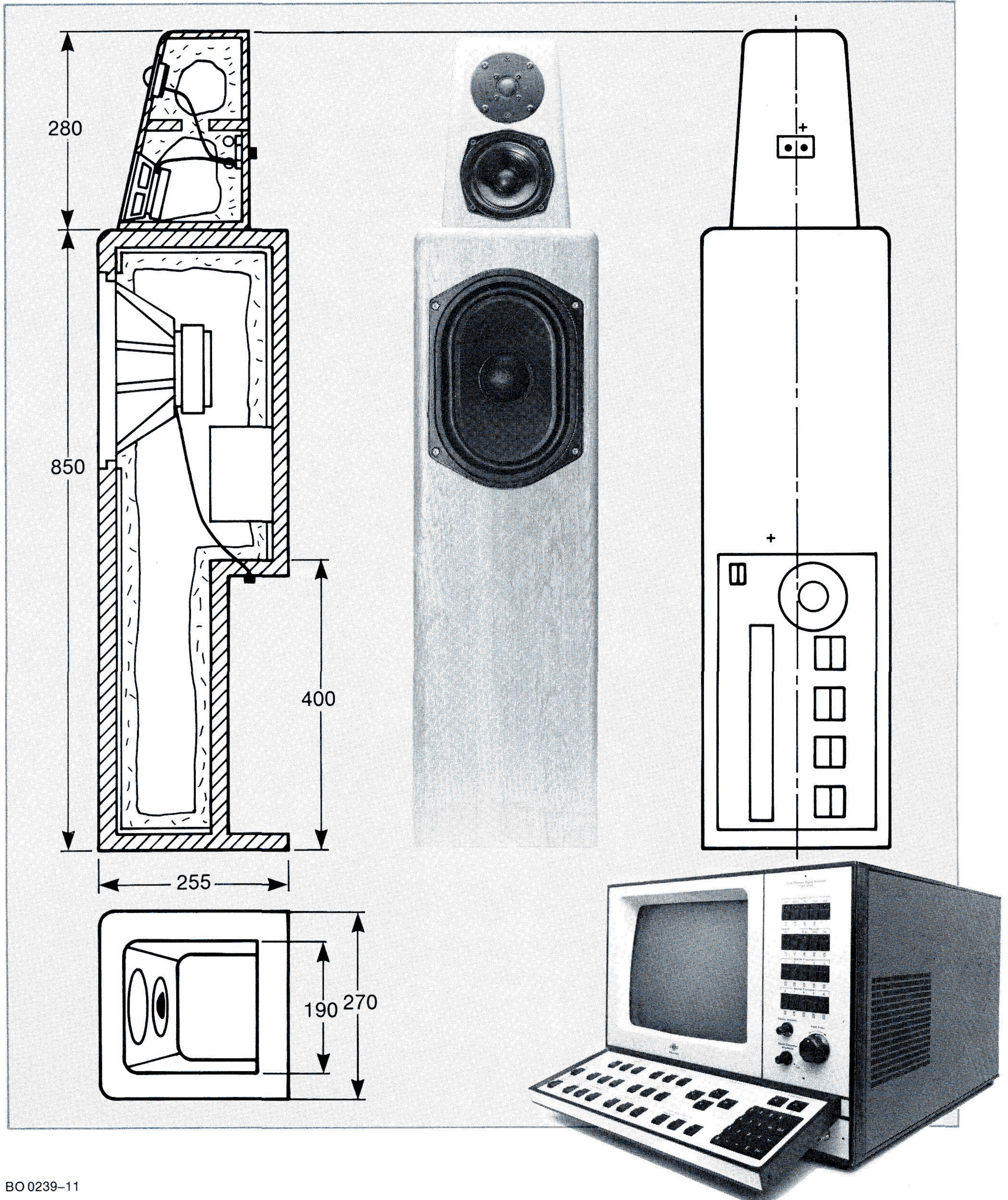




HiFi Loudspeaker R&D using a Dual Channel FFT Analyzer



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Introduction

The “black art” of conceiving, developing and manufacturing the “ultimate” loudspeaker is certainly very fascinating. No amount of advanced research into the realms of psychoacoustics, acoustics and electroacoustics can seem to satisfactorily produce the perfect correlation between what “sounds” good and what “measures” well.

