background noise provided by a second Reference Sound Source Type 4204 which was placed in the corner by the door.
3. Determination of L_W from L_I measurements over a hemispherical measurement surface of radius 0,5 m using a microphone spacing Δr of 12 mm, 50 mm, 100 mm and 200 mm.

Phase-reactivity nomogram

The difference between the pressure level and the maximum intensity level measured is defined as the reactivity of the sound field. The relationship between the intensity level L_I minus pressure level L_p, phase ϕ (between the signals from the two microphone positions), microphone spacing Δr and frequency f for the two microphone method, is shown in Fig.3 which is called the phase-reactivity nomogram. Note that these curves make no allowance for the approximation error at high frequencies. It can be seen that under free-field conditions (reactivity = 0 dB), the choice of a 12 mm spacer yields a dynamic range of 11 dB at 100 Hz, 21 dB at 1 kHz and 31 dB at 10 kHz for a frequency independent phase-matching of 0,1° between the two measuring channels.

The phase matching of the measuring system is frequency dependent: above 250 Hz it is determined mainly by the analyser whereas be-

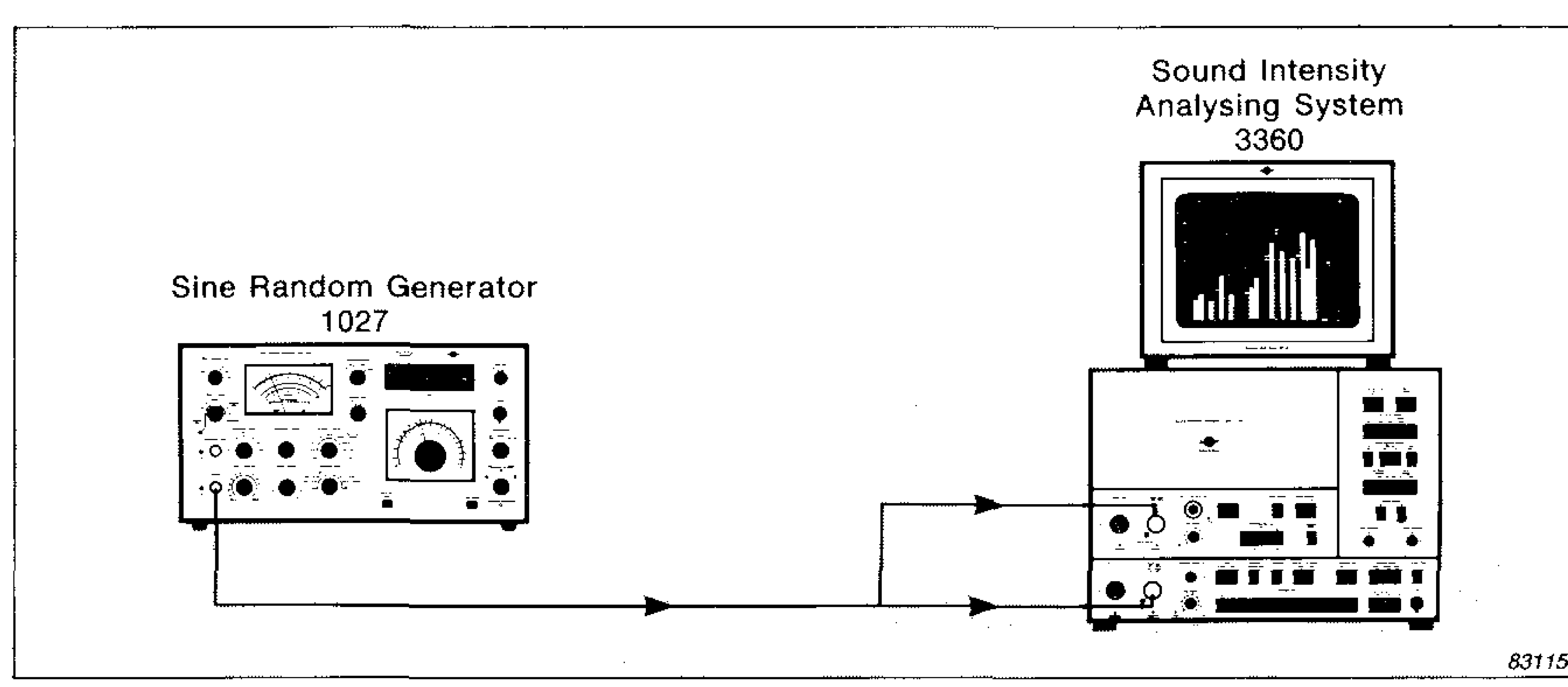


Fig.4. Measurement of the phase-match in the analyser alone

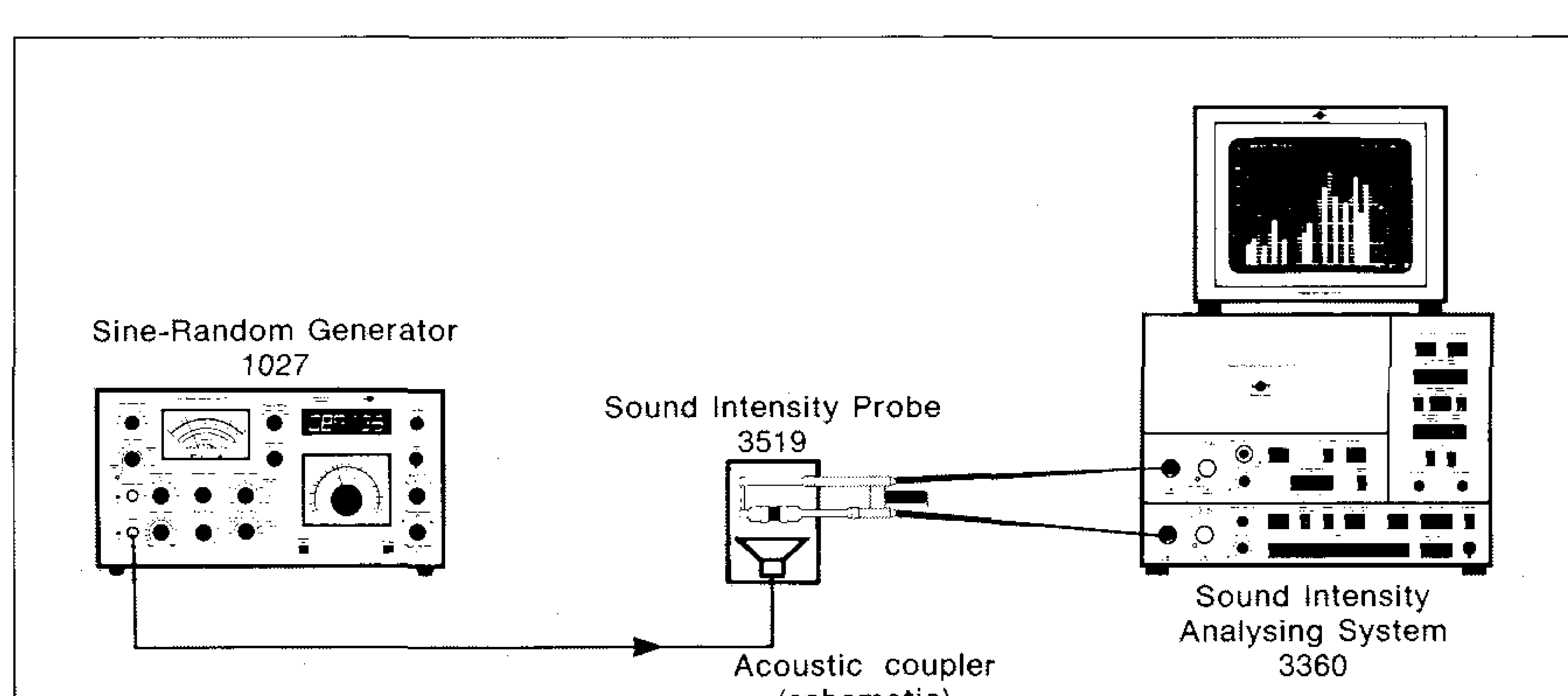


Fig.5. Measurement of the phase-match in the probe/analyser combination

low 250 Hz it is determined mainly by the two microphones which constitute the sound intensity probe.

The dynamic range of the measuring system is defined as the difference between the pressure level and the intensity level when the same signal is applied to both channels. This range was determined for frequencies above 500 Hz by applying electrically generated pink noise to both channels simultaneously (Fig.4), and for frequencies below 500 Hz by applying broad band noise to a small acoustic coupler in which the probe was placed (Fig.5) [3]. The noise signal simulates diffuse field measurement conditions.

