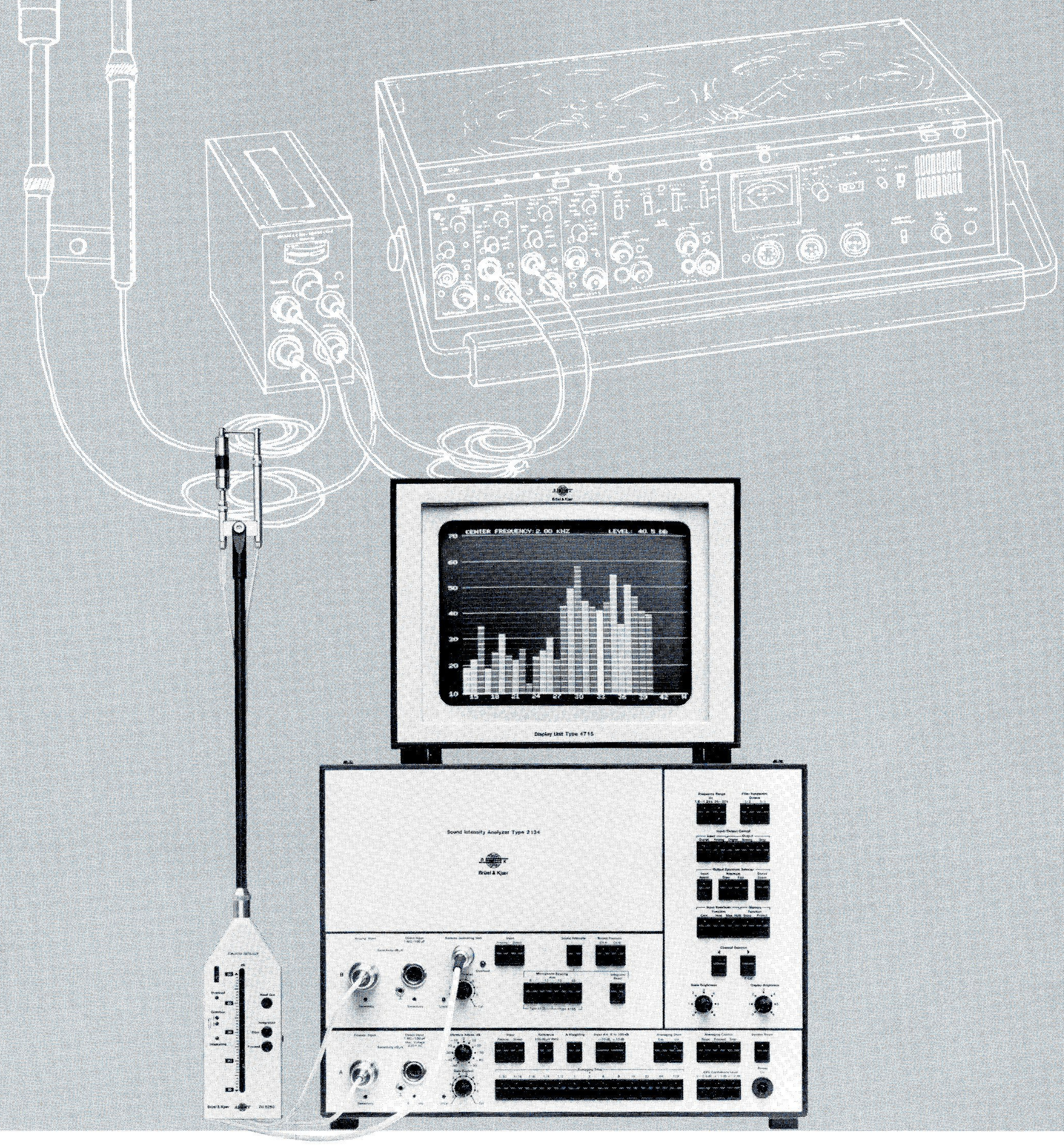
Brüel & Kjær application notes

Intensity measurement using a tape recorder



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Intensity Measurement using a Tape Recorder

by *Michael Brock*
Brüel & Kjær

Introduction

The Sound Intensity Analysing System Type 3360 enables intensity measurements to be made *in situ* and in real time. However, the use of an analogue tape recorder can be convenient for certain applications, e.g.:

1. For measurements in restricted spaces
2. For use with a three microphone probe in order to measure over an extended frequency range
3. For use with four microphones in order to measure the three orthogonal components of intensity simultaneously.

Use of a tape recorder, however, introduces a phase-mismatch into the measurement. This can be minimized and compensated, but cannot be totally neglected for all types of measurements. This subject will be discussed in the following.

This application note is divided into three parts. Part 1 describes phase-mismatch in analogue tape recorders and relates this phase-mismatch to the intensity errors. Part 2 describes the tape recording of intensity measurements in practice. Finally Part 3 presents the results from a practical intensity measurement performed with and without a tape recorder. All results are referred to the B & K Tape Recorder Type 7005 and the Sound Intensity Measuring System Type 3360, but the theory, of course, is valid in general.

Part 1: Theory

The errors in the measured intensity levels due to the different sections of an intensity measuring system (e.g. a tape recorder, a probe or a filter) can be related to phase-mismatching and to amplitude errors.

Intensity error versus phase-mismatch

A one degree phase-mismatch between the two channels might be insignificant or disastrous depending on frequency f, the difference between intensity and pressure level $L_I - L_p$, and the microphone spacing Δr. The relationship between these three parameters and the phase ϕ between the pressures at the two microphone positions is given in the phase-reactivity nomogram shown in Fig.1. If the phase-mismatch in a sound intensity measuring system is known then this nomogram enables the resulting intensity error to be found.

$L_I - L_p$ is in practice determined by two factors:

1. The angle γ between the measuring direction and the direction of the maximum intensity.
2. The reactivity of the sound field.

When the measuring direction and the maximum intensity direction are coincident (i.e. $L_I = L_{I,max}$), then $L_I - L_p$ can be used as a measure for the reactivity of the sound field.

In a free-field where there is propagation of plane waves in only one direction, $L_I - L_p = 0$ dB as the reference levels for pressure and intensity in air have been so chosen.

The reference pressure for sound pressure level is 20×10^{-6} N / m^2. On substituting this value in the free-field relationship between pressure and intensity $I = p^2/\rho c$, and setting the specific acoustic impedance of air ρc to 400 rayls, one obtains an intensity of 10^{-12} W / m^2 which is used as the reference intensity for sound intensity level measurements. On using the more precise value of $\rho c = 415$ which is the value of the specific acoustic impedance of air at 20°C and 1013 mbar, one obtains the

PHASE-REACTIVITY NOMOGRAM

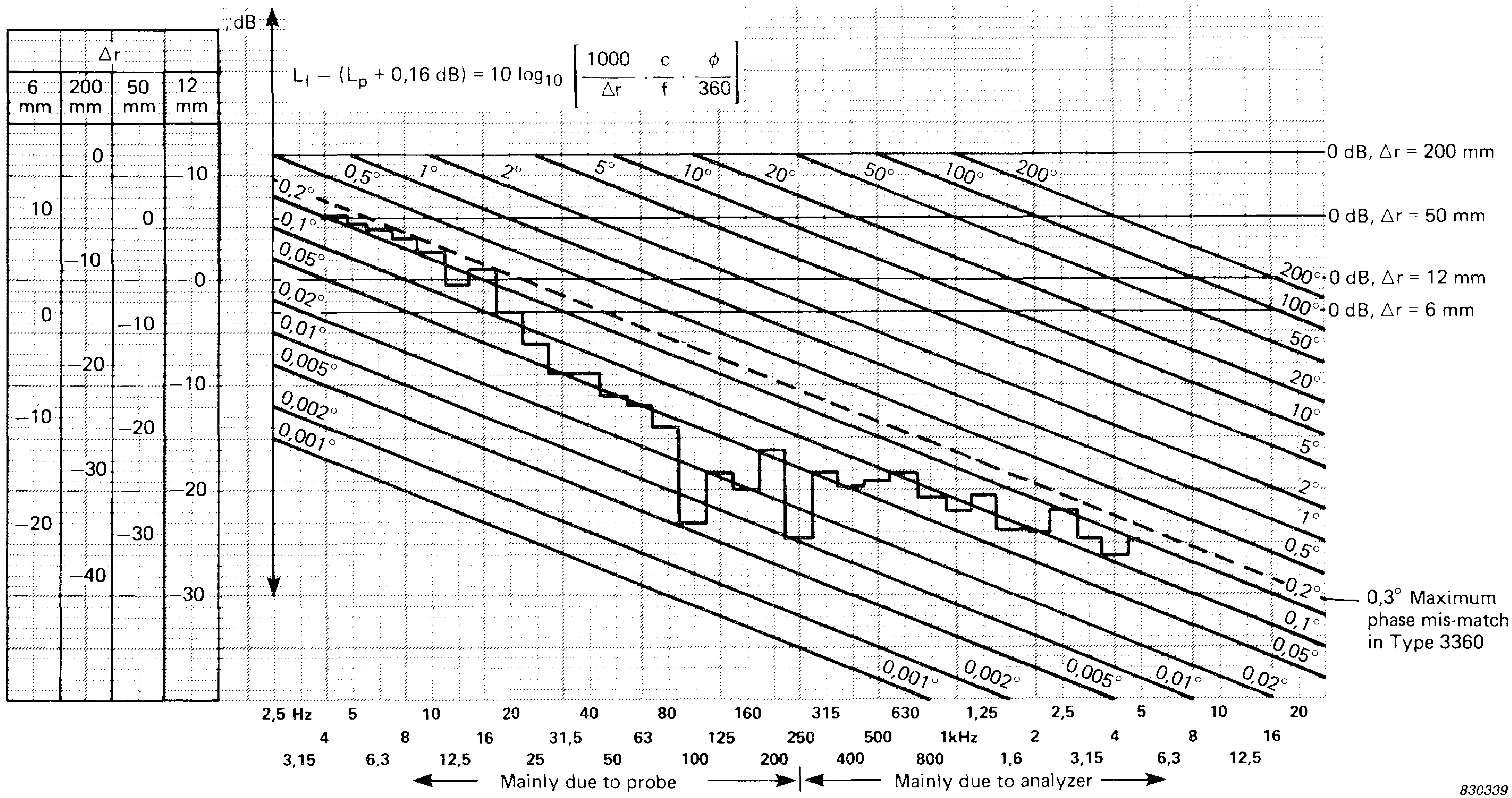

Fig.1. The phase-reactivity nomogram. The phase ϕ between the two microphone positions is shown as a function of frequency, spacer Δr and reactivity $L_I - (L_p + 0{,}16)$. The approximation error which occurs at high frequency is not taken into account by this nomogram.