The parameters which we have adopted as our performance-measures over the years may still be proven to be inappropriate, but until the day when we have irrefutable evidence saying we’ve been barking up the wrong tree, the loudspeaker R&D community is going to have to settle with the traditional yardsticks, i.e. frequency- phase-, impulse-responses, distortion etc.

Every loudspeaker engineer appreciates the worth of an instrument which is simple to use and can make fast and accurate measurements throughout a design project. In this application note we will examine through a case study the important role played by a Brüel & Kjær Dual Channel Analyzer Type 2034 in the development of a pair of high quality loudspeakers.

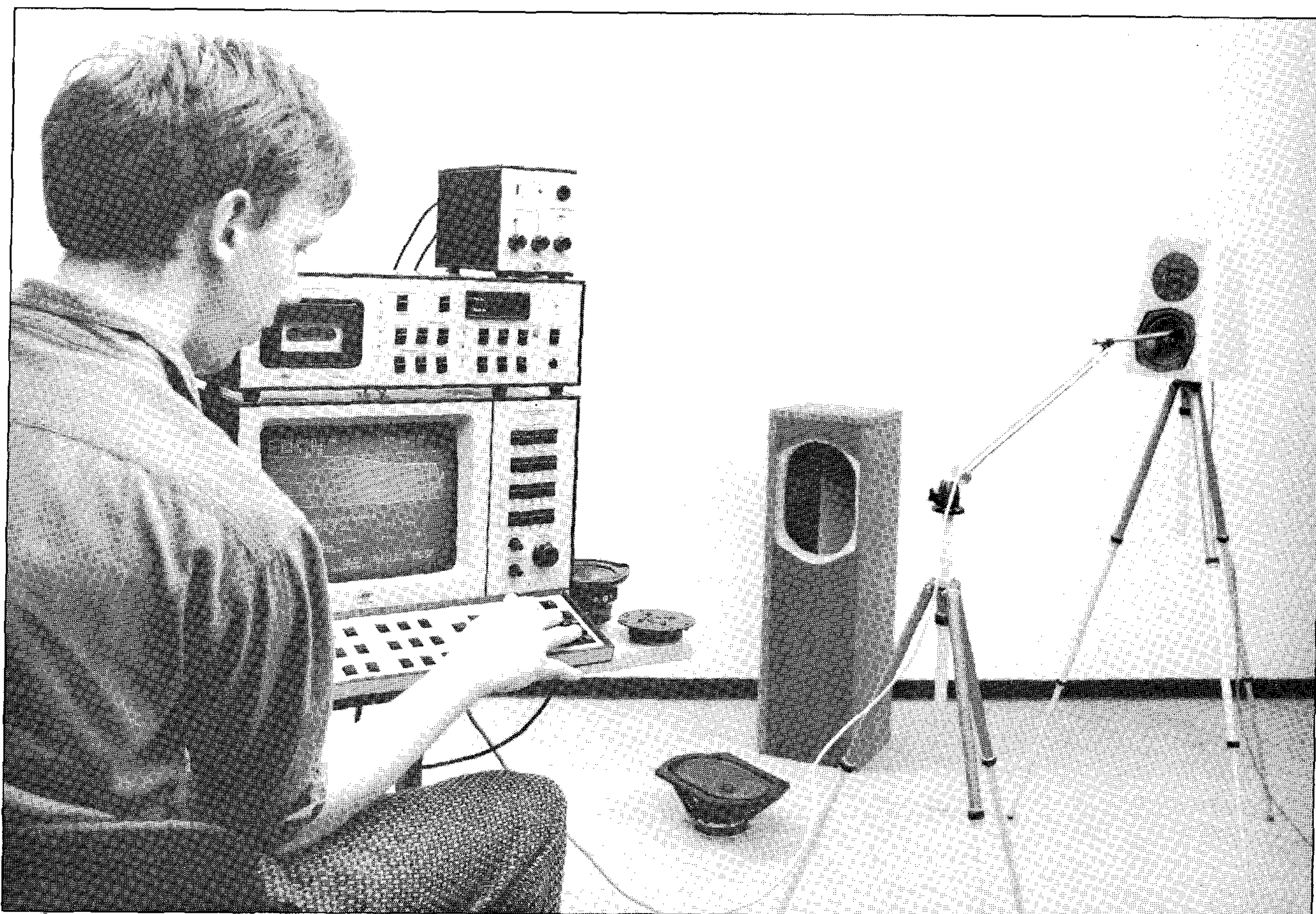


Fig. 1. Fast, accurate and reliable measurements really do make the design of hi-fi loudspeakers simpler

Today's measurement technology

Advances in integrated electronics have brought high speed, highly complex computational equipment down in price and size. Consequently, digital instrumentation is readily available and affordable. Dedicated FFT signal analyzers use such technology to help the engineer tackle research and development problems in his day-to-day activities.