All B&K specifications are conservative and thus some instruments may render far better performance than that stated in the Data Sheet. As indicated in the phase-reactivity nomogram (Fig.3), the phase-mismatch of a typical Sound Intensity Analyzer Type 3360 lies in general well below the 0,3° maximum specified phase-mismatch. The phase-matching is typically 0,05° between 30 Hz and 500 Hz. The lower frequency limit for the measuring system is set mainly by the phase-match due to the sound intensity probe [1]. It can be found from Fig.3, that the lower frequency limit (± 1 dB) of the intensity analyzing system for free field measurements is typically 25 Hz rather than 125 Hz as indicated in the Data Sheet for a maximum phase-mismatch of 0,3° i.e. a frequency 6 times lower (0,3 / 0,05 = 6).

However, the phase-reactivity nomogram also shows that the lower frequency limit is shifted towards higher frequencies by a factor which is equal to the measured degree of reactivity at the measurement positions. Thus 3 dB reactivity corresponds to a frequency shift by a factor of 2. Fig.6 shows the frequency ranges for various microphone and spacer combinations for an accuracy *in intensity measurement* of ± 1 dB for a total phase-mismatch of 0,1°; 0,2° and 0,3° and for three different reactivities.

To give an idea of the degree of reactivity met in practice, a number of values of $L_I - L_p$ found in the literature are tabulated in Table 1 for dif-

Measurement	Source and environment	$L_I - L_p$ dB
Sound power	Turbine in a power station	−4
	Front bearing of turbine	−4
	Between feed pipes to a turbine	−14
	Nail machine in production hall containing 60 identical machines	−4
	Interior panels of a stationary van	−5
	Nail machine in assembly– and repair hall	−6
	Standard sound source in a 106m^3 reverberation chamber	−6
	Standard sound source in a 215m^3 reverberation chamber	−10
	Compressor of a refrigeration unit	−11
	Panel of an aeroplane in flight	−20
Transmission loss	Transmission loss between two rooms: with doors closed with doors open	−11 −18
Absorption coefficient	*Absorption coefficient of approx.* 0,1 in a reverberation chamber	−19

Table 1. Some values of reactivity described in the literature, tabulated for different types of measurements and for various sources and environments

