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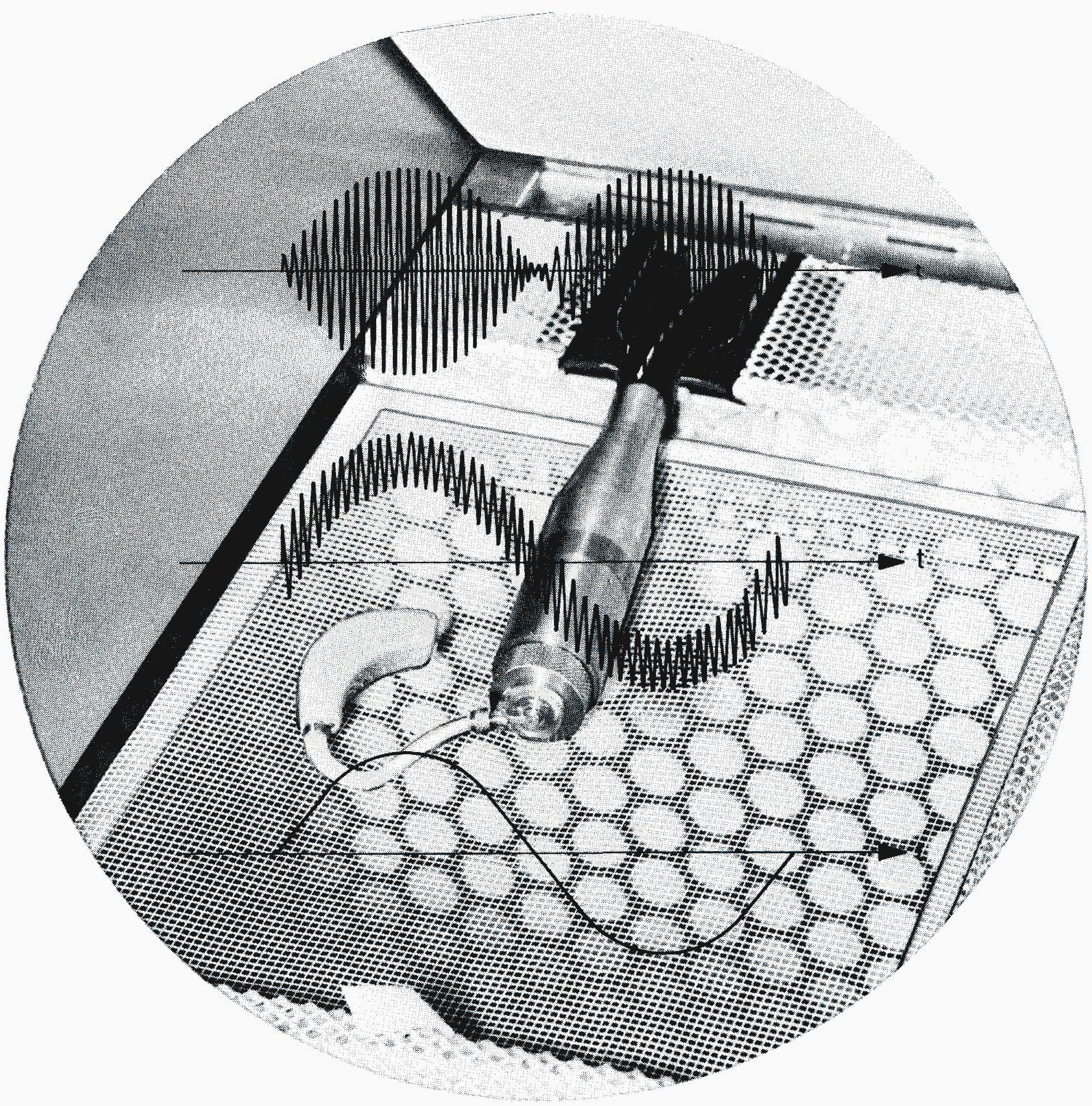
application notes

Swept Measurements of Difference Frequency Intermodulation and Harmonic Distortion of Hearing Aids



Practical Instrument Set-ups

Swept Measurements of Difference Frequency Intermodulation and Harmonic Distortion of Hearing Aids

by *Philip S. White*, Brüel & Kjær

Introduction

In general, amplitude non-linearities of a hearing aid may be measured using three different distortion measurements: harmonic, difference-frequency, and intermodulation distortion. Up to the present time, harmonic distortion measurements have been the easiest to make, and hence the most commonly used. However, with the advent of the new instrumentation discussed in this Application Note, the intermodulation and difference-frequency distortion measurements have become significantly easier and thus merit consideration.

Intermodulation distortion is the interaction of two or more frequencies in a complex signal that results in the generation of new frequency components not present in the original signal. These components are "mixing" products, and hence their frequencies are equal to the sum and difference of the frequencies of the original signals and the integral multiples thereof. A special case of intermodulation distortion is difference-frequency distortion which only considers those components which are the difference between the original components, thus ignoring the sum components.

Intermodulation and difference-frequency distortion measurements are of considerable importance because they represent a more realistic simulation of speech or music than a single tone which is used for harmonic distortion measurements. They are also useful in describing interaction phenomena between several frequencies, which is inherently impossible with a single tone. In addition, since intermodulation components are not musically related, they are more audible, and in many cases, more annoying.

Another significant advantage of intermodulation distortion measurements, is that they permit the measurement of non-linearities up to the cut-off frequency of the system, because many of the distortion components generated are folded back

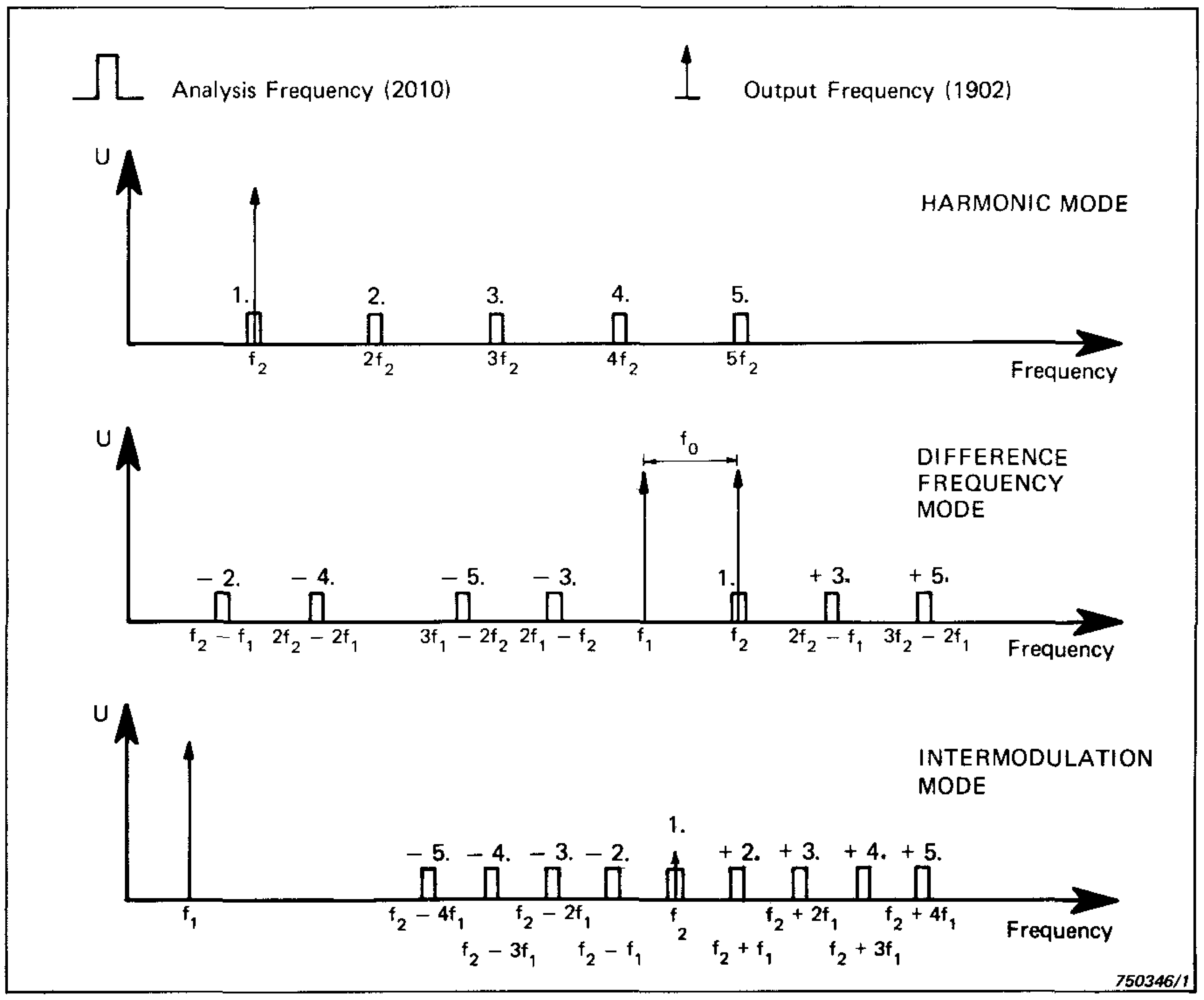


Fig. 1. Test signals and analysis frequencies for distortion measurement

into the band-pass section of the system. However, with harmonic measurements at higher frequencies, the distortion components will fall above the cut-off frequency, and thus will be rolled off. Finally, intermodulation measurements are a more sensitive test of non-linearities since the theoretical amplitude of the intermodulation components is higher than the harmonic components.