Note that for a free-field $L_I - L_p = 0$ and for a reactive field $L_I - L_p < 0\,\text{dB}$.

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.

relationship $L_I - L_p$ = 0,16 dB. In most practical applications this small difference is ignored.

In a reactive field where waves propagate in more than one direction, $L_I - L_p < 0$ dB, and the bigger the difference, the more reactive the field.

It should be noted, that the phase-reactivity nomogram relates the actual phase difference between the two microphone positions in any sound field as a function of frequency and the difference between pressure and **true** intensity. Thus the approximation error which occurs at high frequencies due to the two-microphone method, is not taken into account by the phase-reactivity nomogram.

Two examples will help clarify these ideas. Consider how a phase-mismatch of 0,3° in a sound intensity analysing system, would influence an intensity measurement firstly in a free-field and secondly in a reactive field, using Δr = 12 mm at 800 Hz,

1. Free-field $L_I = L_p$.

   From the phase-reactivity nomogram (Fig.1) it can be seen that the phase between the two channels in this case is 10° and that +3 dB intensity error corresponds to 10° phase-mismatch. Thus 0,3° phase-mismatch corresponds to an overestimation of the measured intensity by approximately 0,1 dB. A −3 dB intensity error corresponds to 5° phase-mismatch. Thus 0,3° phase-mismatch corresponds to an underestimation of approxiamtely 0,2 dB. Therefore a system which is specified to be phase-matched to within 0,3° would give a maximum error in the measured intensity of + 0,1 dB or −0,2 dB depending on the sign of the phase-mismatch.

2. Reactive field $L_I = L_p - 10$ dB.

   The phase between the two channels is now only 1° and +3 dB intensity error corresponds to 1° phase-mismatch. Thus 0,3° phase-mismatch corresponds to an overestimation of the measured intensity by approximately 1 dB. A −3 dB intensity error corresponds to 0,5° phase-mismatch. Thus 0,3° phase-mismatch corresponds to to an underestimation of the measured intensity by approximately 2,0 dB. Therefore 0,3° phase-mismatch corresponds to an error in the measured intensity of +1 dB or −2,0 dB depending on the sign of the phase-mismatch.

These examples clearly illustrate that the influence of a given phase-mismatch is very dependent on the type of field in which the measurements are performed. The resulting intensity error may be evaluated in each case by means of the phase-reactivity nomogram.

Intensity error versus amplitude error

The error in the measured intensity caused by gain errors in the two channels is much easier to estimate than that due to phase-mismatch. The following expression can be used:

Intensity error (dB) = 0,5 × Gain error (dB) in channel A or B

Thus if channel A is correctly calibrated while the gain in channel B is 1 dB re channel A, the resulting Intensity error will be 0,5 dB.

Phase mismatch in tape recorders

The phase shift or the phase-mismatch between the channels of a tape recorder is caused by four independent factors:

1. Deviations in the phase characteristics of the record and reproduce amplifiers and filters.
2. Unequal geometry around the record head gap, e.g. deviations in gap width and gap shape and tape irregularities.
3. Time shift due to unequal distances from record head gap to reproduce head gap. (Azimuth adjustment).
4. Irregularities in the tape transport.

Broadly speaking, the first three factors are referred to as static phase-mismatch and the fourth as dynamic phase-mismatch; the essential difference being that any static phase-mismatch is relatively constant with time.

These four factors are discussed in the following as well as techniques to reduce the influence of them on the relative phase response.

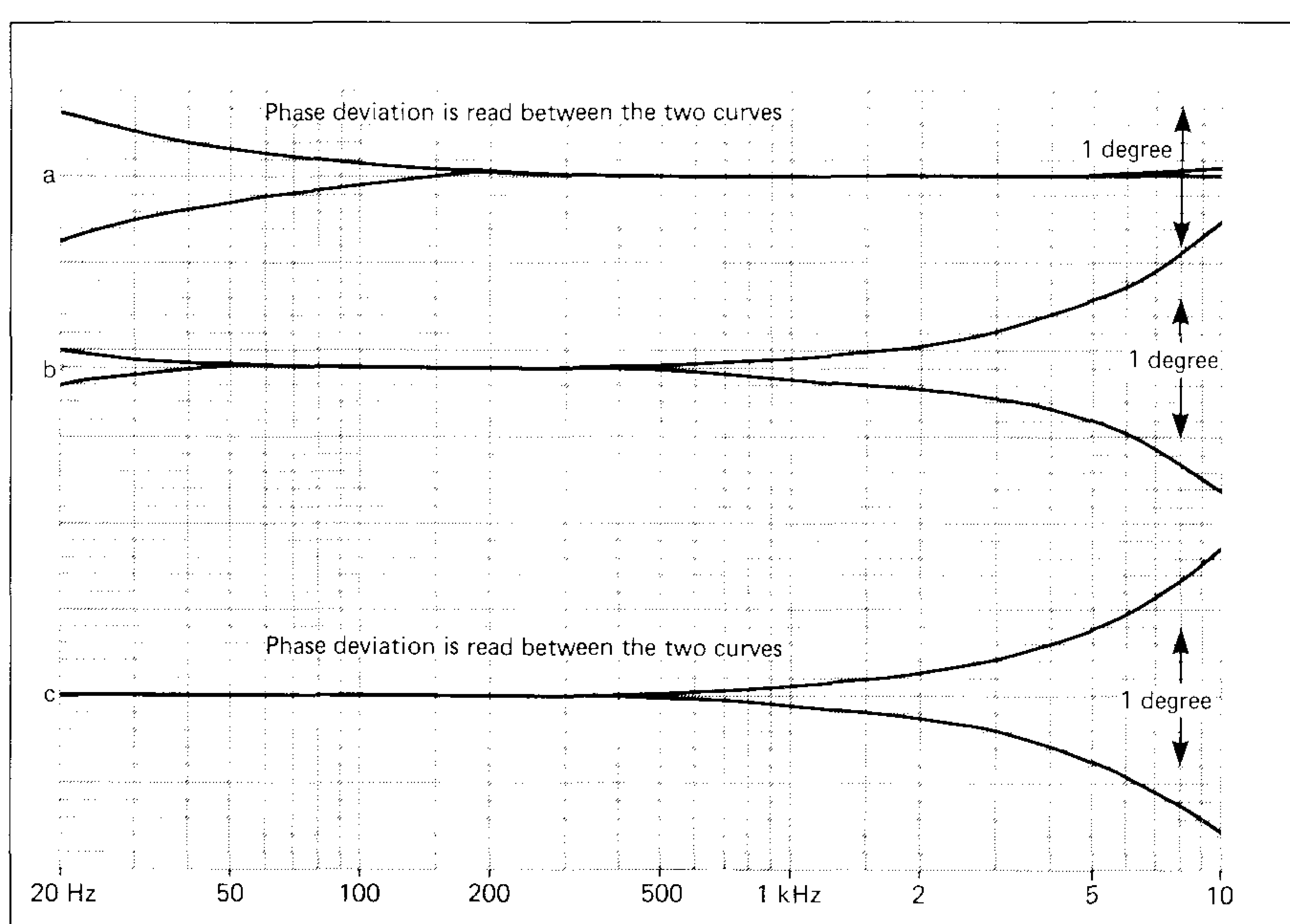

Fig.2. Typical relative phase-mismatch in two record — reproduce amplifiers
a) Direct Unit ZE 0299
b) AC-coupled FM-unit ZM 0053
c) DC-coupled FM-unit ZM 0053

1. Phase characteristics of record and reproduce amplifiers

A typical phase deviation response between two Direct Units (ZE 0299) is shown on Fig.2a for the B & K Tape Recorder Type 7005 and the corresponding curves for two FM-units (ZM 0053) (AC-coupled) and (DC-coupled) are shown on Fig.2b and Fig.2c respectively.

The high frequency relative phase response is obviously best for the direct units, because the upper limiting frequency is higher. However, the FM-units are better phase matched at low frequencies because they are DC-coupled. Even the AC-coupled FM-units are in general better phase matched than the direct units because they have a lower cut-off frequency.

2. Phase response of the magnetic recording process

The magnetic imprint on the tape does not take place right at the middle of the record head gap. As the magnetic field strength at this point is much higher than the coercive force of the tape, the imprint is erased by the high frequency bias. Therefore, the actual magnetization of the tape takes place at a certain distance from the gap. This distance depends on frequency and also on the geometry of the gap (width and shape) as well as the tape thickness and position relative to the gap.

Furthermore direct analogue magnetic recording cannot be employed down to DC because only dynamic variations in the magnetic flux from the tape are registered during the reproduction procedure. Apart from the lower limiting frequency inherent in the direct analogue recording method, there is also the limit set by the highpass filters in the direct plug-in units which increases the lower limiting frequency even further.

A typical phase response between two channels using direct recording is illustrated in Fig.3 where it is seen that the low frequency phase response is worse than for the input-output amplifiers alone (Fig.2a). Fig.3 also shows the poor phase response at the midrange frequencies due to direct recording. To summarise, it is difficult to obtain a good relative phase response between two channels in an analogue tape recorder, using direct recording.