Method of Determining L_W	L_W dB(Lin.)	L_W dB(A)
L_p ISO 3745 (Calibration Chart)	92,4	91,8
L_p ISO 3741 using 3360 in pressure mode	92,7	92,1
L_p ISO 3741 using 4418	92,6	92,2
L_I r = 1,5 m Sym.	84,2	84,9
L_I r = 1,0 m Sym.	89,6	89,4
L_I r = 1,0 m Asym.	90,1	89,8
L_I r = 0,5 m Sym.	92,8	90,9
L_I r = 0,5 m Sym. With prototype windshield	91,3	90,8
L_I r = 0,5 m Sym. With prototype windshield plus background noise	89,6	89,4

Table 2. The overall sound power levels, L_W, for the test source in dB(Lin.) and dB(A) as calculated from the various measurements. The spacer used for intensity measurements was 12 mm

Δr mm	6	12	50	100	200
f_{lower} Hz(± 1dB)	500	250	63	31,5	16
f_{upper} Hz(−1dB)	10000	5000	1250	630	315
$f_{first\ zero\ crossing}$ Hz	28000	14000	3400	1700	850

Table 3. Theoretical limits for the accuracy of intensity measurements for a system phase-matched to $\varphi = 0{,}05°$ in a field with a reactivity of 10 dB

ferent types of measurements and for various sources and environments.

If it should happen that the dynamic range of the analyser is insufficient for a particular measurement then the phase-matching between the two channels can be somewhat adjusted to provide even better phase-matching at certain frequencies at the expense of a worse matching at others.

Measurement results

L_W from L_p

The sound power of the test sound source was determined according to ISO 3741 using the formula:

$$L_W = L_p - 10\log_{10}(T/T_o) + 10\log_{10}(V/V_o) + 10\log_{10}(1 + S\lambda/8V) - 10\log_{10}(B/1000) - 14\,dB$$

where

L_W = sound power level of source under test in dB re 1pW

L_p = sound pressure level in dB re 20μPa

T = reverberation time in seconds

T_o = 1 second

V = volume of the room = 215 m^3

V_o = 1 m^3

λ = wavelength at the centre frequency of the frequency band in metres

S = total surface area of the room = 238 m^2

B = barometric pressure = 995 mbar

The reverberation time of the room was measured using the Building Acoustics Analyzer Type 4418 and the Sound Source 4224. The sound pressure level was measured within the room at 5 different positions in the diffuse field, using a linear averaging time of 16 s at each position, firstly by using the Sound Intensity Analysing System Type 3360 in its pressure mode and then by using the Building Acoustics Analyser Type 4418. The values of L_W obtained, agree very well with the values from the calibration chart for the sound source (Table 2).

Reactivity in the reverberation chamber

The reactivity of the sound field at the measurement points was found from the difference in the L_p and L_I values where each of these was the average of 10 measurements (Fig.7). L_I was measured using various microphone separations (12 mm, 50 mm, 100 mm and 200 mm) to optimise the dynamic range of the analyser at different frequencies. The reactivity (referred to in [6] as "the indicator of the validity of intensity measurements") was found to be approximately 10 dB for most frequencies. For a reactivity of 10 dB and a phase-matching of 0,05°, the theoretical lower frequency limit of the measuring system as a function of microphone separation is shown in Table 3.

L_W from L_I using surfaces with various radii and Δr of 12 mm

The total acoustic intensity, $\bar{I}$, leaving the surface which encloses the source multiplied by the area of the surface yields the sound power of the source, W. When the source is placed outside the closed surface, the total intensity flowing through the closed surface is zero. This is known as Gauss' Theorem. Mathematically:

$$W = \int_S \bar{I} \cdot d\bar{S}$$

Thus the sound intensity method allows sound power determinations to be performed even in the presence of stationary background noise. When applying Gauss' Theorem in practice, one must ensure that there is no mean flow of the air, that there is no absorption within the