The traditional approach

The laboratory of most loudspeaker companies is often well equipped with facilities for measuring the frequency response of loudspeakers and loudspeaker drive-units. Swept sine and/or $1/3$ octave band measurements would normally be made in the design stages of a new product or in the post-production quality control stages.

Common pieces of equipment would probably include a signal generator, power amplifier, measuring microphone and preamplifier, filter set, and chart recorder. Coupled with the requirement for an anechoic chamber or/and reverberant room, the cost of such a set-up to perform the most basic measurements is considerable.

A Dual Channel Signal Analyzer can almost replace this entire set-up at reduced costs. In addition simpler and faster operation is offered and many more different measurements are possible. Too good to be true? This case story aims to illustrate these claims.

The project

The aim of the project was to design, construct and evaluate a pair of hi-fi loudspeakers (see Fig. 3) with the following design features:

- A closed-box satellite and subwoofer in each channel.
- A passive 24dB/octave crossover in each satellite to divide the signal between the tweeter and the midrange.
- An active crossover network between the subwoofer and the satellite unit.
- An active bass-equalization network to compensate for the roll-off characteristic of the subwoofer to extend the bass response.
- Built-in power amplifiers.



Fig. 2. Loudspeakers are big business — but smaller companies can also benefit from FFT-technology (photograph courtesy of Electroacoustic Industries Limited (ELAC), England)

Measuring the drive-units

The drive-units used were manufactured by Electroacoustic Industries Ltd. (ELAC) of England and were all conventional moving-coil units; the tweeter was a one-inch soft dome type, the midrange had a five-and-a-half inch bextrene diaphragm similar to the popular KEF B 110 driver, and the bass-unit had a solid-polystyrene diaphragm type of a "race-track" shape.

The first step to take was to measure the acoustic response of each drive-unit to check for matching between left and right, and also to find the best crossover frequencies.

The actual measurement of the frequency response of the drive-units was simple to make. For the woofer a near-field measurement was made by using a pseudorandom noise, with the microphone placed very close to the diaphragm and with the drive-unit