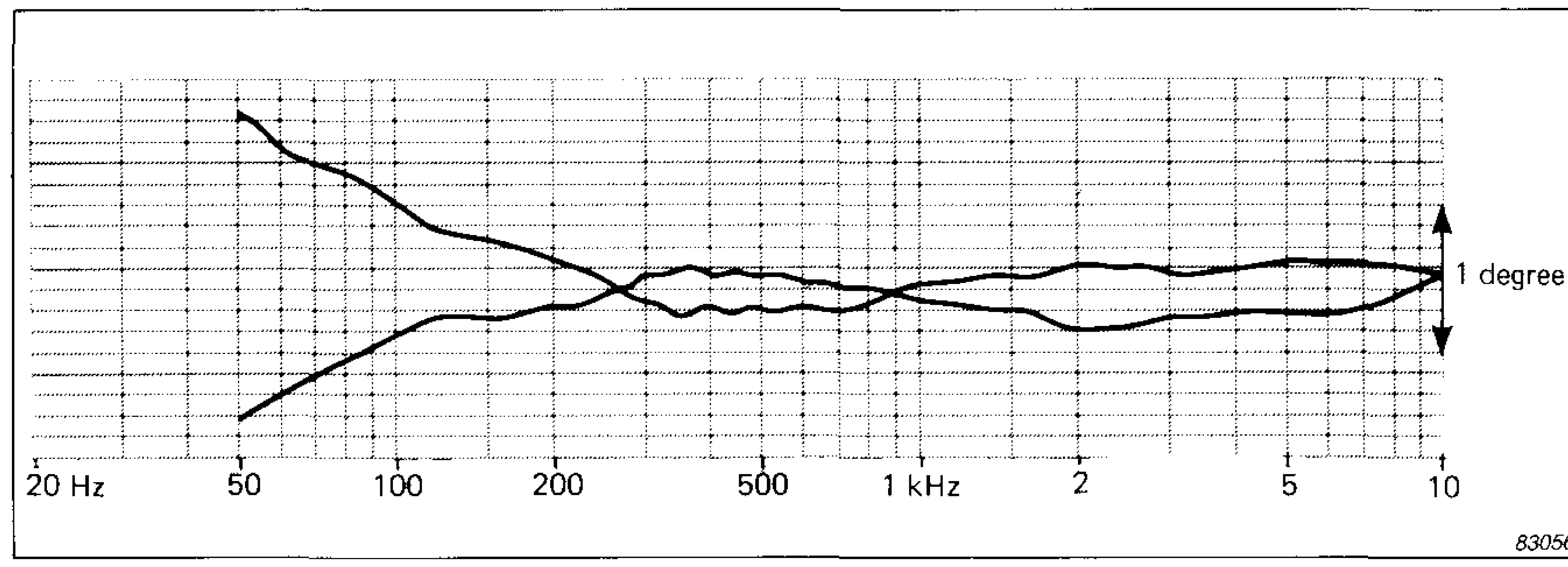

Fig.3. Typical relative phase-mismatch between two channels using direct recording with optimal azimuth adjustment

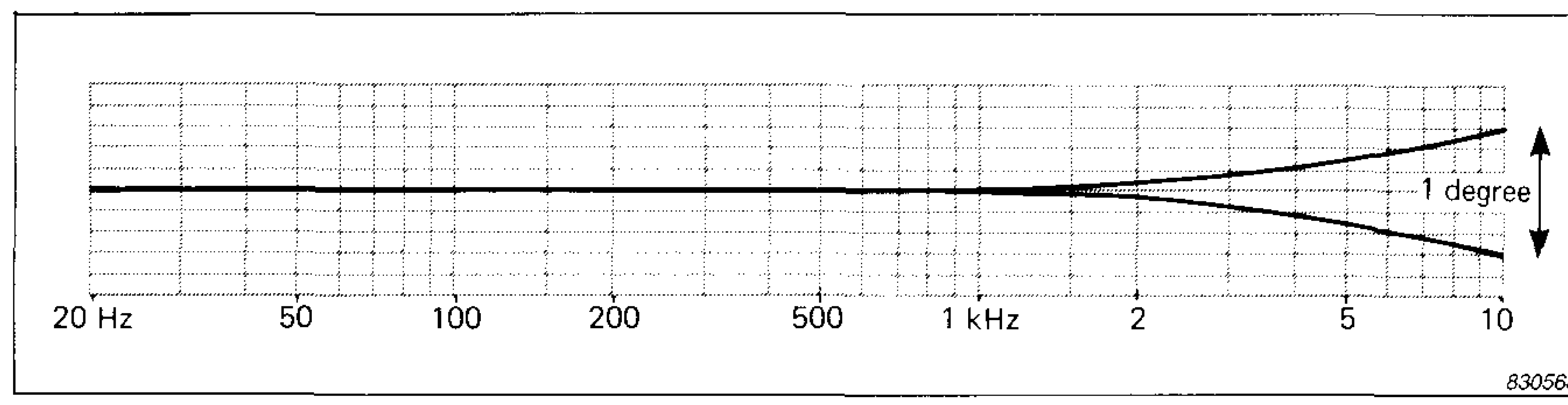

Fig.4. Typical relative phase-mismatch between two channels using FM recording with optimal azimuth adjustment