Let's take a look at the advantage of each of the three measuring methods.

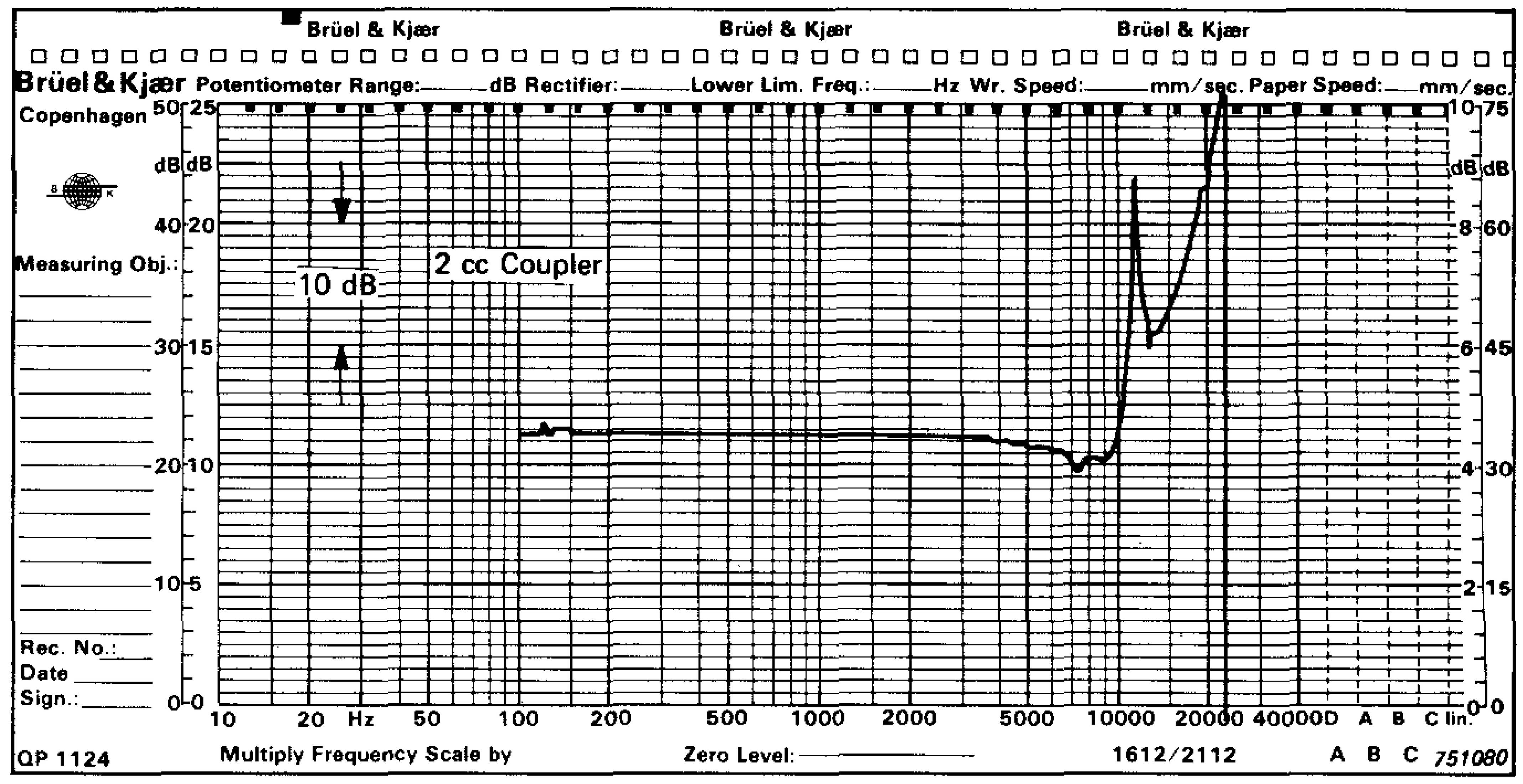


Fig.2. Impedance curve of a 2 cc coupler

Harmonic Distortion

Looking at Fig.1a, harmonic distortion is measured by exciting the hearing aid with a single sinusoidal tone, f_2. The sound pressure level of f_2 is to remain constant at the microphone of the hearing aid.

One of the merits of measuring harmonic distortion is that it requires a fairly simple instrumentation system. When using a spectrometer for this purpose, the harmonics are simply measured by offsetting the center frequency of the contiguous filters with respect to the sine generator by a constant factor corresponding to the number of the desired harmonic.

One of the disadvantages of measuring harmonic distortion is related to the hardware; the type of coupler used in conjunction with the earphone of the hearing aid normally has one or more resonances at high frequencies (Fig.2). With a resonance peak at 12 kHz it means that the amount of second order harmonic distortion at f = 6000 Hz will be more than 20 dB too high. Same for third harmonic at f = 4000 Hz.

Another disadvantage of harmonic distortion measurements is due to the frequency response of the hearing aid.

Looking at Fig.3, showing frequency response and harmonic distortion of a behind-the-ear hearing aid, we see that the sharp roll-off of the frequency response above 5 kHz causes the harmonics to roll-off at correspondingly lower frequencies. This, however, does not imply that the hearing aid does not exhibit amplitude non-linearity at higher frequencies within the pass-band of the hearing aid. This quantity can be measured as:

Difference Frequency (DF) Distortion

DF distortion (Fig.1) is measured by exciting the hearing aid with a twin-tone test signal with frequencies f_1 and f_2. The sound pressure levels of f_1 and f_2 are equal. The two tones are swept through the frequency range of interest while keeping a small fixed interval in hertz between the two tones.

DF distortion considers only the components which are the difference between the original frequency components (f_1 & f_2) and their harmonics (Fig.4).

For hearing aids, normally second order ($f_2 - f_1$) and third order ($2 f_1 - f_2$) would be measured (Fig.5).

$f_2 - f_1$ was chosen to be 160 Hz, which means that when sweeping to measure the second order DF distortion, the filter of the analyzer is steadily tuned to 160 Hz. Some standards call for $f_2 - f_1$ equal to 80 Hz. This may in some cases be inconvenient as some hearing aids have a very low output capability at 80 Hz. It is therefore suggested that $f_2 - f_1$ be chosen such that the hearing aid has a reasonable output at $f_2 - f_1$. When sweeping to measure the third order minus DF distortion at $(2 f_1 - f_2)$ Hz the analysis frequency of the filter is $(f_2 - f_1)$ Hz lower than the lower tone (f_1) of the test signal, meaning that the third order DF distortion is measurable throughout the pass-band of the hearing aid. Similarly when measuring third order plus $(2 f_2 - f_1)$, the filter of the analyzer is tuned just $(f_2 - f_1)$ Hz higher than the upper tone (f_2) of the test signal.