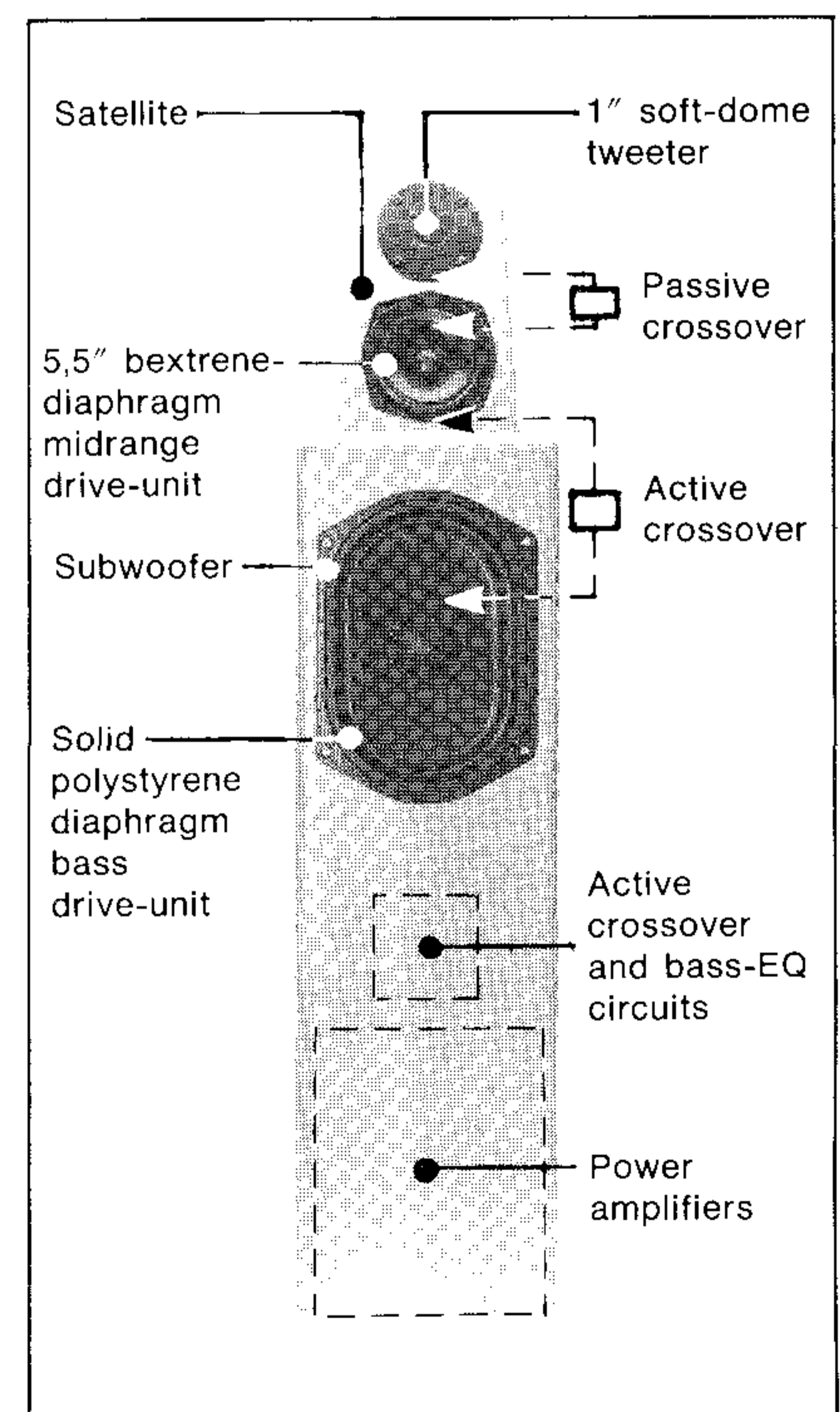


Fig. 3. The satellite and subwoofer loudspeaker — the aim of the project

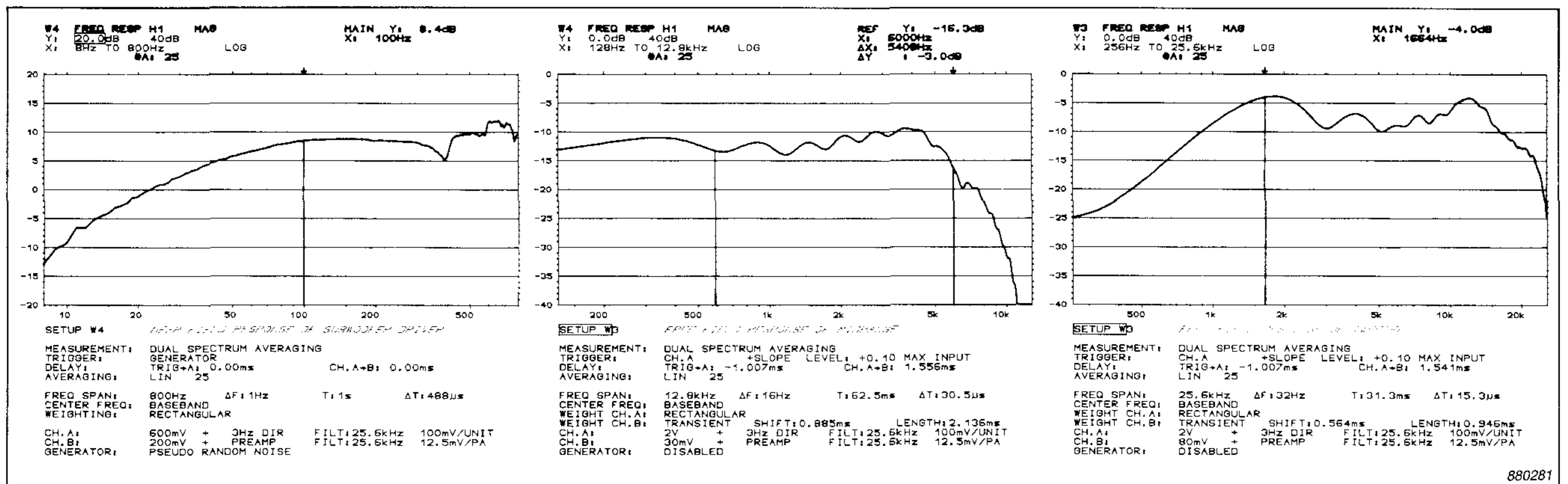


Fig. 4 The near-field frequency response of the woofer measured using pseudo-random noise. Also shown are the far-field frequency responses of the midrange and the tweeter measured using impulses