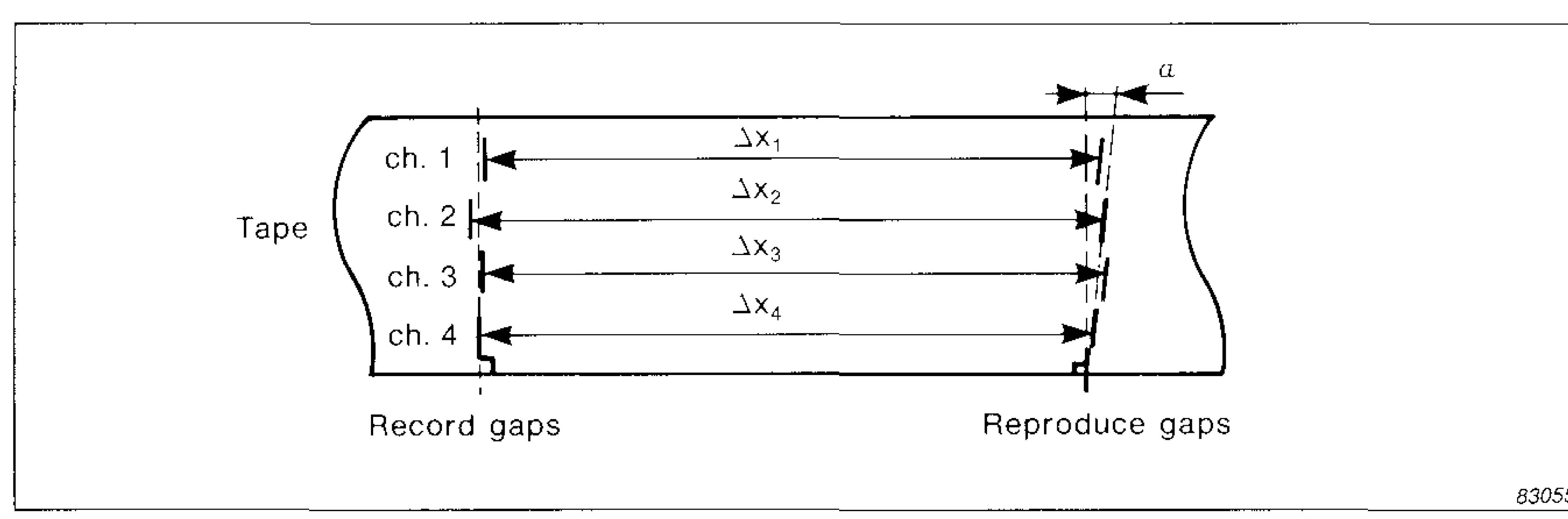

Fig.5. Record gaps and reproduce gaps in a 4-channel tape recorder

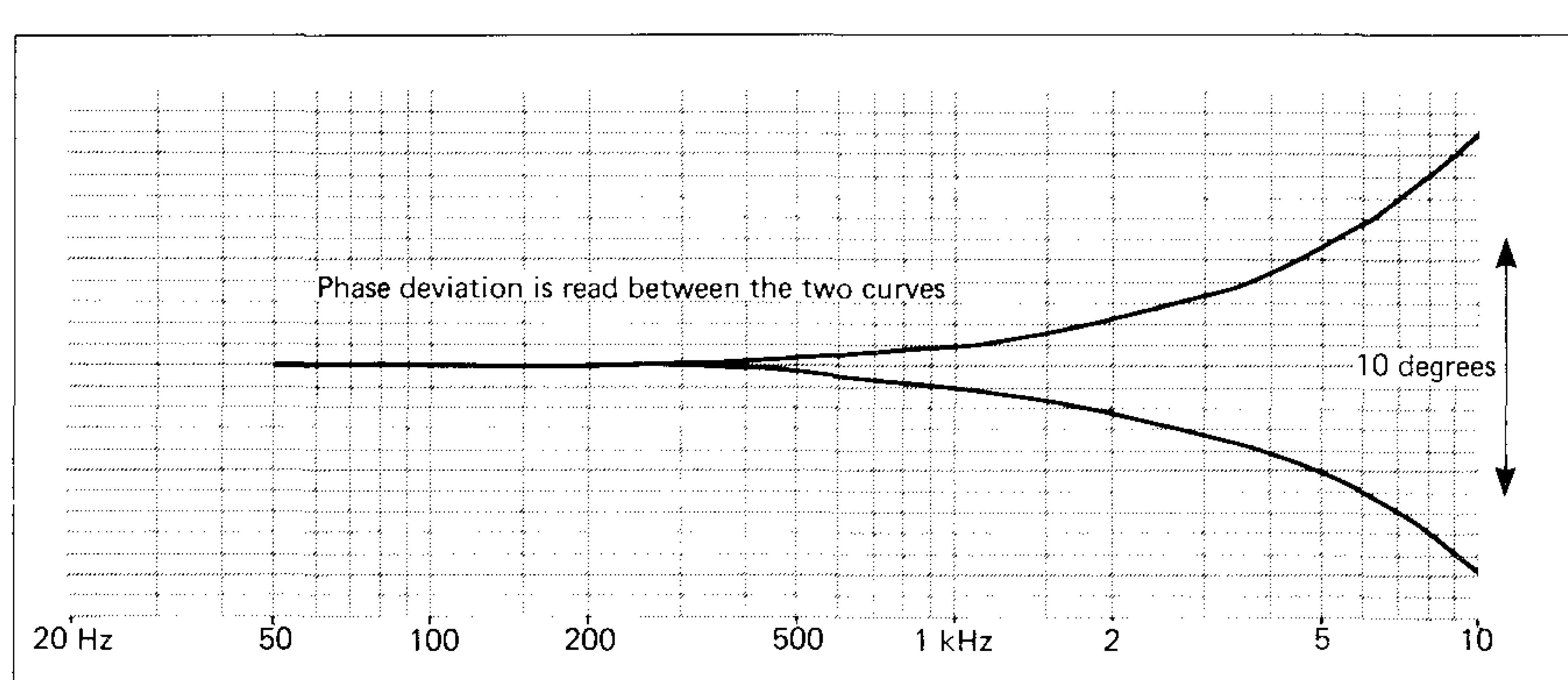

Fig.6. Relative phase-mismatch between two channels using FM recording with non optimal azimuth adjustment

For high frequency recording (as in FM-recording) these problems do not exist. Fig.4 shows the measurement which corresponds to Fig.3 using ZM 0053 FM-Units instead of ZE 0299 Direct Units. On comparing the FM-recording to the direct recording, the improvement in the relative phase response is clearly seen.

3. Azimuth adjustment

The phase mismatch between two channels in an FM tape recording is mainly due to unequal distance between record and reproduce gaps. Fig.5 illustrates this effect.

By adjusting the angle α, azimuth adjustment, the distance from record to reproduce gap can be set. An optimal adjustment, however, (e.g. $\Delta x_1 = \Delta x_2$) is only possible between two channels at one time, because the gaps in the record and reproduce heads are not ideally aligned (see Fig.5).

Fig.4 shows the phase response with an optimal azimuth adjustment in two channels being employed while Fig.6 shows the phase response with a non-optimal setting.

The azimuth phase-mismatch is proportional to frequency and to a good approximation this is also the case with the phase mismatch in the record-reproduce amplifiers for frequencies below 10 kHz. It is therefore possible to a great extent to compensate for this electrical phase-mismatch with the mechanical azimuth adjustment, and special phase matching of the FM-units is unnecessary. Hence, an FM tape recorder with an optimal setting of the azimuth possesses a very low overall phase deviation.

Effect of residual phase-mismatch at high frequencies

From Fig.4 it is seen that a phase-mismatch of 1° or less at 10 kHz is obtainable for a tape recorder with an optimal azimuth adjustment. As this error is mainly proportional to the frequency, the resulting intensity error will be almost constant in all the third octave bands.

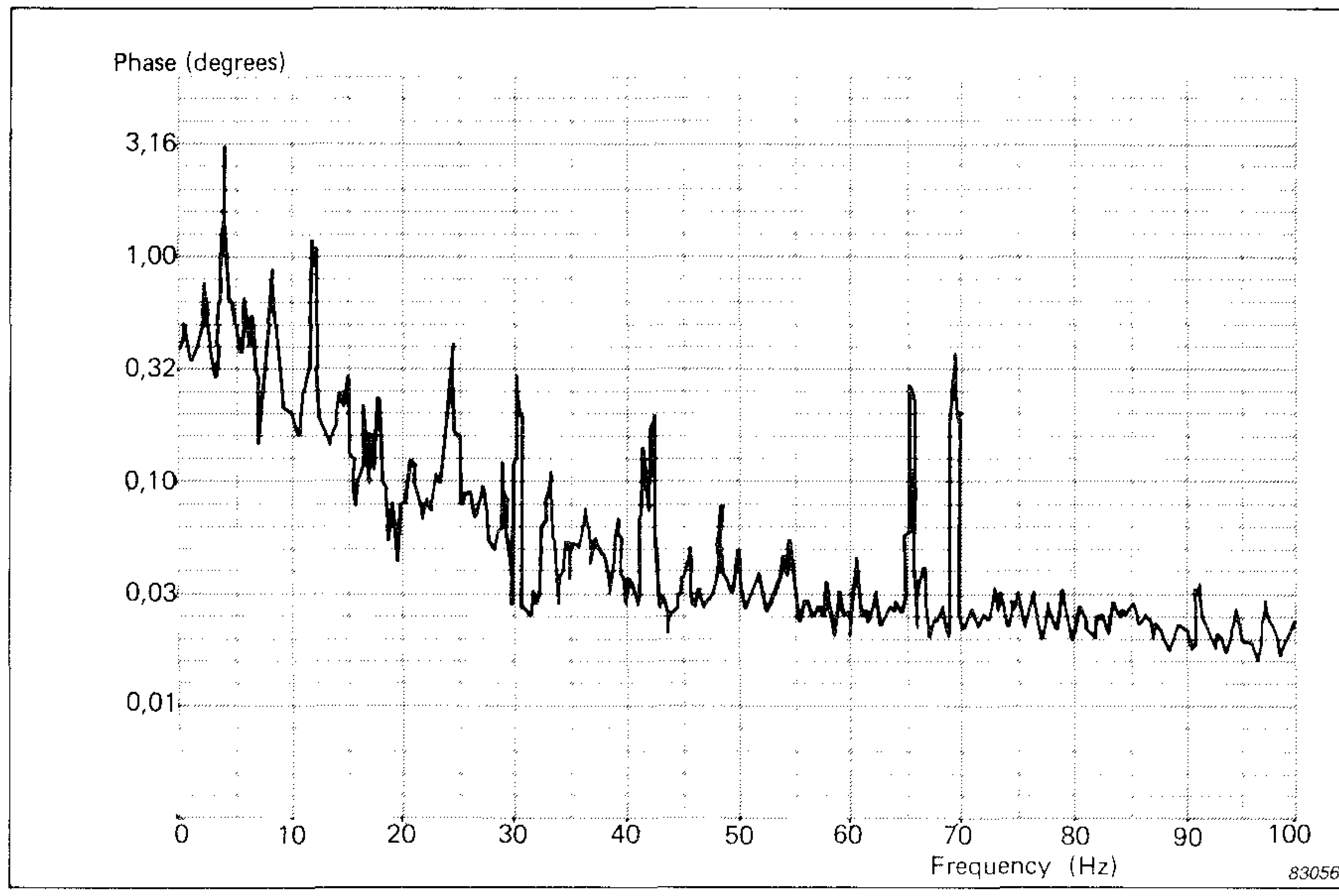

Fig.7. Spectrum of relative phase fluctuations between channel 1 and 4 measured by recording a 10 kHz signal in both channels at a tape speed 381 mm/sec and passing the outputs through a phasemeter and frequency analysing the phase fluctuations. The sharp peaks can be related to the dimensions of the wheels of the tape transport system

Under free field conditions for Δr = 12 mm and where $L_I = L_p - 0{,}16$ dB, the phase-reactivity diagram in Fig.1 shows that the phase difference in the two measuring channels at 8 kHz is 100 degrees, and that −50° phase error will result in −3 dB intensity error. Thus the effect of 1,0° phase-mismatch at 8 kHz has an insignificant influence on the measured intensity level, giving an error of approximately 0,06 dB.

The more reactive the measuring field, the more influence the phase-mismatch has and the more significant the errors on the measured intensity level become. If $L_I = L_p -$ 10 dB, the phase difference between the two microphone positions is 10°. A −5° phase error would correspond to −3 dB intensity error. Thus 1,0° corresponds to an underestimation of approximately 0,6 dB. If $L_I = L_p -$ 20 dB, the phase difference between the two microphone positions is 1,0°. Thus a phase-mismatch of 1,0° would yield an intensity error of either +3 dB or −∞ dB, so that in this very reverberant field, at this frequency, tape recording of sound intensity measurements is not recommended.

4. Dynamic phase-mismatch

Only static phase-mismatch has been discussed so far. However, any irregularities in the tape transport system and in the tape itself, cause some phase fluctuations referred to as dynamic phase-mismatch, which may also be observed in the tape recording process. For intensity measurements this mismatch will normally be averaged out, but for transient intensity analysis it can be significant.

A typical spectrum of the relative phase fluctuations is shown in Fig.7. This spectrum was measured under the worst conditions because the outer channels (1 and 4) were used. By using two neighbouring channels the fluctuations will be reduced to less than 1 degree at 10 kHz. However, good maintenance of the tape transport system as well as a high quality tape is important to keep within this specification.