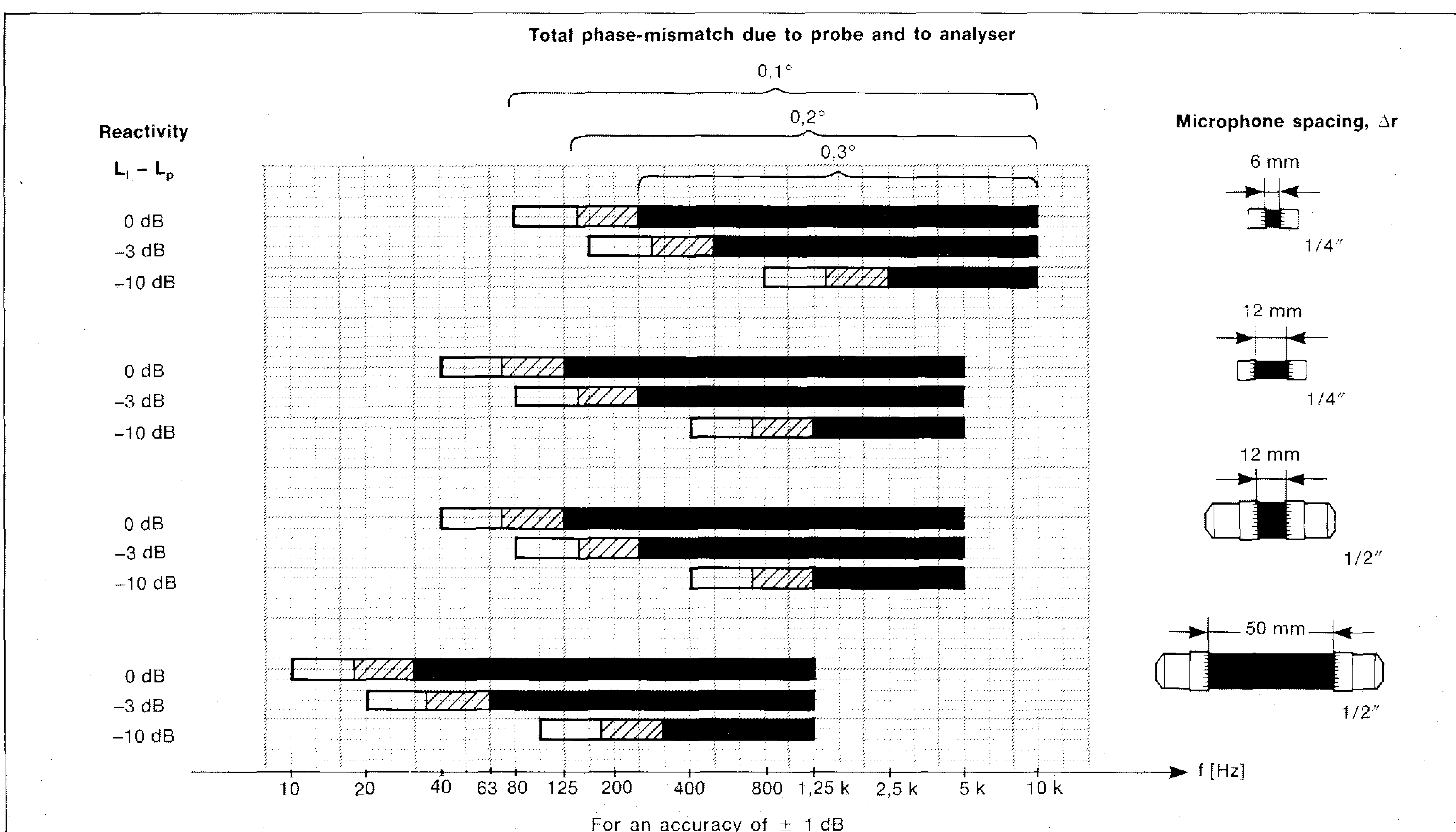


Fig.6. Frequency ranges for various microphone and spacer combinations for an accuracy in intensity measurement of ± 1dB for a total phase-mismatch of the probe/analyser system of 0,1°; 0,2° and 0,3° and for three different reactivities

closed surface and that noise from external sources is stationary during the measurements.

The 3360 was set in the sound intensity mode and the sound intensity was measured normal to each of the small areas of the hypothetical hemisphere using a longer linear averaging time (32 s) than that used for the sound pressure measurements (16 s). The test surface was arbitrarily chosen to be a hemisphere although theoretically when employing sound intensity measurements any closed surface would do. The distribution of measurement points over the test surface was as in ISO 3745. The sound power level was determined from:

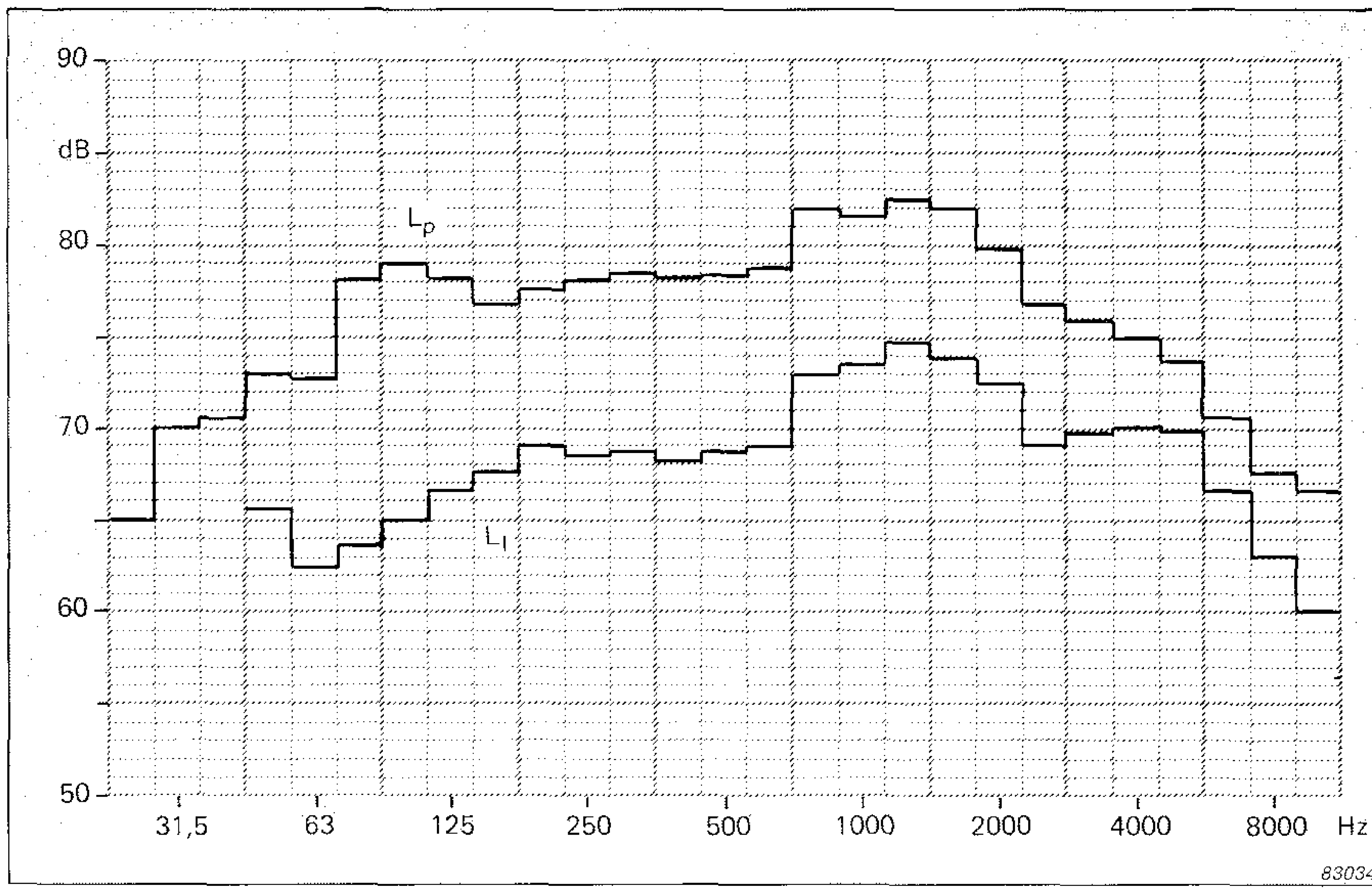


Fig.7. L_p (upper) and L_I (lower curve) averaged over 10 measurement positions. The reactivity of the sound field is the difference between the two spectra

$$L_W(I) = \Sigma L_I + 10 \log_{10}(S/S_o) - 10 \log_{10}(N) + C \text{ dB}$$

where

$L_W(I)$ = sound power level of source re 1 pW determined from L_I

ΣL_I = sum of measured sound intensity levels re 1 pW/m^2

$S = 2\pi r^2$ area of test hemisphere

$S_o = 1\text{m}^2$

N = number of linear averages i.e. number of measuring positions

C = influence of ambient temperature & pressure in dB

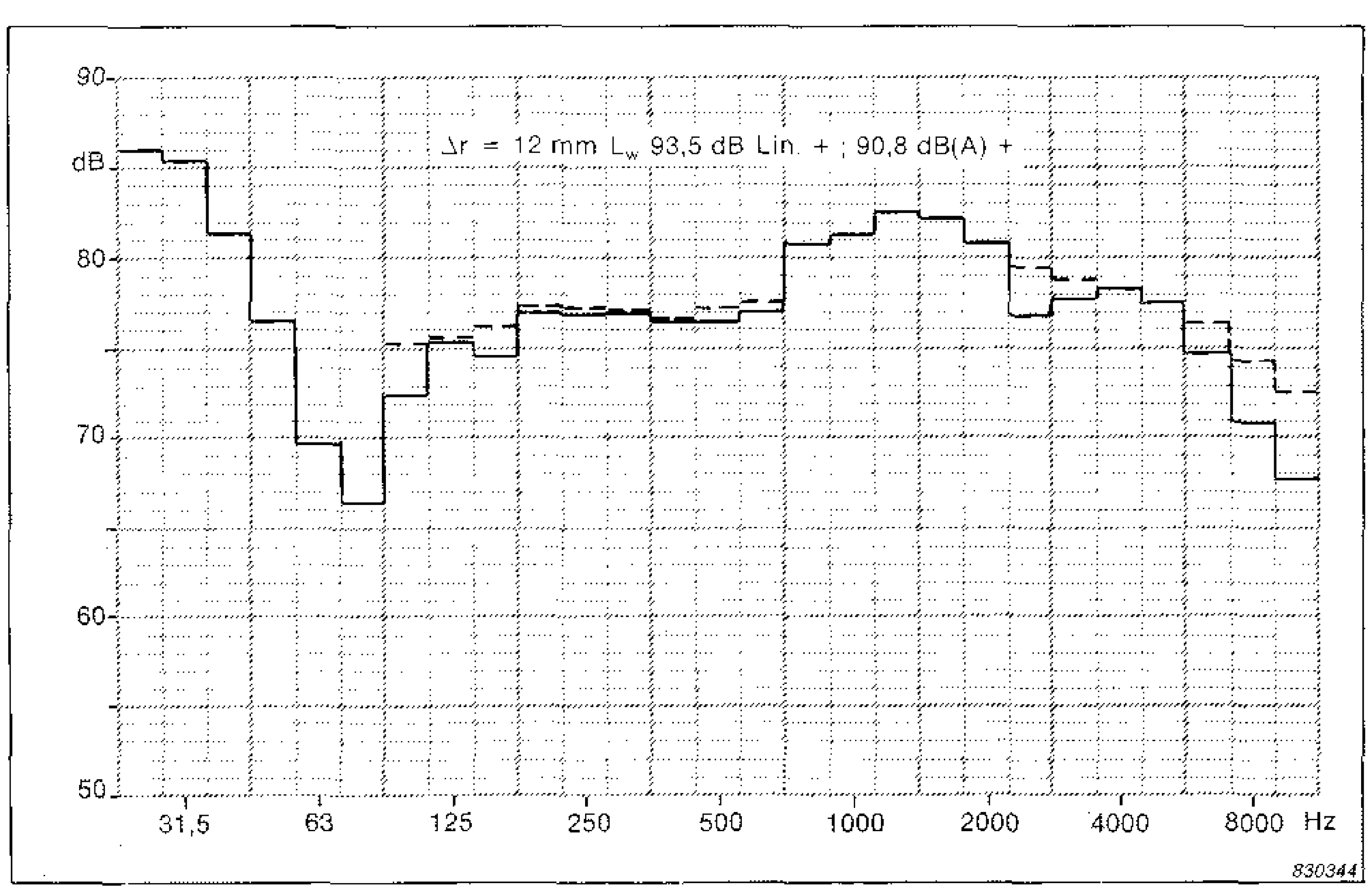


Fig.8. Sound power of a reference sound source determined from sound intensity measurements using Δr = 12 mm. The sound power determined according to ISO 3745 is shown by the dashed line. The sign suffixed to the dB Lin and dB(A) levels indicates that the total intensity level is either "positive" or "negative"