mounted on the end of a tripod. The measurement — made in an ordinary room — is shown in Fig. 4. The Brüel & Kjær Dual Channel Analyzer Type 2034 supplied the power for the microphone and also a pseudo-random test signal which was fed via a power amplifier to the drive-unit. The 2034 was able to compute and display the frequency response function in a matter of seconds and store the result on digital cassette tape for future reference. A comparison of two drive-units was instantly available at the press of a button by using the *equalized* facility of the 2034. Hard copy colour plots were available at the press of a button using the Graphics Plotter Type 2319.

By mounting the midrange and tweeter units on a baffle and using an impulse train as excitation it was possible to measure the far-field response of these drive-units (see Fig. 4). Once again, the measurement was made in a matter of seconds and provided good, easy to interpret information.

Examination of the measurements showed that the midrange unit and tweeter could be crossed over at 3.5 kHz using a 24 dB/octave (fourth order) passive filter. The subwoofer and midrange unit could be crossed over actively at 100 Hz. 100 Hz was chosen here because when the midrange unit was mounted in its small five litre cabinet its half-power point was actually 100 Hz; additionally, the subwoofers could be stood away from the satellites in the corners of the room to give a 9 dB bass boost from the $\pi/8$ radiation pattern found there.

The high-pass roll-off characteristic of the midrange unit could be made up of its acoustical roll-off in its sealed box (12 dB/octave) and a 12 dB/octave assistance from the filter combining to give 24 dB/octave.