Part 2: Tape Recording of Sound Intensity

In Part 1 the phase-mismatch in an analogue tape recorder using direct and FM-recording were discussed. The conclusion was that FM-recording must be used if good phase matching is required as indeed it is for intensity measurements. In practice the phase-mismatch is not infinitely small but can, however, be

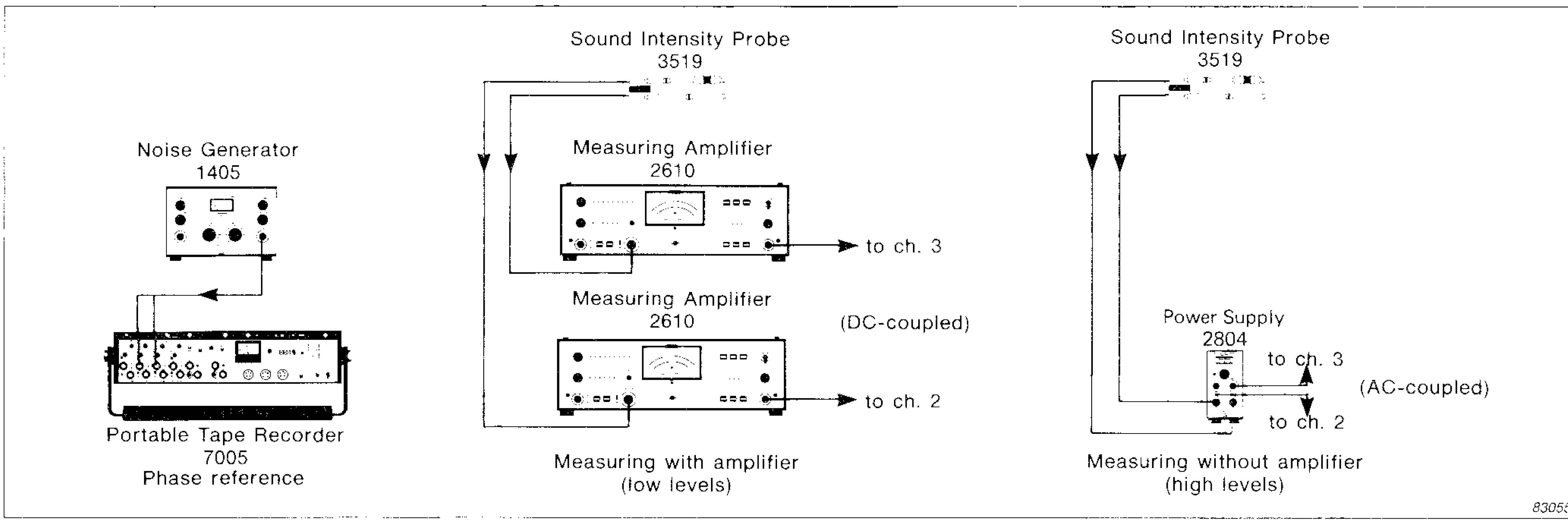

Fig.8. Left: recording a pink noise reference signal.
Centre: amplification of the signals from the probe by means of measuring amplifiers. This technique is used for low level signals.
Right: supply to the preamplifiers of the probe by means of a power supply which is the more usual technique

minimized or alternatively a compensation technique can be introduced. These principles and their practical applications and limitations for intensity analysis are discussed in this part.

Switching technique

By averaging over two time periods of equal duration and changing the sign of the phase-mismatch between the two periods, the phase-mismatch will be practically eliminated. Therefore, no minimizing of the phase-mismatch is necessary. However, this switching technique (ref. 1) has several disadvantages:

1. The source, as well as the background noise, has to be stationary.
2. The technique is more time consuming because the probe has to be turned 180 degrees for each measurement.
3. One is not sure that the measurement conditions remain constant.
4. Measurements with a 3-microphone or a 4-microphone probe (for 3-dimensional or broad band use) are not possible.

Optimal tape recording technique for intensity measurements

In this technique, the phase-mismatch is minimised by adjusting the azimuth. However, this delicate adjustment will not remain optimal for a longer period of time, and especially not if the tape recorder is jolted around or exposed to large changes in temperature. It is worth noting that only one micron misalignment in the relative positions of the reproduce gaps in two channels will result in a phase-mismatch of 1° at 1 kHz at a tape speed of 381 mm/s. As mentioned above, this azimuth adjustment is not stable for a longer period of time. Therefore the adjustment should be made immediately before reproducing the measurement signals.

To enable the azimuth adjustment to be perfomed, a high frequency reference signal must be recorded in phase in the relevant channels immediately before the measurement, and, as a check, again after the measurement. In this way, excellent phase matching is obtained from the moment when the measurements are made to the moment they are reproduced.

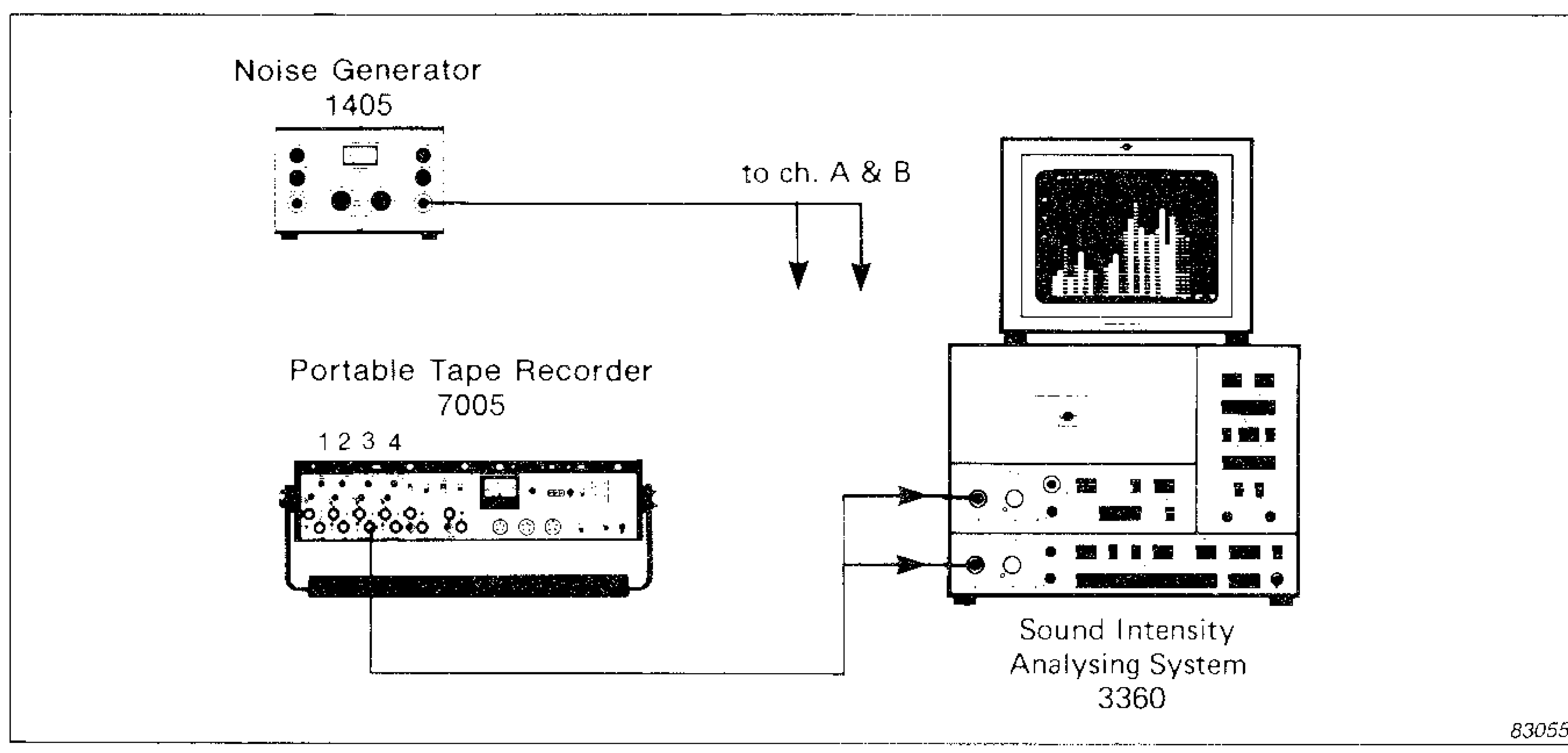

Fig.9. The dynamic range of the analyser alone (without the probe) can be checked by putting the same noise signal into both channels simultaneously. This simulates a diffuse field. Alternatively a reference signal may be taken from one channel of the record / reproduce units of the Tape Recorder