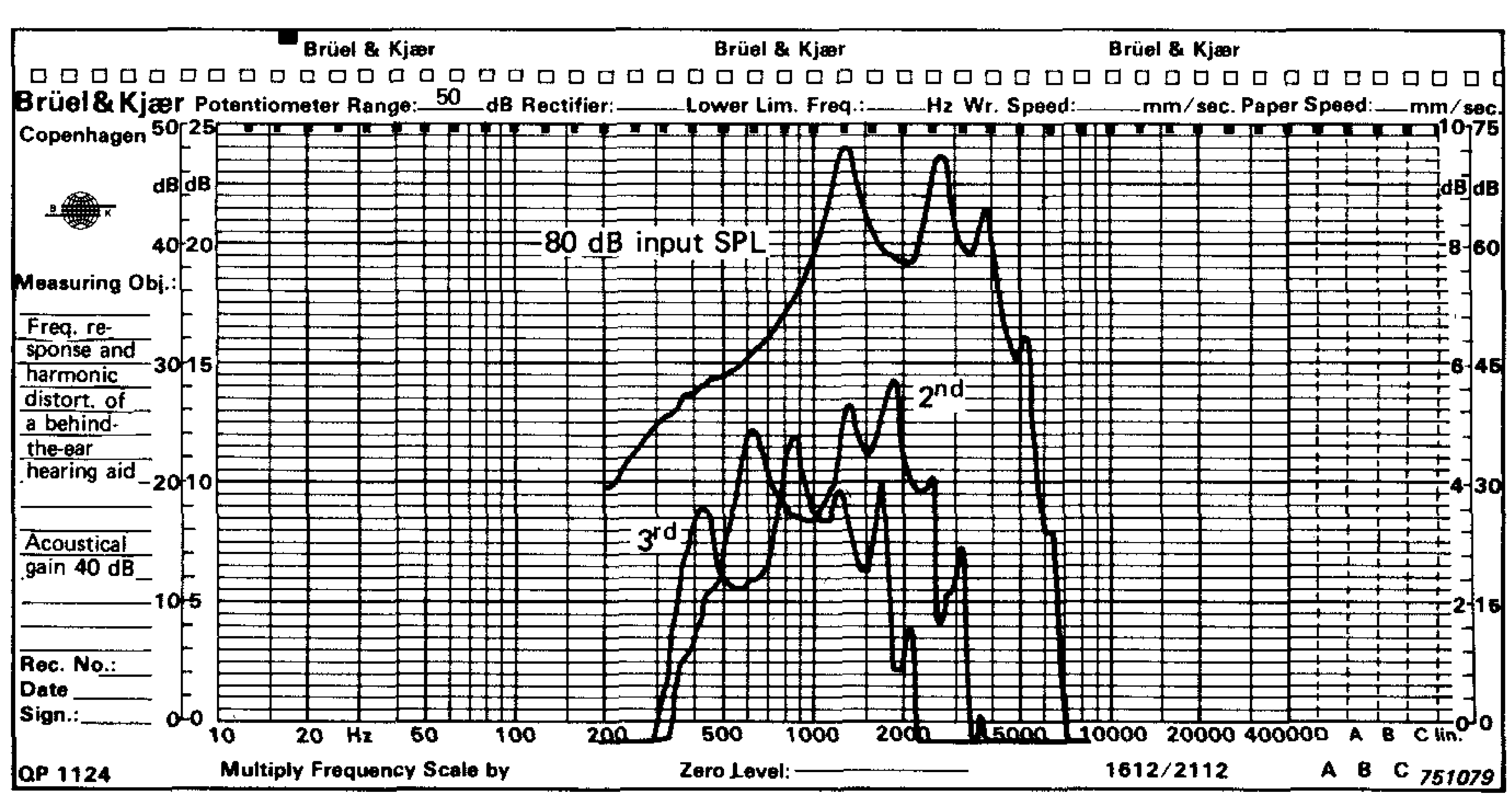


Fig.3. Frequency response and harmonic distortion of a hearing aid

Since the analysis frequency is very close to the test signal(s) when measuring third order DF distortion, a mandatory requirement is that the filter of the analyzer be very steep and have a narrow bandwidth. In other words, the filter must let through only the signal at the analysis frequency and cut-out the test signal(s). The filter should also have low distortion and a wide dynamic range.

Thus, for example, if $f_2 - f_1 = 80\,\text{Hz}$ and we want to measure third order distortion ($2f_1 - f_2$) down to 0,1% (—60 dB) we see from Fig.6 that the filter should have a bandwidth $B \leqslant 80/3{,}5 \sim 23\,\text{Hz}$ — a 10 Hz bandwidth would be appropriate.

Interpretation of DF Distortion Curves

Again, looking at Fig.5 we see that the third order distortion is quite significant and bears some resemblance to the frequency response curve. Specifically we see that the peaks in the frequency response curve also occur in the third order distortion curve offset by 320 Hz. This is due to the fact that $f_2 - f_1 = 160\,\text{Hz}$ and the analysis frequency $f_a = 2f_1 - f_2$. Solving for f_a we see that $f_a = f_2 - 320$, hence the frequency offset of the two curves. The peaks in the distortion curve may be attributed to the fact that at the peaks (high gain) in the frequency response, the "loop gain" will be lower because of saturation phenomena or too heavy drain on the power supply (battery). Symmetrical clipping of the signal will result in "odd order" distortion. The second order distortion ("even order") may e.g. be attributed to a rectification phenomenon. This could be the case if the hearing aid employs a compressor circuit or if an amplifier stage causes assymetrical clipping of the signal.

Intermodulation (IM) Distortion

IM distortion (Fig.1) is measured by exciting the test specimen with a twin-tone test signal f_1 and f_2. Keeping the amplitude of both signals constant, the amplitude of f_1 is 12 dB higher than the amplitude of f_2. f_1 is kept at a fixed low frequency, while f_2 is swept through the frequency range of interest. In a non-linear system the IM distortion