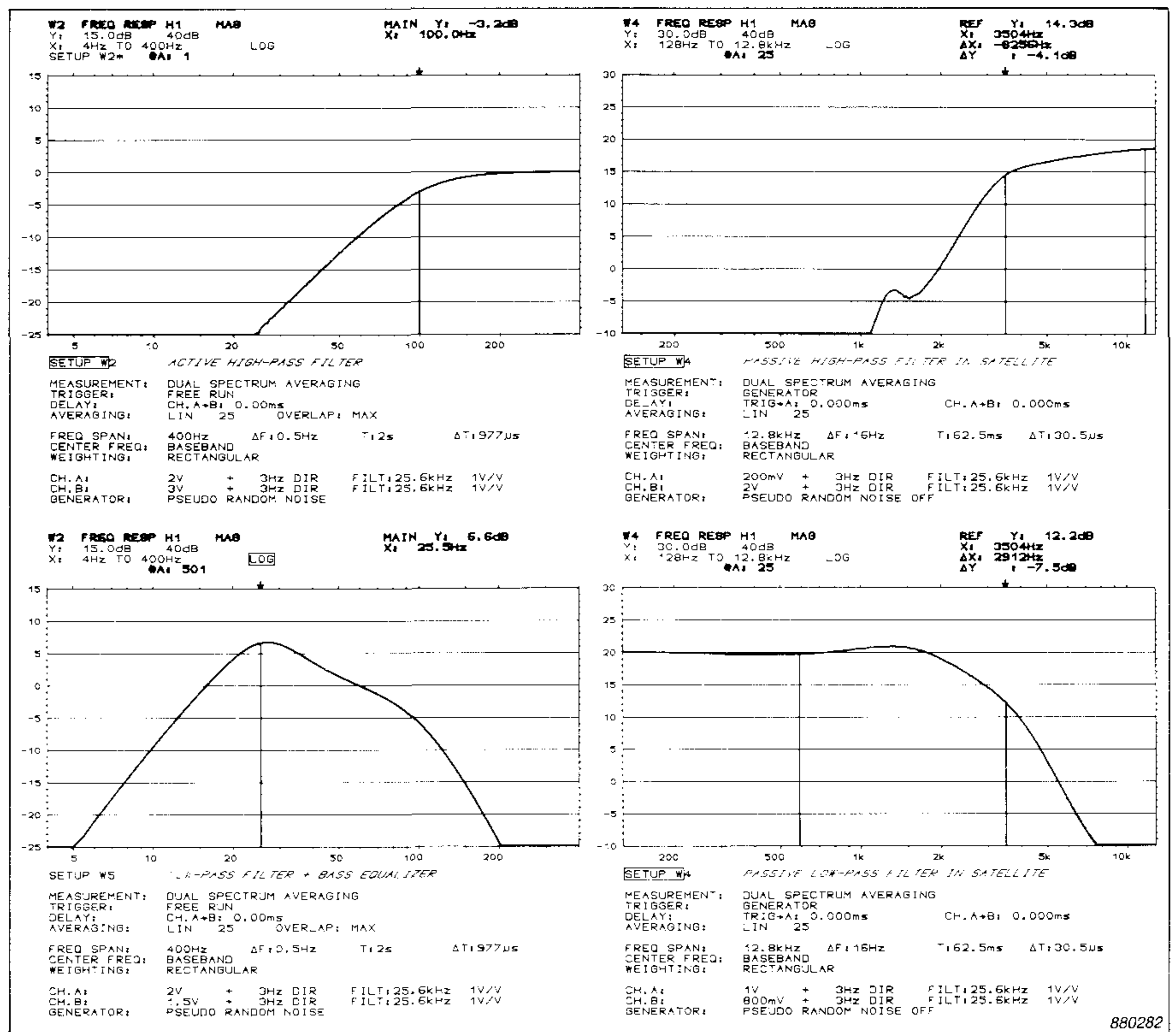


Fig. 5. The transfer functions of the active filters and the passive filters).

The subwoofer is rolled off above the crossover frequency at 24 dB/octave electrically. The low-frequency roll-off was a special case and will be discussed separately later.

Crossover testing

The design of the passive and active crossovers was a straightforward affair once the crossover frequencies and roll-offs were known. The verification of the crossover performance was extremely simple. The 2034 was used to generate a random noise signal which was fed directly to the crossover input and channel A of the 2034. The output of the crossover was fed to channel B

of the analyzer and the transfer function found immediately (see Fig. 5). The sheer simplicity of the testing procedure cannot be emphasized enough.

In addition, at a press of a button it was possible to see the *phase* response, and *impulse* response of the crossover *without* needing a new measurement.

As is typical in practical projects like this, things rarely work first time or as theory would predict. This was certainly true of the passive networks which were designed on the assumption of a perfectly resistive load on the outputs of the filters. Loudspeakers, however, offer a reac-

tive load due to their inductive nature. The 2034 was used to plot the reactive response of the drive-units by measuring the variation of the voltage across the drive-units terminals when a fixed resistance was placed in series with the drive-unit. An extra network — a zobel network — having the inverse characteristic of the driver impedance response was added to the crossover to cancel out the impedance variation of the drive-unit, thus improving its performance. The impedance curves before and after the addition of the zobel are shown in Fig. 6.

The role of the 2034 in troubleshooting more unpredictable faults will be examined later.

Cabinet design

Any cabinet vibration at all is a bad thing, adding sound colouration and blurring of the stereo image. In addition, certain cabinet geometries can give diffraction problems at any edge and certain edge-length ratios can help standing waves to set up inside the cabinet. The cabinets were designed with these factors in mind, and featured the following:

- The insides of the subwoofer cabinet were lined with ceramic tiles and fixed with a special cement to add mass and damping to eliminate troublesome resonances. The satellite cabinet was internally braced and made as small as possible to improve stereo imagery while still offering sufficient "acoustic suspension" to allow for a 100 Hz crossover. To minimize diffraction effects all edges were curved and the cabinet fronts were made as narrow as possible.

- The Thiele-Small parameters of the subwoofer and midrange drivers were calculated from the impedance curves and the manufacturer's specifications for the drive-units. This was all very easy to do on the 2034. Knowing these parameters it was possible to predict the cut-off frequencies of the drive-units when placed in their sealed cabinets. In addition, the effect on the Q of the subwoofer of adding or removing damping material from inside the cabinet could be seen quickly and directly from the impedance curve of the subwoofer. See Fig. 7.