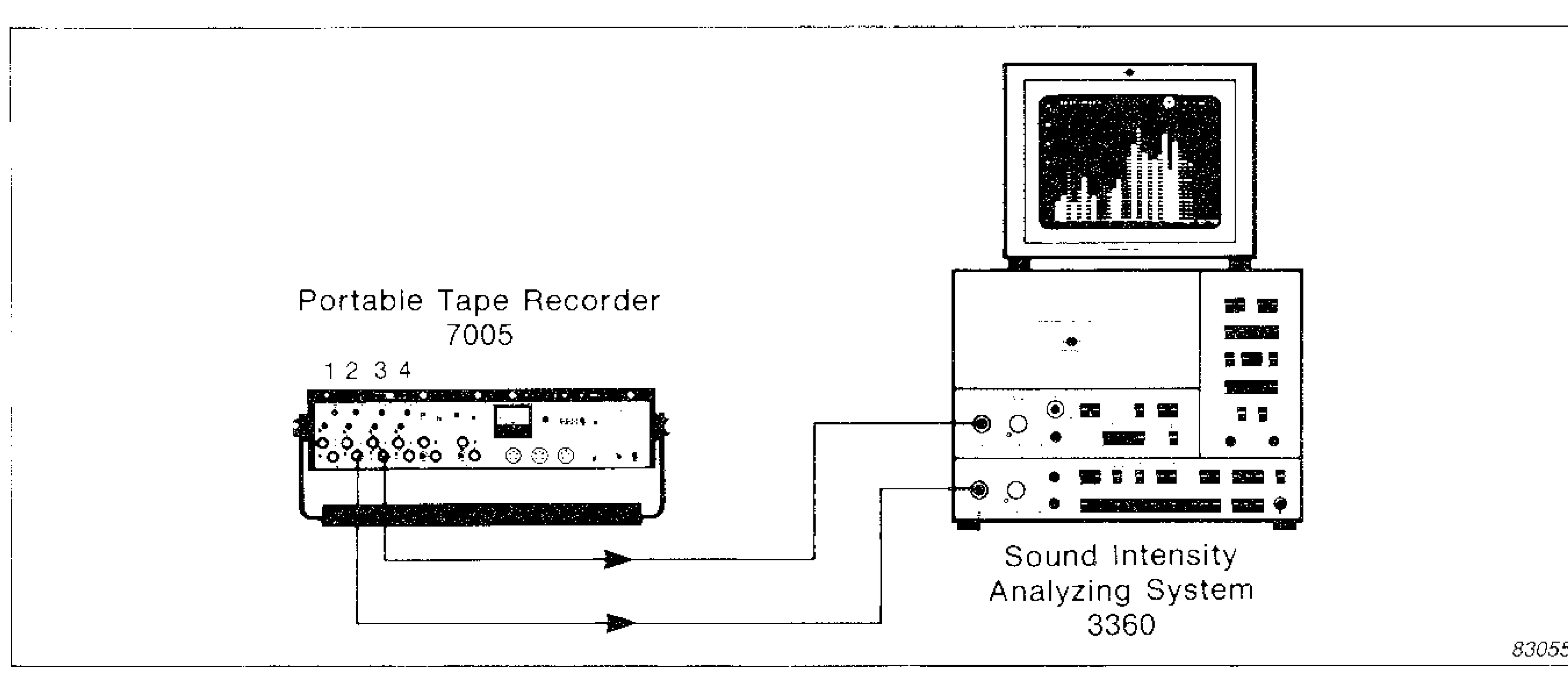

Fig.10. Set-up for analysis of the tape recorded Intensity measurement

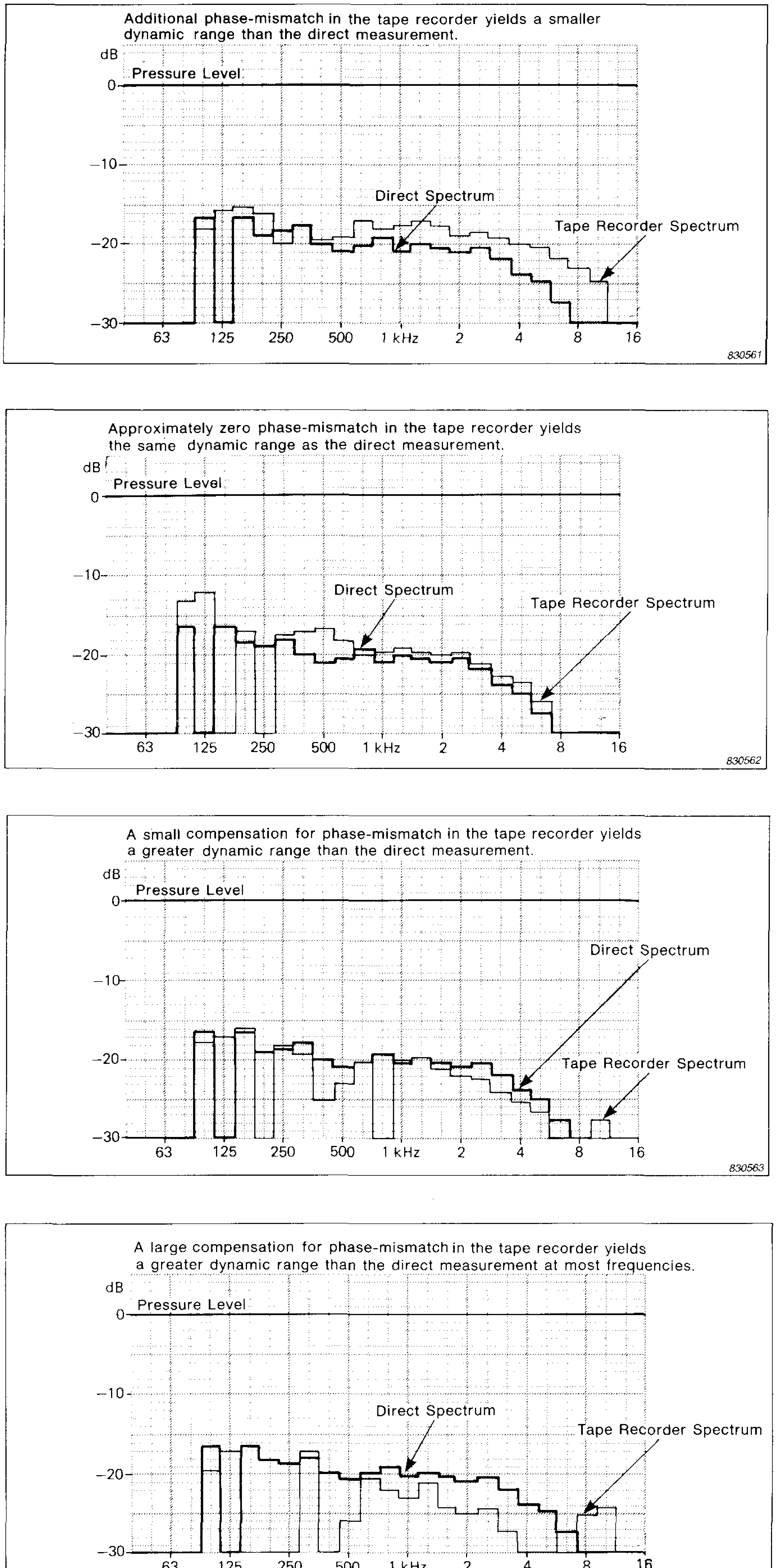

Fig.11. Pressure, direct intensity and tape recorded intensity spectrum for 4 different azimuth adjustments. Dynamic range of the system is in each case the difference between pressure and intensity levels

This technique enables all 4 channels to be used and then to be phase-matched in pairs before reproduction. The phase matching is optimal, and the measurements can be performed without previous adjustments, although reference signals have of course to be recorded.

Practical measuring procedure

A detailed description of the entire measuring procedure is described below:

Recording:

1. Prior to the recording of the measuring signals, a reference signal must be recorded simultaneously in the relevant channels. The reference signal can be supplied by the 1 kHz internal generator although an external 10 kHz or broad band (pink noise) source is preferable. At least 60 seconds of the reference signal must be recorded. Some possible calibration and measuring set-ups are shown in Fig.8.

2. The measurement signals from the Sound Intensity Probe Type 3519 via the Power Supply Type 2804 are recorded on the Tape Recorder Type 7005.

3. After recording the measurement signals, it is preferable to record a new reference as explained above. Also, if drastic environmental changes occur during the measurement, a new reference should be recorded. In general, the tape recorder should be handled as carefully as possible after the reference signal has been recorded.

Reproducing:

1. The same reference signal as was used prior to the measurement, must be led simultaneously to the two channels of the Intensity Analyzer Type 2134. If the internal generator in the Tape Recorder Type 7005 is used, the signal must be taken from only one of the record/reproduce units to avoid any phase-mismatch in the record/reproduce amplifiers. (See Fig.9). The pressure level is noted, and the intensity level (spectrum), averaged over at

least 32 seconds, is stored in the analyser and read-out to an X-Y Recorder Type 2308 (see examples in Fig.11). The intensity level should in this case theoretically be zero (−∞ dB), but because of a residual phase-mismatch in the analyser, there will also be a residual intensity level. An estimation of the phase-mismatch in the analyser as a function of frequency can be obtained from the phase-reactivity nomogram. The measurement of the spectrum of the residual intensity level gives an excellent description of the dynamic range of an intensity analyser.

2. The tape recorded references in the two channels that are going to be analysed are connected to channel A and B on the Sound Intensity Analyser Type 2134, and the pressure level in each channel is adjusted to the level that was noted before (see Fig.10).

3. The Sound Intensity Analyzer Type 2134 is switched to the intensity mode, and 2 or 4 seconds exponential averaging is selected. By adjustment of the azimuth during the reproduction of the reference signals the same intensity level or spectrum as previously stored can be tuned in. The final adjustment should be checked with 32 seconds linear averaging. When the direct intensity spectrum and the tape recorded intensity spectrum are almost identical (see example in Fig.11), the phase-mismatch in the tape recorder has been minimized.

4. The measured signals can now be analysed.

5. After the analysis, the azimuth adjustment should be checked again by making a 32 seconds linear averaging on the reference signal recorded after the measurements.