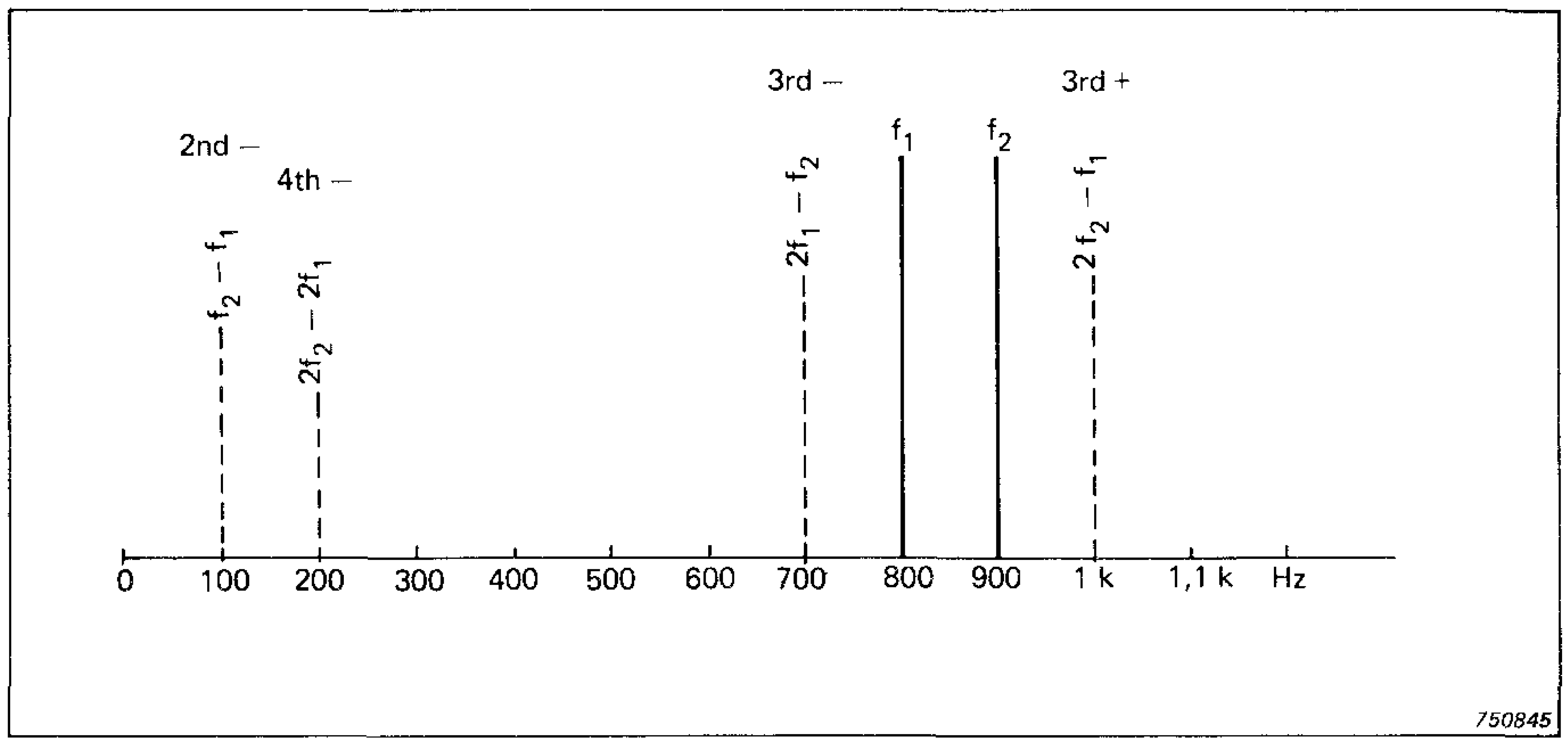


Fig.4. DF distortion of 800 and 900 Hz signals

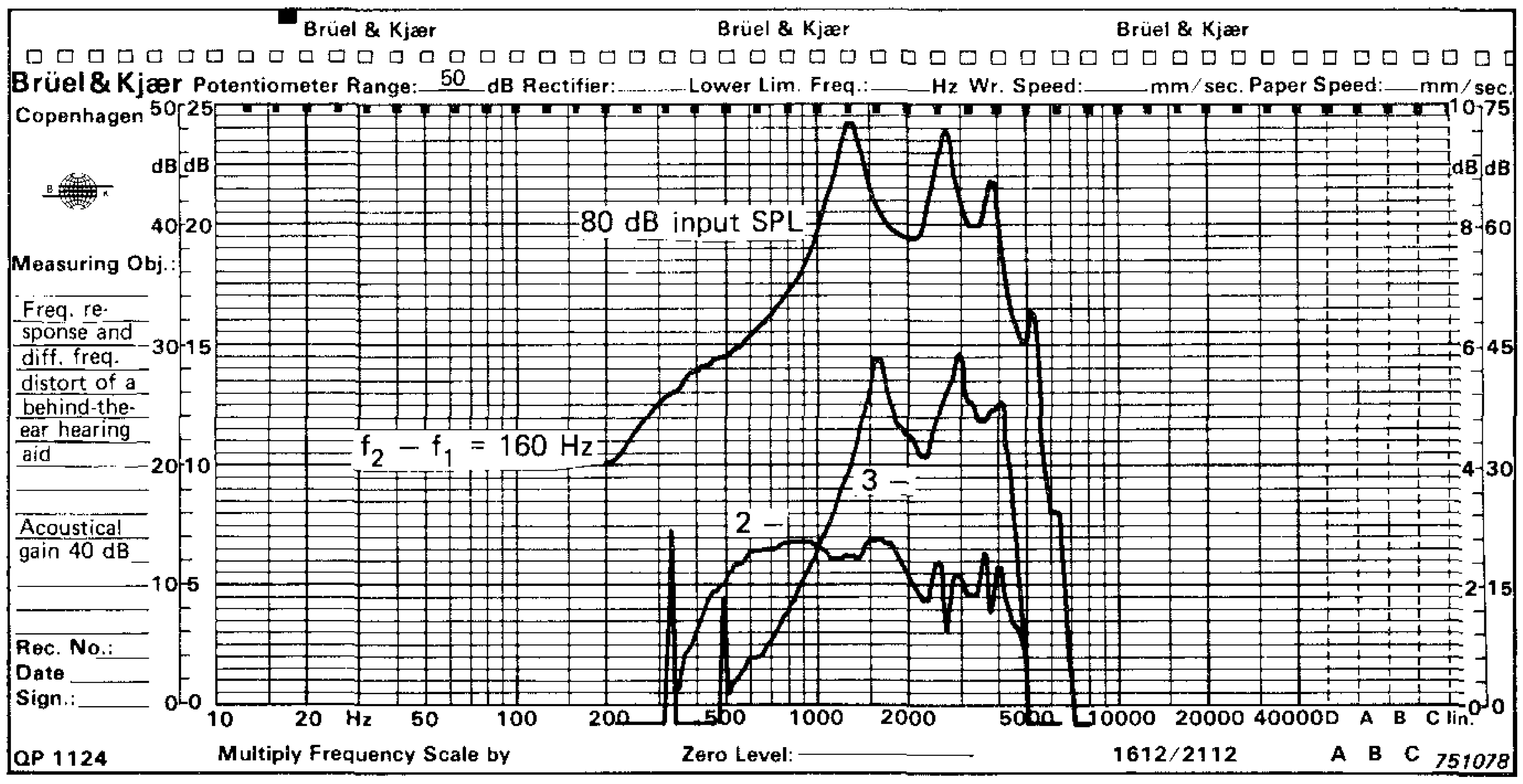


Fig.5. Frequency response and DF distortion of a hearing aid

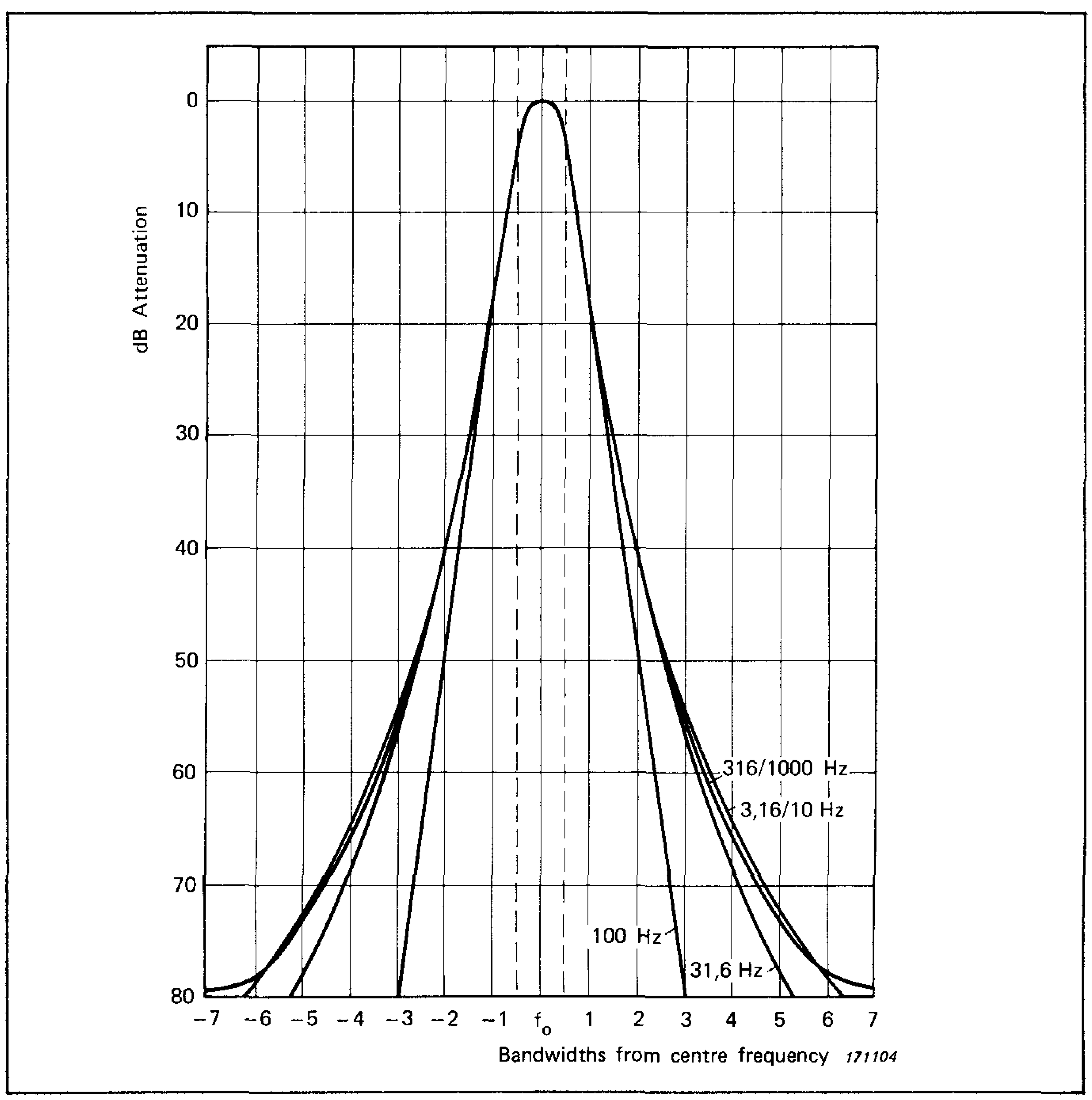


Fig.6. Typical filter characteristics of a Type 2010 Heterodyne Analyzer

shows up as a number of side bands located on both sides of f_2 — the distance between the side bands being equal to f_1.

Similarly to DF measurements, the filter of the analyzer should be very steep and have a narrow bandwidth, especially if f_1 is chosen such that the IM sidebands are very close to the upper test tone f_2.

An example of an IM distortion measurement is shown in Fig.7.