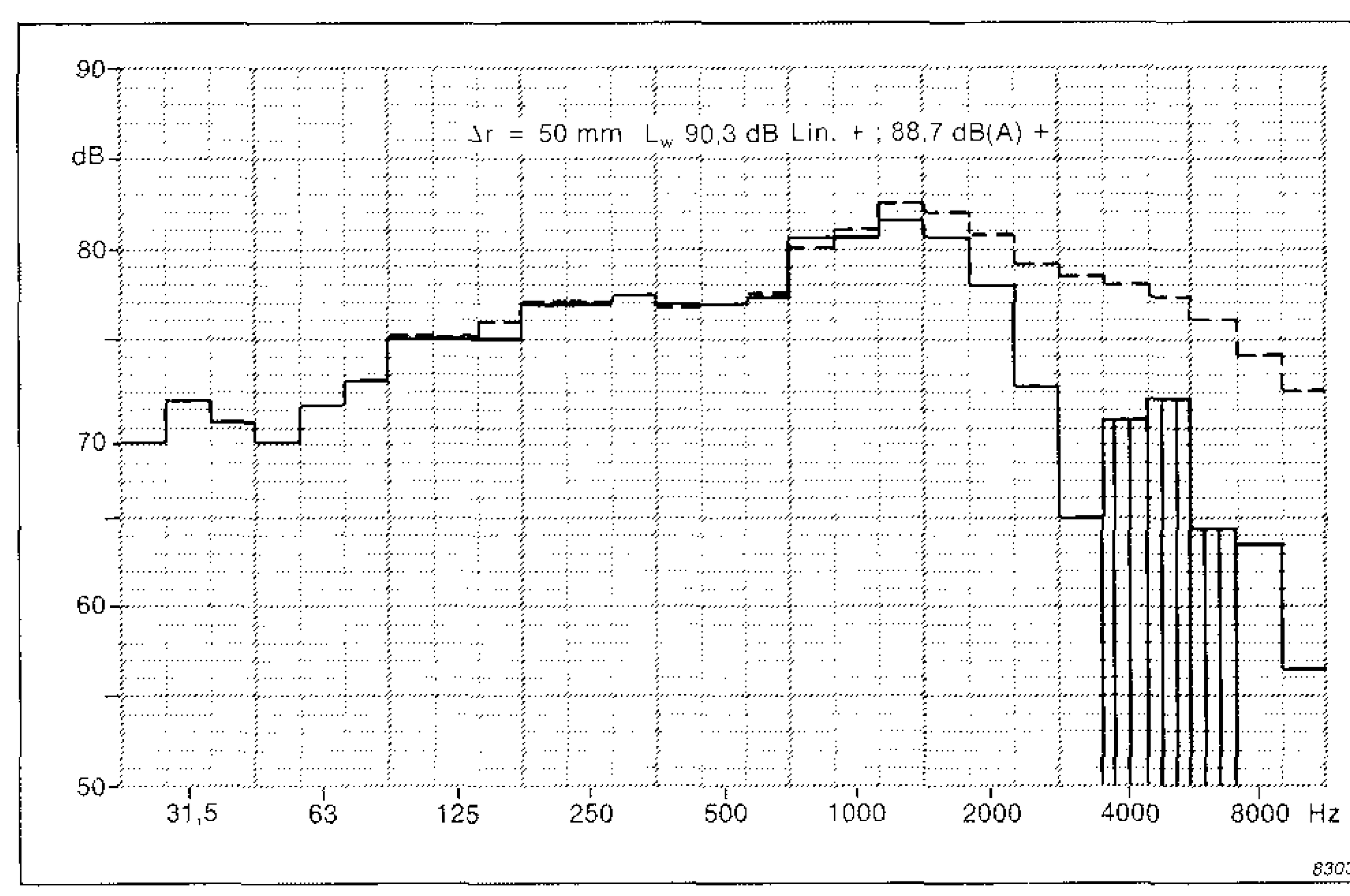


Fig.9. As for Fig.8 but with Δr = 50 mm. The "negative" intensity indicated by the hatching, which occurs just above the cut-off frequency is due to the first side lobe in the sin(kΔr)/kΔr function which appears as a consequence of the finite difference approximation used to estimate intensity from pressure measurements and which results in an underestimation at high frequencies