6. The above procedures must be repeated when any other pair of channels are analysed.

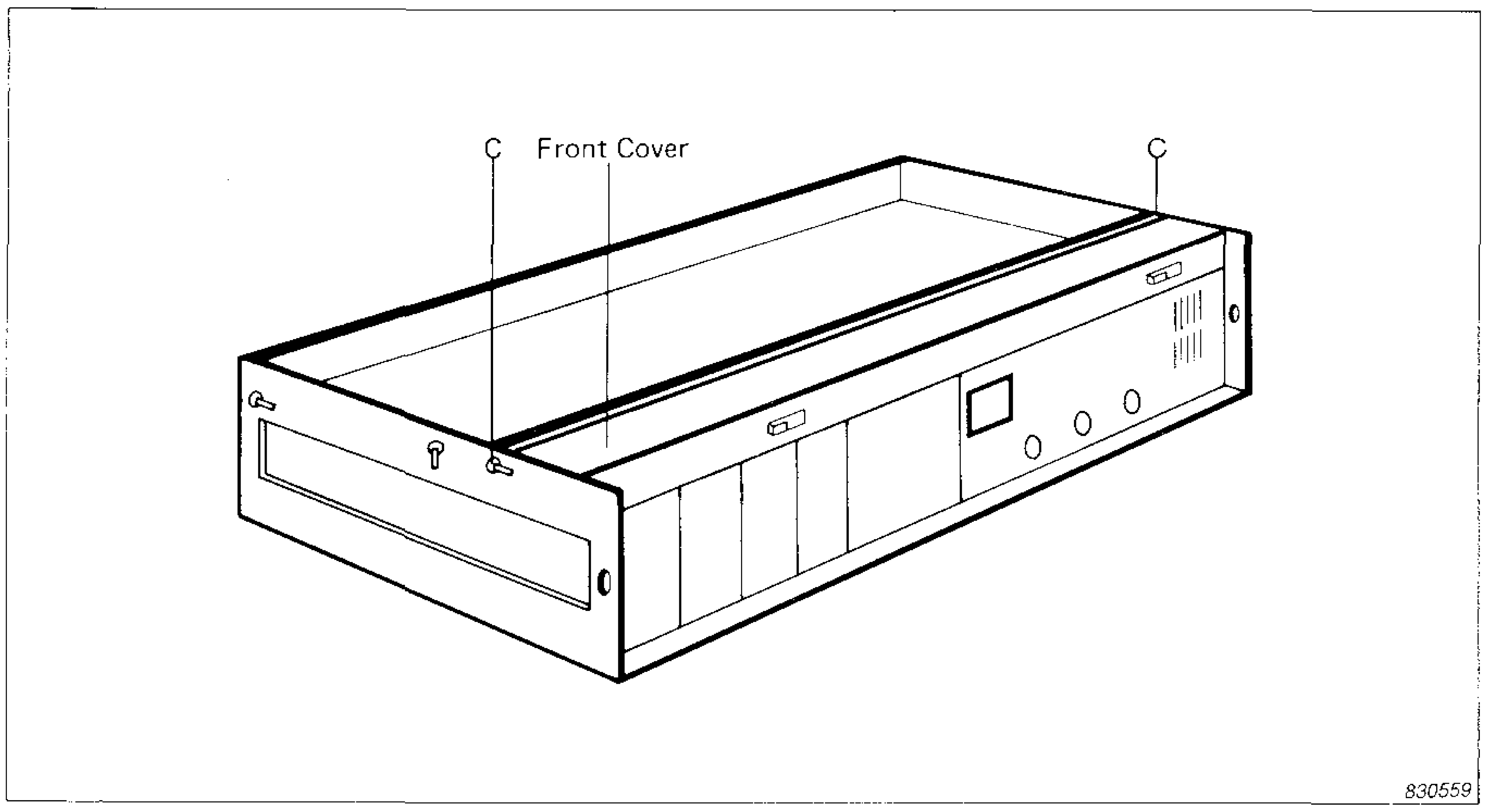

Fig.12. Chassis of the Tape Recorder Type 7005 showing the screws which secure the front cover

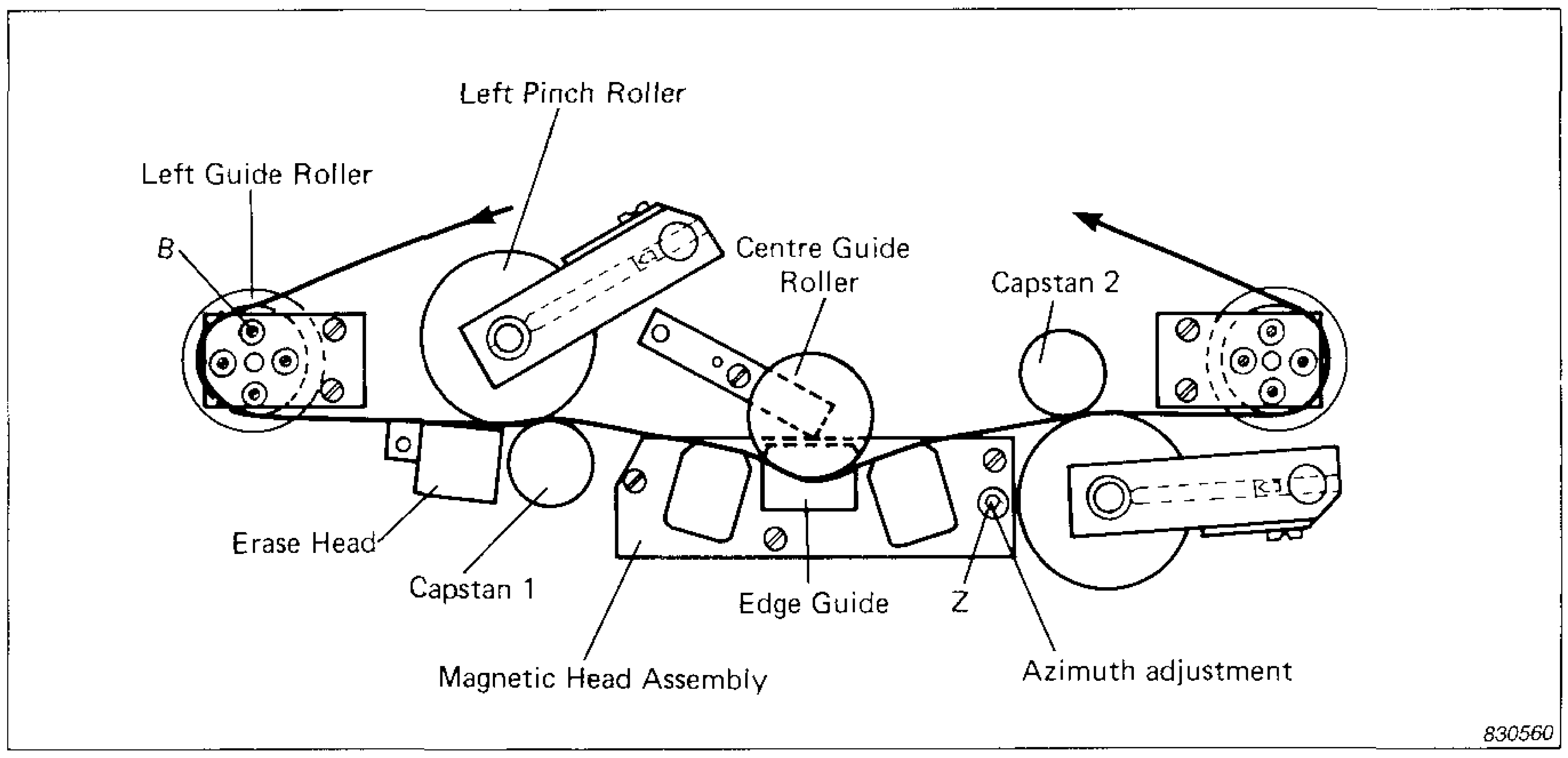

Fig.13. Tape transport and the magnetic head assembly under the front cover. Azimuth adjustment is performed by gently turning screw Z

Practical azimuth adjustment

The chassis of the Tape Recorder Type 7005 is shown in Fig.12. To adjust the azimuth, it is necessary to remove the front cover by unscrewing the two screws C five full turns. The cover can then be lifted up at the rear edge to expose the magnetic head assembly as illustrated in Fig.13. The azimuth can then be adjusted by carefully turning screw Z with a 2 mm allen key.

Practical guidelines

A number of practical tips that can help in making a delicate intensity recording successful are listed below.

Phase-mismatch is approximately ten times lower at the higher tape speed so 381 mm/s must be employed.

Neighbouring tracks should preferably be used i.e. 1–2, 2–3 or 3–4. For multichannel intensity measurements (3-D probe or broad band probe) ch.2 or 3 must be the common reference.

High quality tape is essential and rather new tapes must be used in order to avoid dynamic phase-mismatch due to tape sag. The tapes should always be rewound after use.

The tape transport system and the magnetic heads should be maintained in good condition and regular service is necessary.

During the reproduction procedure, the tape recorder must not be moved.

Part 3: Experimental Results

The results of some practical measurements are given here to demonstrate the value of the measurement technique described in Part 2.

The sound power level of a reference sound source was determined from sound intensity measurements using the Sound Intensity Analyzing System Type 3360 and the Tape Recorder Type 7005. The measurements were performed directly as well as recorded on tape using the set-up shown in Fig.14, so that the influence of the tape recorder could be precisely evaluated. The measurements were performed over a hemispherical measurement surface with a radius of 1 m using 10 measurement positions distributed as described in ISO Standard 3745. The environment was the most reactive available, namely a reverberation room of 215 m^3 with a reverberation time of 18 s at 100 Hz falling to 5 s at 3150 Hz. The reactivity of the sound field as function of frequency was found from the difference $L_I - L_p$ averaged over the 10 measuring positions. Fig.15 shows that the difference is approximately 10 dB for most frequencies. From the phase-reactivity nomogram, it can be seen that this reactivity puts very high demands on the phase-matching of the system, and these measurement conditions were thus a severe test for the instrumentation.

The linear averaging time was 32 seconds in each measuring point, and channels 2 and 3 equipped with FM-units ZM 0053 were used. The FM-unjts were switched to AC-mode to avoid low frequency overload of the input amplifiers. A pistonphone reference signal was recorded in each channel then the procedure given in Part 2 was precisely followed for each tape-reel. Broad band pink noise was used as a phase reference on the tapes.