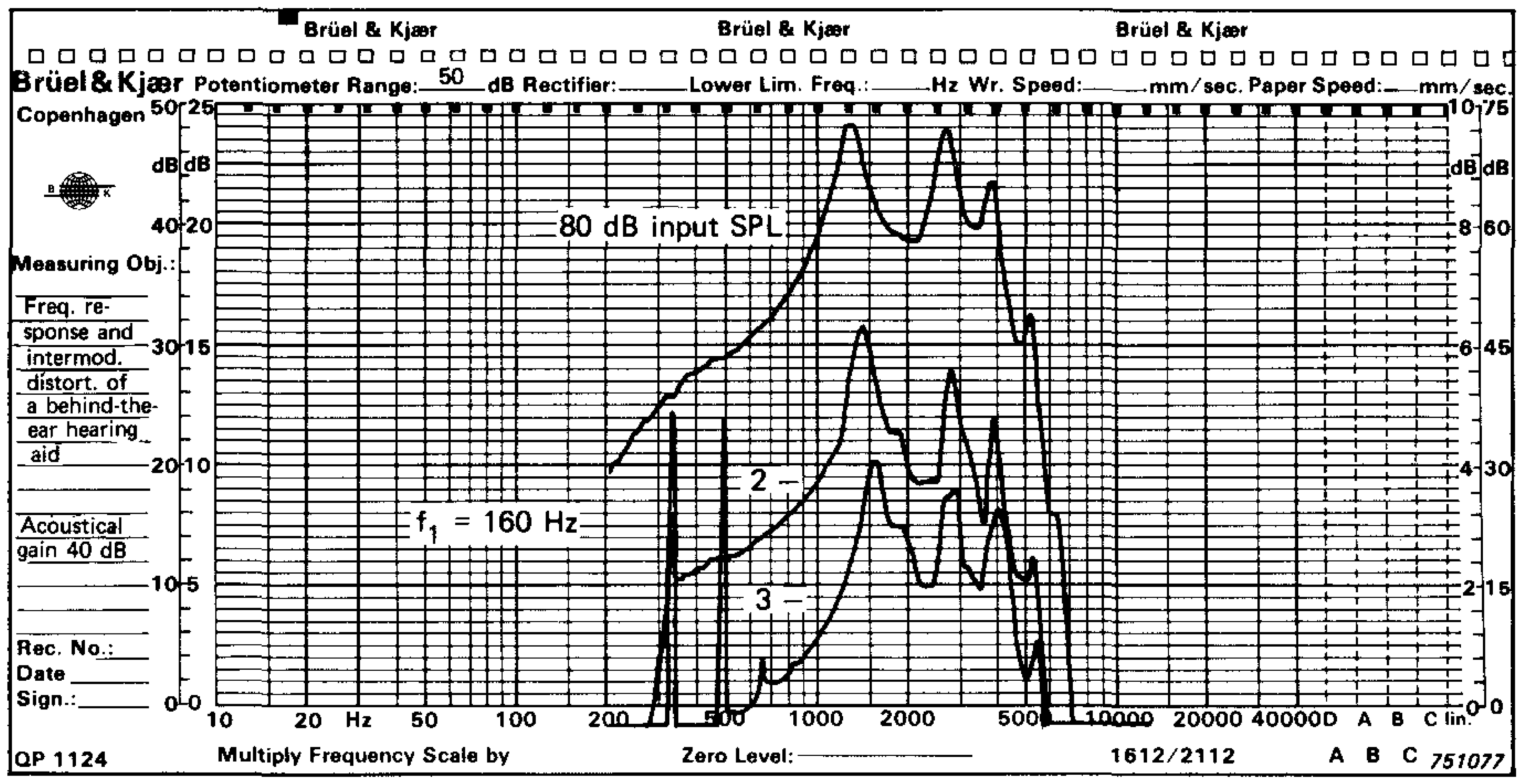


Fig.7. Frequency response and IM distortion of a hearing aid

System Description

With the advent of the 1902/2010 combination, a distortion measurement control unit and heterodyne analyzer, the user now has a unique tool for making swept harmonic, difference frequency (DF) and intermodulation (IM) distortion measurements accurately and conveniently on electroacoustic devices. The 1902/2010 combination automatically generates the necessary test signal(s) as well as tunes its filter to the desired distortion component, one through fifth order.

The 1902/2010 combination readily lends itself to harmonic distortion measurements of hearing aids, but things get slightly more complicated when it is desired to make difference frequency and intermodulation distortion measurements.

The problem is this: when making frequency response and distortion measurements the sound pressure level at the hearing aid should be kept constant throughout the frequency range of interest. IEC Recommendation No. 118 specifies that the sound source be kept at a constant level (± 2%) between 200 Hz and 5 kHz. For this purpose a compressor loop is often employed. In the case of harmonic distortion measurements this is straight forward and simple, but in the case of a twin-tone test signal such as used in IM and DF testing, special consideration has to be given to the compressor loop(s).

In the case of DF measurements, the two test signals f_1 and f_2 are normally close to each other in frequency (typically $f_2 - f_1 = 80$ Hz). When this twin-tone signal is fed into the sound source, e.g. the speaker of Hearing Aid Test Box, Type 4212, there will be some difference in amplitude between the two tones because the frequency response of the speaker is not completely flat.

Fig.8 shows the relative deviation between the two test tones when using one common compressor. It is seen that if $f_2 - f_1 = 80$ Hz, the difference in level is approximately 1 dB (300 — 10000 Hz) (Fig.8a). An instrument set-up utilizing one common compressor is described later. If the two test frequencies f_2 and f_1 are further apart, larger amplitude deviations will occur (Fig.8b-c). The roll-off at lower frequencies of f_1 can be attributed to the roll-off of the speaker.

If better amplitude accuracy is desired and the test signals f_2 and f_1 lie far apart, we have to use two separate, filtered compressor loops. This could be accomplished by using two separate tracking/slave filters. However, by using the B & K Type 2020 Heterodyne Slave Filter, only one filter is necessary. The concept is this:

The 2020 Slave Filter has two outputs: one is the regular bandpass output with the center frequency equal to the BFO frequency and the other a rejection output passing all frequencies except the BFO frequency. f_2 is the BFO frequency and we can thus separate the two signals by taking f_2 out of the bandpass output and f_1 out of the rejection output and feeding them into two separate compressors.

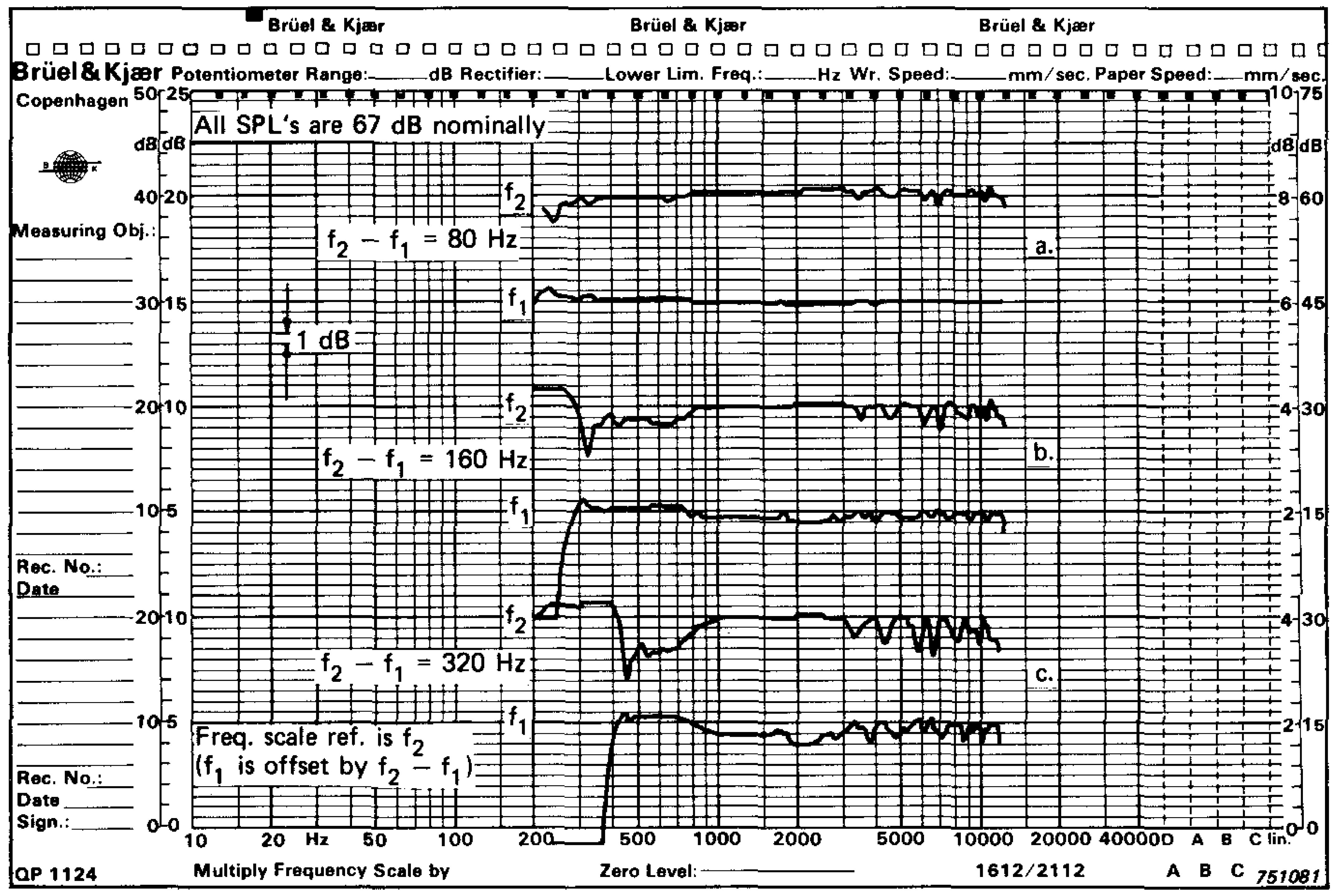


Fig.8. Amplitude deviation between f_1 and f_2 when using common compressor in conjunction with Hearing Aid Test Box, Type 4212

System for Measurement of Harmonic, Difference Frequency, Intermodulation Distortion with dual Compressor Loop

The system described here is particularly suited for twin-tone measurements where good amplitude stability of both test signals is required and where the frequency difference between f_1 and f_2 is large. The system is shown in Fig.9.

The two test signals f_1 and f_2, although both normally available at the output of 1902, are in this case derived separately from the outputs of 1902 (f_1) and 2010 (f_2).

The compressor microphone hooked up to a measuring amplifier (2608) receives the twin-tone test signal and feeds it into a heterodyne slave filter (2020). The slave filter is tuned to the BFO frequency (f_2) of the 2010 Heterodyne Analyzer and at the socket "Output" on 2020 we have f_2 available while "Rejection Output" gives us f_1. The twin-tone signal is thus split up for two separate compressor loops. f_2 is via a Measuring Amplifier (2608) fed into the "Compressor Input" of the Heterodyne Analyzer (2010). The 2608 serves as a signal conditioner and readout for the level of f_2.

f_1, originating from the generator section of 1902, utilizes the compressor circuitry of a 1405 Random Noise Generator. f_1 is from the "Rejection Output" of 2020 fed into a Measuring Amplifier 2608 serving as a signal conditioner and readout of the level of f_1. From 2608 the signal is fed into the "Ext. Gen. Input" of 1405 which is operated in the compressor mode.*

* For 1405 Noise Generators with serial nos. pre 571512, a minor modification reducing compressor distortion is recommended; consult factory.