Objectively assessing just how good a cabinet is is not easy. However, the 2034 provided a possible solution by measuring the transfer function be-

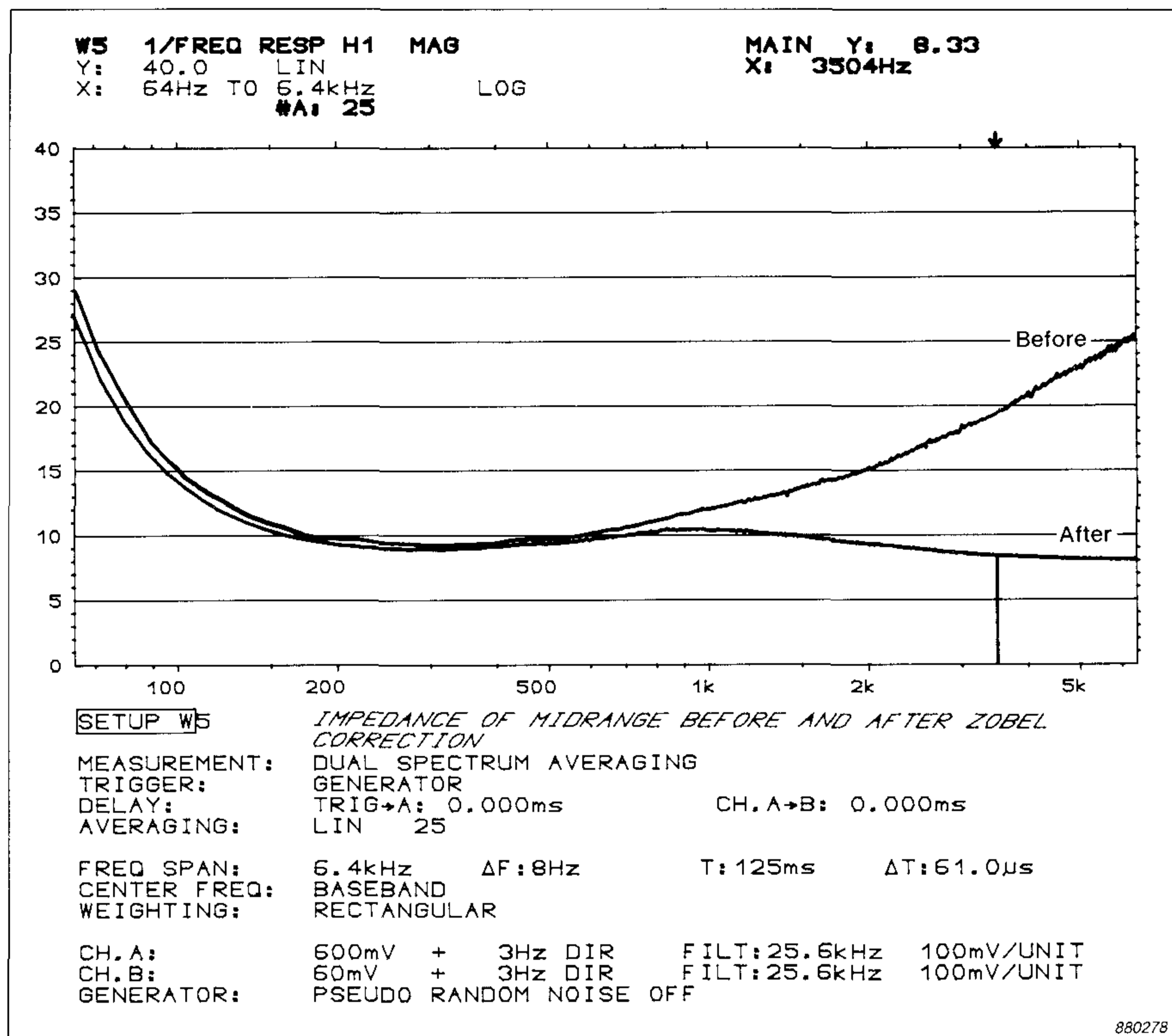


Fig. 6. The electrical impedance curve of the midrange unit before the addition of the zobel correction network. Superimposed is the impedance after correction