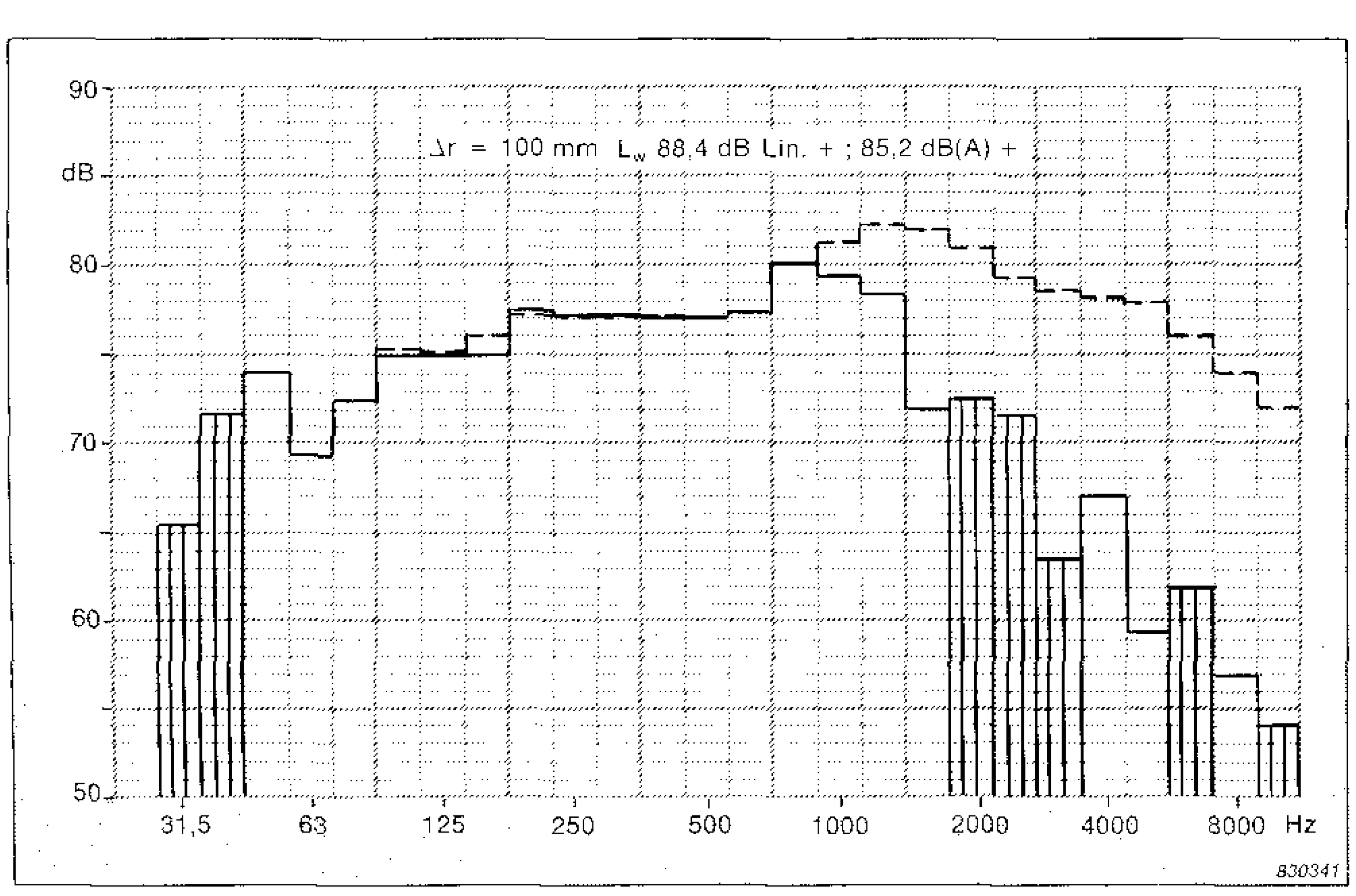


Fig.10. As for Fig.8 but with Δr = 100 mm

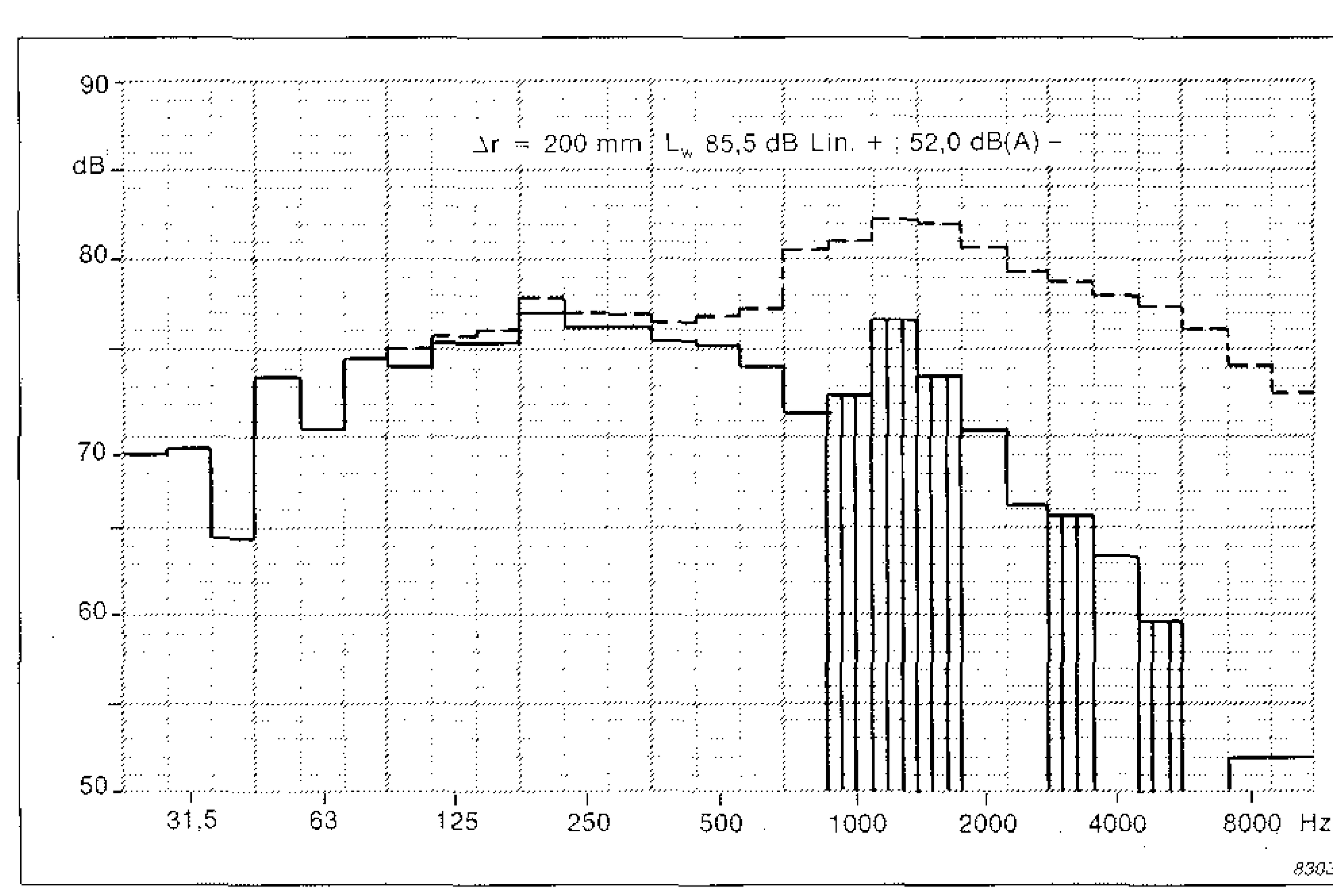


Fig.11. As for Fig.8 but with Δr = 200 mm

Effect of altering radius

The results for L_W from L_I show that for measurements in a diffuse field, for a fixed number of measurement points that the accuracy obtained increases as the size of the measurement surface is reduced, provided that the source is omnidirectional. This is due to the fact that the reactivity of the sound field increases with increasing distance from the sound source. The results for r = 0,5 m (symmetrical) in Table 2 agree well with the results obtained from L_p measurements. The greater the distance from the source, the greater the number of measurement points should be or, better still, the probe should be swept over each part of the measurement surface.

Reproducibility

To test the reproducibility of the measurements, another test series was performed consisting of 40 measurements (4 sound power determinations) with a 12 mm spacer over a test hemisphere of radius 1,5 m. The relatively high amount of random error observed at low frequencies [7] was due to the high reactivity of the sound field at the measurement positions. This error is not normally seen under free field conditions [5].

Effect of windshield

Wind noise may distort measurements especially at low frequencies. To investigate this problem, measurements were made with and without a prototype windshield. The results in Table 2 show that a lower L_WdB(Lin) value is obtained with a windshield than without whereas the value for L_WdB(A) remains practically the same as the A-weighting effectively removes the low frequencies at which the wind occurs.

Effect of background noise

The results indicate that in practice, background noise tends to add to L_p whereas it tends to subtract from L_I measurements.

L_W from L_I using various spacers and a radius of 0,5 m

The results of the sound power determination are shown in Figs.7 to 11 and compared with the values from the calibration table of the sound source. The lower frequency limits indicated in Table 3 could not be verified from these measurements directly as the lowest frequency on the calibration table of the sound source was 100 Hz. However comparison of pairs of spectra measured with the various spacers showed that there was consistently good agreement at low frequencies where the usable frequency ranges of the spacers overlap. The pairs of spectra for the spacers 12 mm & 50 mm, 50 mm & 100 mm and 100 mm & 200 mm show good agreement down to the frequencies of 125 Hz, 80 Hz and 50 Hz respectively. This supports the notion that sound intensity measurements can be used to determine sound power at frequencies and in environments where sound pressure measurements would be inappropriate. The measured intensity, $\hat{I}_r$, obtained from a finite difference approximation technique, is related to the actual intensity I_r by:

$$\hat{I}_r = I_r \sin(k\,\Delta r)/(k\,\Delta r)$$

where k is the wave number and Δr is the microphone spacing. The measured intensity $\hat{I}_r$ becomes zero when $k\,\Delta r$ becomes zero. The frequency at which a zero crossing occurs, depends upon the wavenumber, k, and the spacing, Δr, and is independent of the reactivity. This is clearly shown in Figs.7 to 11 where the measured zero-crossings correspond exactly to the predicted theoretical values for the plane wave approximation indicated in Table 3. Thus the upper frequency limit for intensity measurements is *not* shifted towards higher frequency as a function of increasing reactivity as suggested in [6].

Conclusion

For practical sound intensity measurements the difference between the intensity level and the pressure level or the reactivity should always be measured. Not only is the reactivity an excellent descriptor of how diffuse the sound field is but it is also an expression of the difficulty of the measurement. The greater the reactivity of the field then the better the phase-matching in the analyser must be for real-time measurements. Using the real-time, two-microphone technique of the B & K Sound Intensity Analysing System Type 3360, sound power determinations can be performed in highly reactive environments to a high degree of precision. However, the dynamic range of the analyser should be greater than the measured reactivity as it is the reactivity which sets the lower frequency limit of the system.

A systematic approach to a new measurement situation would be:

1. Determine the phase-match of the analysing system.
2. Measure the reactivity of the sound field using different spacers.
3. Calculate the lower limiting frequency for various spacers under these conditions using the phase-reactivity nomogram or from the bar-chart of Fig.6.
4. Select the spacer (or spacers) which covers the frequency range of interest and perform the measurements.

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Brüel & Kjær
DK-2850 NÆRUM, DENMARK
Telephone: + 45 2 80 05 00
TELEX: 37316 bruka dk

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