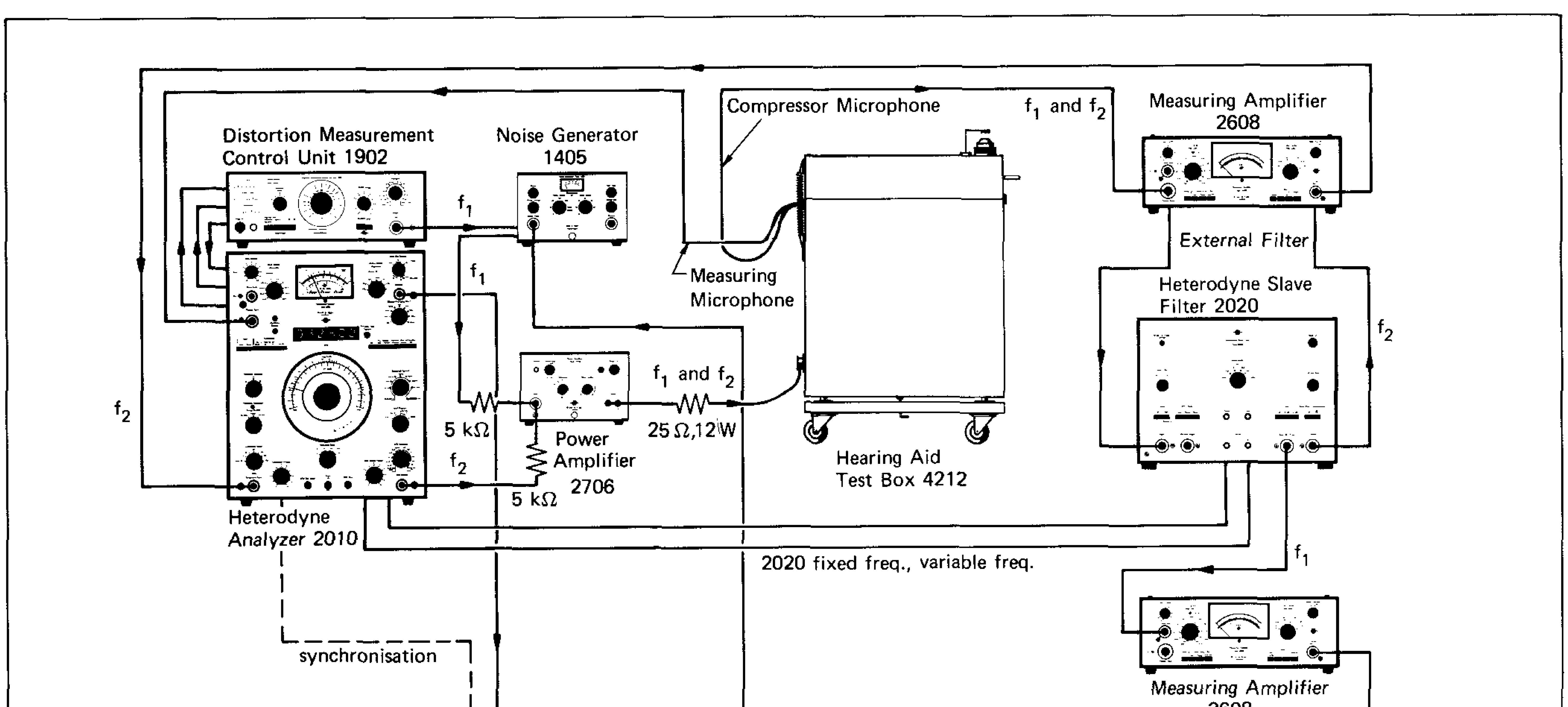


Fig.9. Set-up for diff. freq., harm. and IM distortion measurements with dual compressor loop

We have now formed two separate compressor loops. The two signals from the generator outputs of 1405 and 2010, f_1 and f_2, are "summed" in two 5 kΩ resistors at the input of the Power Amplifier (2706), which drives the speaker of the Hearing Aid Test Box 4212.*

The hearing aid parameters to be established are measured by means of the Microphone/Artificial Ear of 4212, the measuring amplifier and heterodyne filter of 2010 in conjunction with Distortion Measurement Control Unit 1902. A 2305 or 2307 Graphic Level Recorder serves as a read-out of test results. The artificial ear filter switch on the 4212 Hearing Aid Test Box should be in the "Off" position. This is important when measuring second order DF distortion, because the high pass filter cuts-off below 150 Hz. A summary of typical knob settings for a difference frequency test ($f_2 - f_1$ = 80 Hz) is given in Fig.10.

System for Measurement of Harmonic, Difference Frequency, Intermodulation Distortion with single Compressor Loop

If it is desired to make DF distortion measurements with a small interval between f_2 and f_1, say around 100 Hz or less, and small deviations between the sound pressure levels of f_1 and f_2 can be accepted, the system shown in Fig.11 will suffice. The twin-tone signal from the Type 1902 Distortion Measurement Control Unit is fed into the compressor of the Type 1405 Noise Generator. It is recommended to keep the generator signal at 1 V or below. From the regulator microphone of the Hearing Aid Test Box, the feedback signal is fed into the compressor via a 2608 Measuring Amplifier serving as a signal conditioner and read-out of the sound pressure level of f_2.

With the system in the same configuration, it may also be used for harmonic distortion testing. By adding a high-pass or notch filter to the 2608 Measuring Amplifier and rerouting the cables as shown with the dotted lines, the system is ready for IM testing. As the tone f_1 has a fixed frequency and amplitude which is 12 dB higher than f_2, it is necessary to filter out f_1 to be able to compress f_2. A high-pass or notch filter such as found in Frequency Analyzers 2120/2121 will suffice, but any other good 4-pole high-pass or notch filter, passive or active, which rejects f_1 by minimum 22 dB, will do.

System for Measurement of Harmonic and Intermodulation Distortion

By eliminating the compressor (Type 1405) from the scheme described in Fig.11 the system will perform harmonic and intermodulation distortion measurements. This system is shown in Fig.12. The high-pass or notch filter used for IM testing is similar to the one shown in Fig.11. Note that the Power Amplifier Type 2706 has been omitted:

The generator outputs of 1902 and 2010 have some power capability — enough to drive 4212's speaker at low-to-moderate sound pressure levels (50 — 70 dB SPL). Using the speaker (no current limiting resistor to be used) as a "floating" load, it is simply connected directly between the two center posts (hot leads) of the generator outputs. The two "grounds" of the generator outputs should be connected together. The two generators have a current drive capability of 70 mA, so voltage levels above approx. 0,4 V into the speaker (6 Ω) should be avoided to keep the distortion of the test signal low (the outputs are protected against excessive currents). If higher sound pressure levels, up to approx. 90 dB are required, the power amplifier scheme outlined in Fig.9 and Fig.11 should be used.

2608 (I)
Filters: **Ext.**
Meter Function: **Fast**
All other knobs: **As required**

2020
Input filter: **In**
Output: **0°**
BFO Mode: **Sine**
Bandwidth: **31.6**
Gain: **0 dB**
Bandwidth Compensation: **Off**

2608 (II)
Filters: **Linear, 2 – 200000**
Meter Function: **Fast**
All other knobs: **As required**

2010
Read Out Selector: **DC Lin**
Effective Averaging Time T: **0.1 sec.**
Selectivity Control: **10 Hz**
B&T program: **Manual**
BFO Attenuator: **1V**
BFO Output Voltage: **7**
Frequency Scale: **x 1 Log**
Compressor Speed: **100**
All other knobs: **As required**

1902
(Mode Selector): **Difference – frequency**
Distortion Order: **As required**
Difference – frequency: **80 Hz or as required**
Generator Stop: **f_2(in)**
Output Voltage: **Fully clockwise**
Attenuator: **1V**

1405
Compr. Voltage: **As required**
Compr. Speed: **30**
(Mode Selector): **Compr. only**
Output: **n/a**

2706
Current Limit: **1.8 A RMS**
Attenuator: **10**
Gain Control: **Fully clockwise**

2307
Potentiometer Range: **50**
Rectifier Response: **DC**
Lower Limiting Frequency: **200**
Writing Speed: **250 mm/sec**
Paper Speed: **1 mm/sec**
All other knobs: **As required**

4212
Art. Ear Filter: **Off**
Attenuator for speaker: **H**

760124

Fig.10. Typical knob settings for a difference frequency distortion measurement

* A word of caution here: since the speaker in 4212 is rated at max. 4 V-RMS and 2706 is capable of delivering 15 V-RMS in 3 Ω, it is strongly recommended to insert a minimum 25 Ω/12 W resistor in series with the speaker leads to prevent speaker burn-out. When doing a sweep it is also recommended to turn down the "Gain Control" of 2706 while the BFO is at low frequencies, say below 100 Hz, to avoid excessive excursions of the speaker diaphragm.