The tape recorded results were analysed after some days and again, as a control after some weeks. Once again the reproducing procedure given in Part 2 was precisely fol-

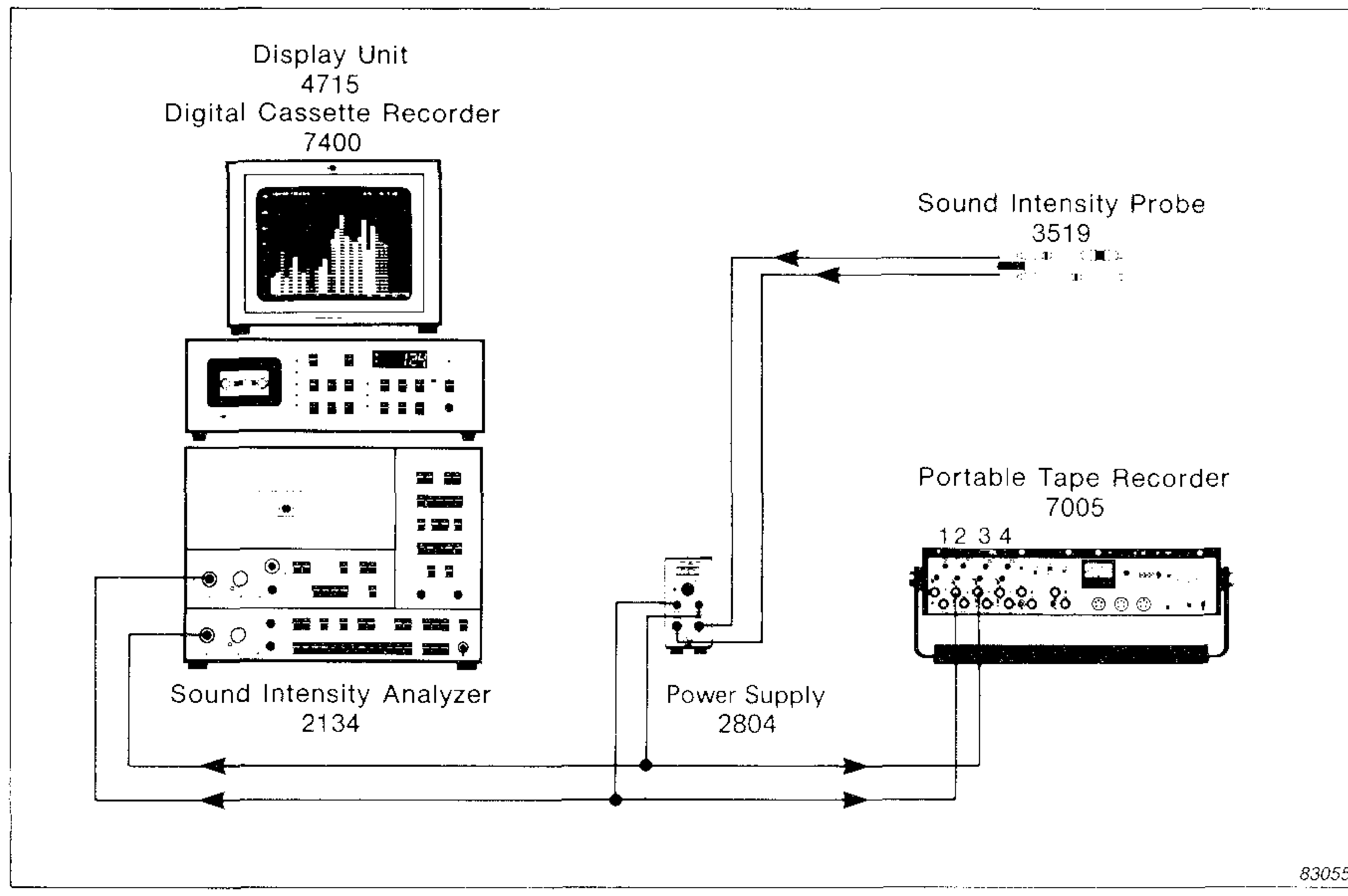

Fig.14. Measurement set-up for simultaneous analysis and tape recording of sound intensity

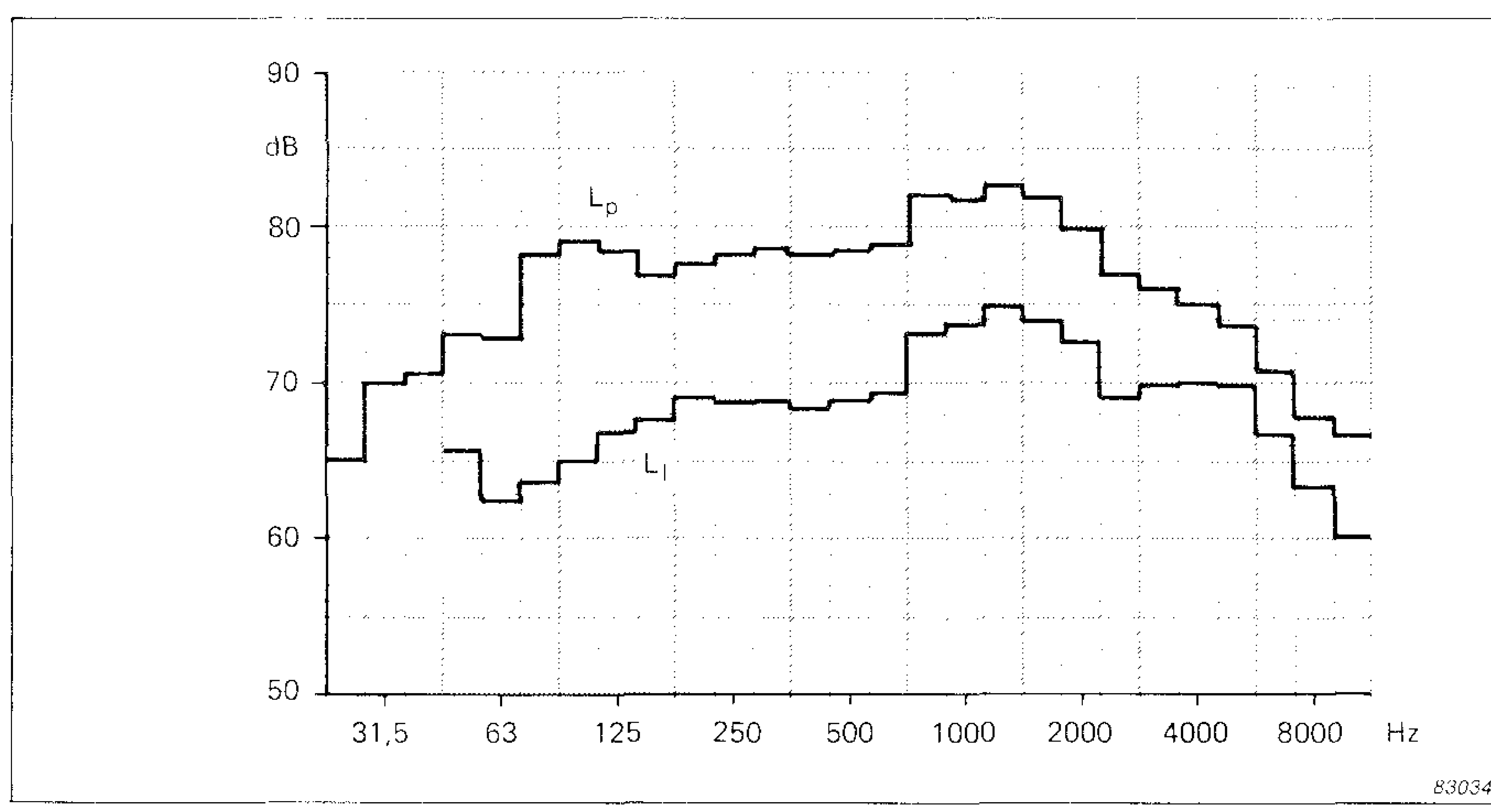

Fig.15. L_p and L_I averaged over 10 measurement positions. The reactivity of the sound field is the difference between the two spectra

dB \ Hz	125	160	200	250	315	400	500	630	800	1k	1,25k	1,6k	2k	2,5k	3,15k	4k	5k	6,3k	8k	10k	dBA
Tape recorded intensity	75,5	74,3	77,1	76,8	77,1	76,6	76,7	77,4	81,0	81,6	82,7	82,1	80,5	77,1	77,7	78,2	77,6	74,6	70,9	67,8	91,0
Direct Intensity	75,1	74,4	76,9	76,5	76,6	76,2	76,3	77,0	80,7	81,4	82,5	81,9	80,3	76,9	77,6	78,1	77,6	74,5	70,8	67,7	90,8
Calibration reference	75,0	76,2	77,1	77,1	77,0	76,8	77,2	77,5	80,4	81,3	82,5	82,1	80,9	79,3	78,7	78,2	77,7	76,1	74,2	78,3	91,2

Table 1. Reference 1/3 octave sound power levels for sound source compared with results from direct intensity analysis and tape recorded intensity analysis

lowed. The difference between these two results were less than 0,1 dB at all frequencies. The "spectrum of the dynamic range" for the system with and without tape recorder is shown in Fig.11. It is seen that the dynamic range is only slightly reduced when the tape recorder is used. For some frequencies the dynamic range is even better with the tape recorder.

The 1/3 octave sound power levels for the tape recorded intensity analysis, the direct *in situ* intensity analysis and the calibration reference for the sound power source are given in Table 1. The influence of the tape recorder is very small, being less than 0,2 dB at most frequencies. Thus despite the extremely difficult measuring conditions, the tape recorded analysis proved to be very successful.

Conclusion

Tape recording of intensity measurements is a delicate undertaking and should only be performed where use of the complete Sound Intensity Analysing System Type 3360 is impossible or very inconvenient. The entire measuring procedure must be performed with great care and the tape recorder itself must be maintained in excellent condition. However, if these conditions are fulfilled very good results can be obtained.

In general the "spectrum of the dynamic range" as shown in Fig.11, is the best way to evaluate the validity of a sound intensity analysis, whether or not a tape recorder is employed. The rule is that the dynamic range has to be better than the reactivity of the sound field. Fig.11 shows that tape recording need not necessarily reduce the dynamic range available and may at some frequencies even increase it. However, meticulous care must be employed to obtain this result and all the guidelines given in this application note must be followed.

Literature

1. *Gade, Svend:* Sound Intensity, Part I and II B & K Technical Review No. 3 and No. 4 1982
2. *Mee, C.D.:* The Physics of Magnetic Recording. 1964
3. *Rasmussen, Knud:* Magnetic registration (Danish text) 1977. The Acoustics Laboratory, Denmark
4. *Brock, M.:* Preisach distribution in magnetic tapes (Danish text) 1979. The Acoustics Laboratory, Denmark

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