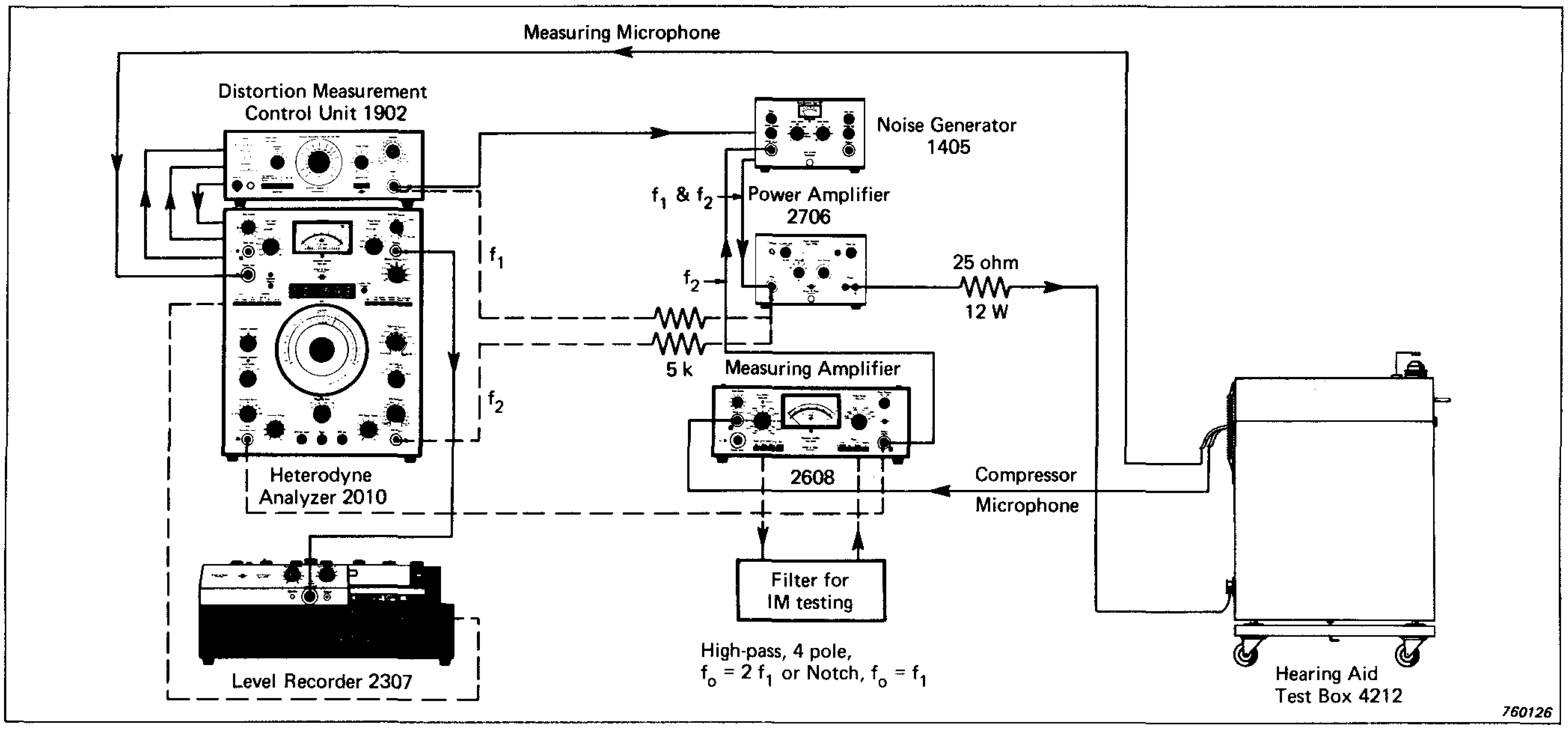


Fig.11. Set-up for diff. freq., harm. and intermod. distortion measurements with single compressor loop

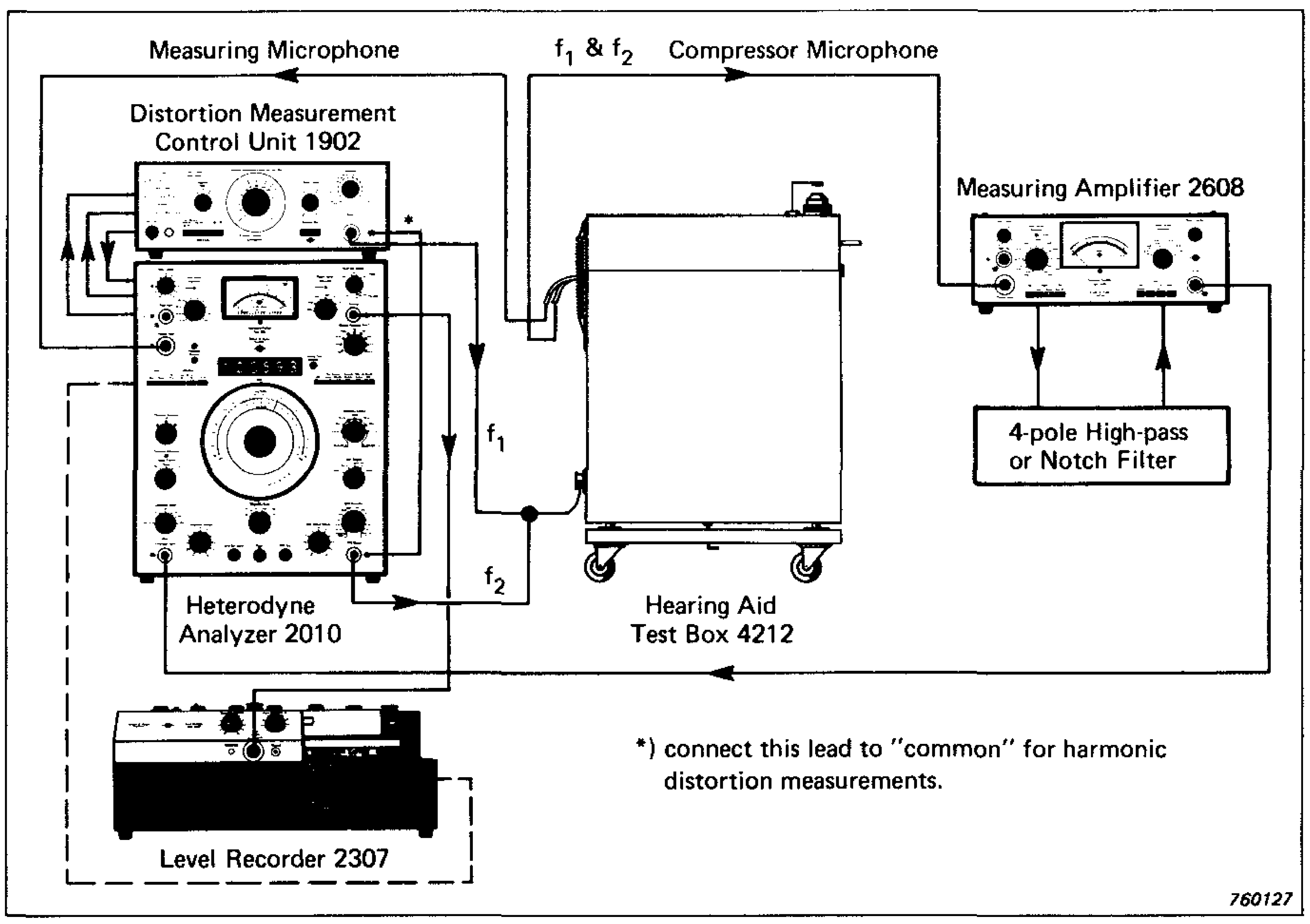


Fig.12. Set-up for IM and harm. distortion measurements

Distortion Measurements on Individual Parts of Hearing Aids

While the previously discussed set-ups were mainly for establishing the overall performance of the hearing aid under assumed, well defined working conditions, it is a simple affair also to use the 1902/2010 combination for measuring frequency response and distortion levels for individual parts of the hearing aid.

A general set-up is shown in Fig.13.

This type of measurement is valuable when it is desired, for design purposes, to relate distortion and frequency response to individual parts of the hearing aid. Amplifier and compressor circuits are typical examples of this. Also, utilizing an artificial ear, measurements on the ear-phone alone can be performed.

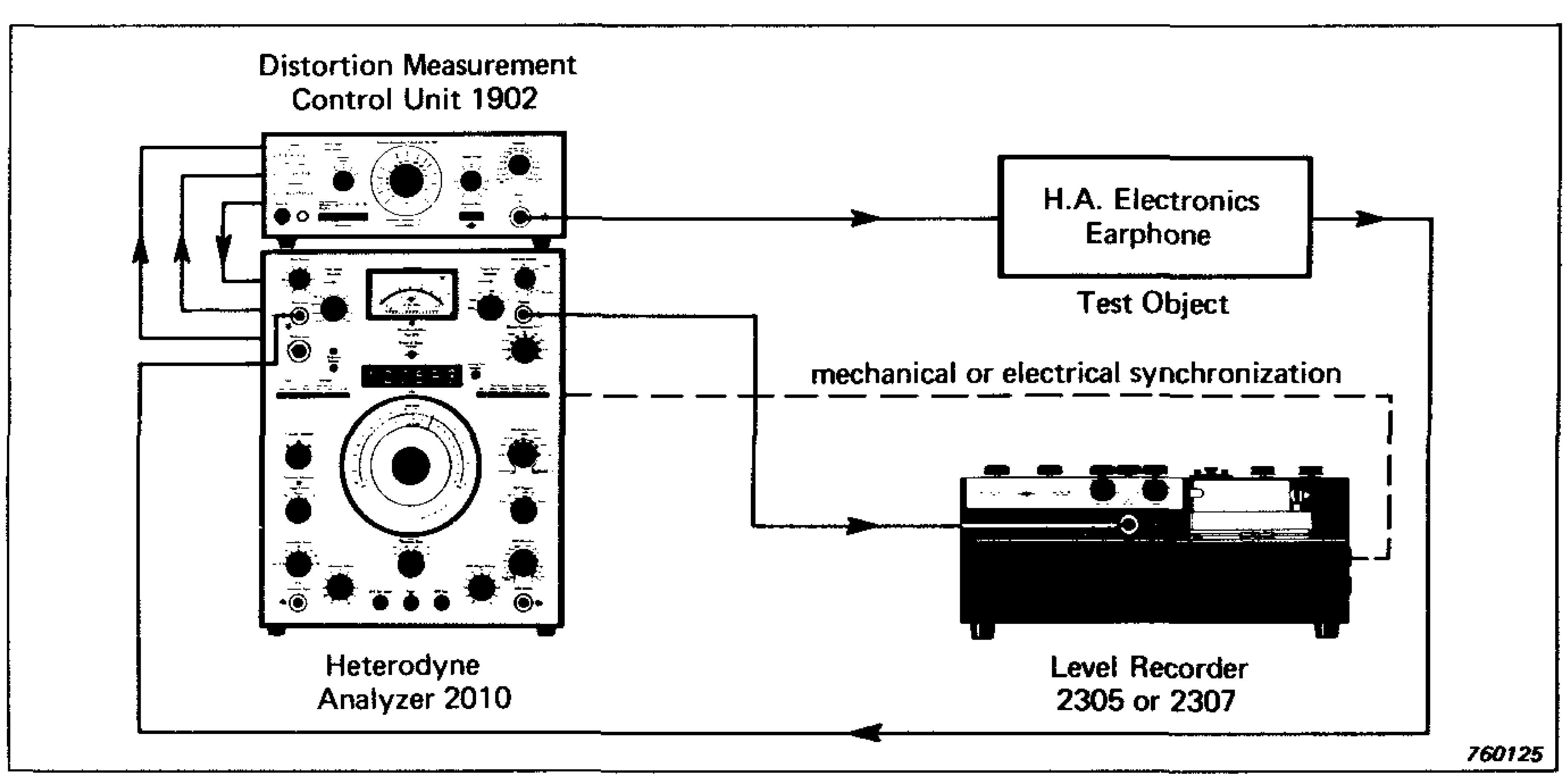


Fig.13. General set-up for measurement of individual parts of hearing aids

Performance of the Measurement System

To establish the overall performance of the system, we let the system analyze itself. The two main goals were:

1. Establishing accuracy of compressor regulated sound pressure level when using a) a single-tone test signal (harm. distortion) and b) a twin-tone signal (IM and DF distortion) with single or dual compressor loop(s).

2. Establishing the level of harmonic, difference frequency and intermodulation distortion of the system itself.

Compressor Loop(s)

Using the system outlined in Fig.9, and looking at Fig.14a to c, we see that in all cases the sound pressure level is kept constant to within a fraction of a dB throughout the frequency range of interest (200 Hz to 5 kHz). In graph 14b the combined sound level of f_1 and f_2 was recorded. Graph 14c shows the sound level of f_2 only — f_1 remains at a fixed amplitude and frequency anyway.

The bandwidth of the 2020 Slave Filter was set at B = 31,6 Hz. This was found to yield the best compromise between compressor loop stability and compressor loop frequency selectivity.

When using the single compressor loop system for DF measurements as outlined in Fig.11, refer to Fig.8 and section System Description, where the merits of this method are discussed.

Residual Distortion of the Measurement System

While most of the distortion in the system no doubt can be attributed to the speaker in 4212 and the compressor (1405), it was found that the system's distortion was generally well below 0,3% at any distortion component in the frequency range of interest (200 Hz to 5 kHz). Generally, hearing aids exhibit distortion figures considerably higher than this. Figures 14a and 14c show second and third order

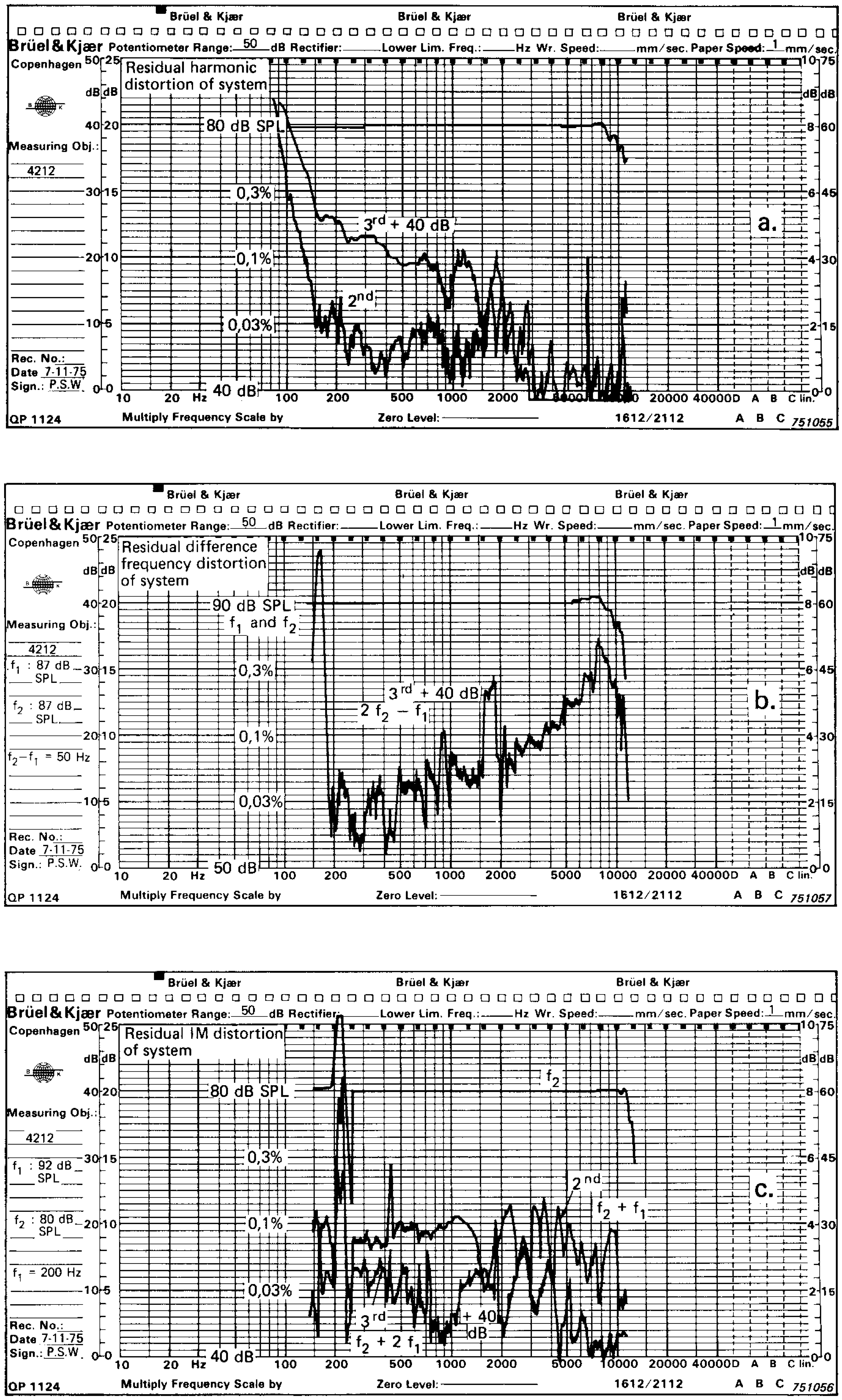


Fig.14. Performance curves of hearing aid test system for harm., diff. freq. and IM distortion

harmonic and IM distortion curves. Fig.14b shows only third order difference frequency distortion — the second order component was too low to be measured, because it approached the level of the ambient noise.

Conclusion

The 1902/2010 combination, Distortion Measurement Control Unit and Heterodyne Analyzer already covering a wide range of applications in the electro-acoustic field by providing convenient, accurate swept measurements of harmonic, difference frequency and intermodulation distortion components can also be used to measure these parameters on hearing aids. The use of frequency selective compressor loops ensure a uniform sound pressure level throughout the frequency range of interest when making twin-tone tests. When making DF measurements with single compressor loop and $f_2 - f_1$ equal to approximately 100 Hz or less, the relatively flat response of the speaker of the 4212 Hearing Aid Test Box ensures that only a small level difference between f_1 and f_2 will occur.

The system itself has low residual distortion and is able to detect distortion components, second through fifth order, down to a fraction of one percent.

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