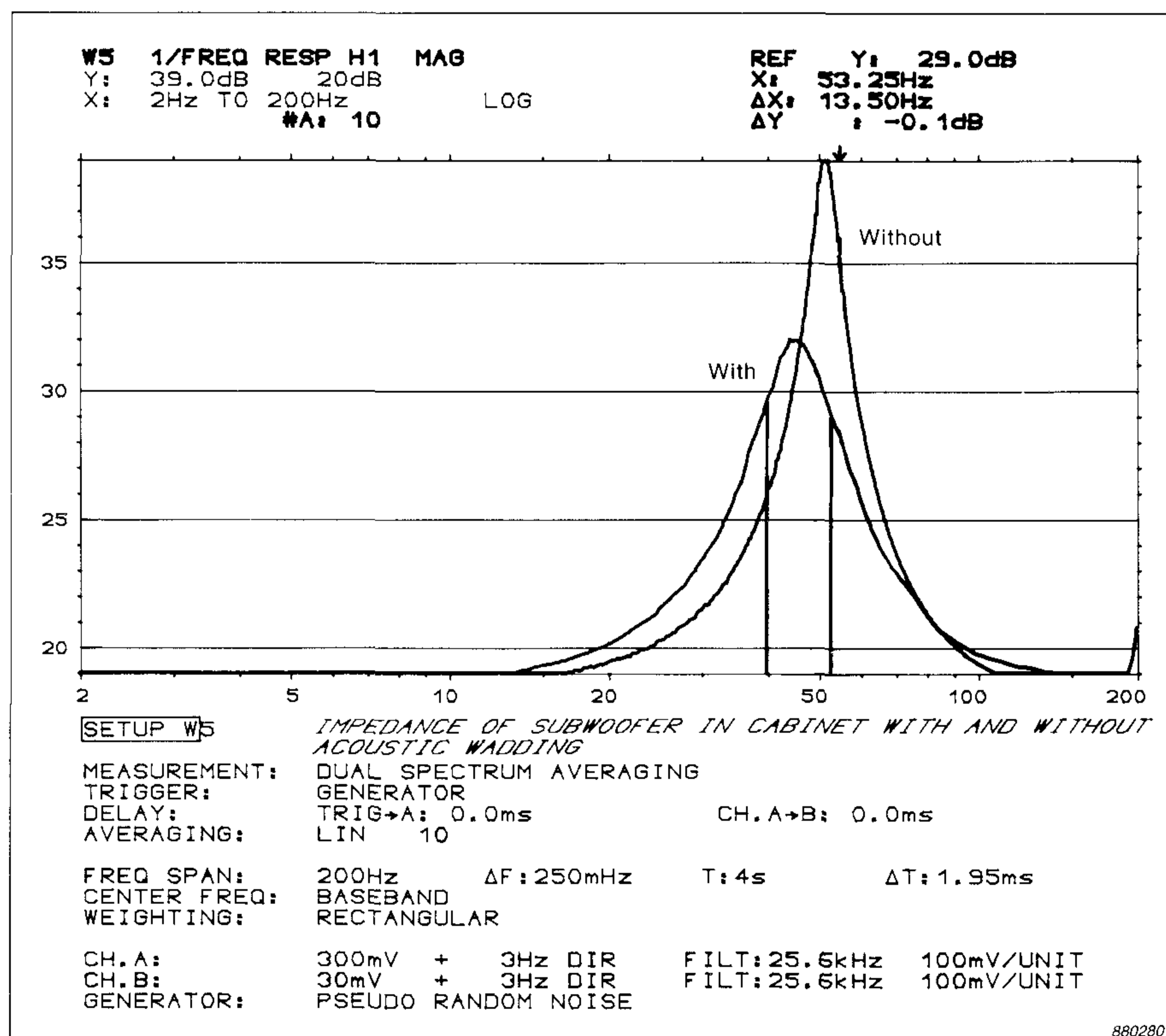


Fig. 7. The electrical impedance curve of the subwoofer alone. The Q of this part of the system can be measured easily by using the delta cursor facility of the analyzer. Superimposed is the effect of varying the amount of damping material inside the cabinet

tween the subwoofer diaphragm and the cabinet. This was measured very easily by placing a lightweight accelerometer on the centre of the diaphragm

and another accelerometer at various locations on the cabinet. The subwoofer was excited with a random noise signal from the 2034 via an am-

plifier. If the cabinet was good the transmission would be very low, and fortunately it was. See Fig. 8.

If the cabinet had proved too mobile at certain frequencies then the 2034 could have been used to form the heart of a *modal analysis system* to troubleshoot the problem and indicate a solution.

Bass-EQ network design

The near-field response of the subwoofer — without crossover — in its cabinet was measured on the 2034. The sealed box acts according to the theory like a second order high pass filter. An active filter whose transfer function was an “upside down” version of the subwoofer response was used and then tested on the 2034. When this was used in conjunction with the subwoofer it could compensate for the roll-off of the subwoofer by sinking more power into the drive-unit at the lower frequencies in a way determined by the filter shape. In this way the bass response was extended flat down

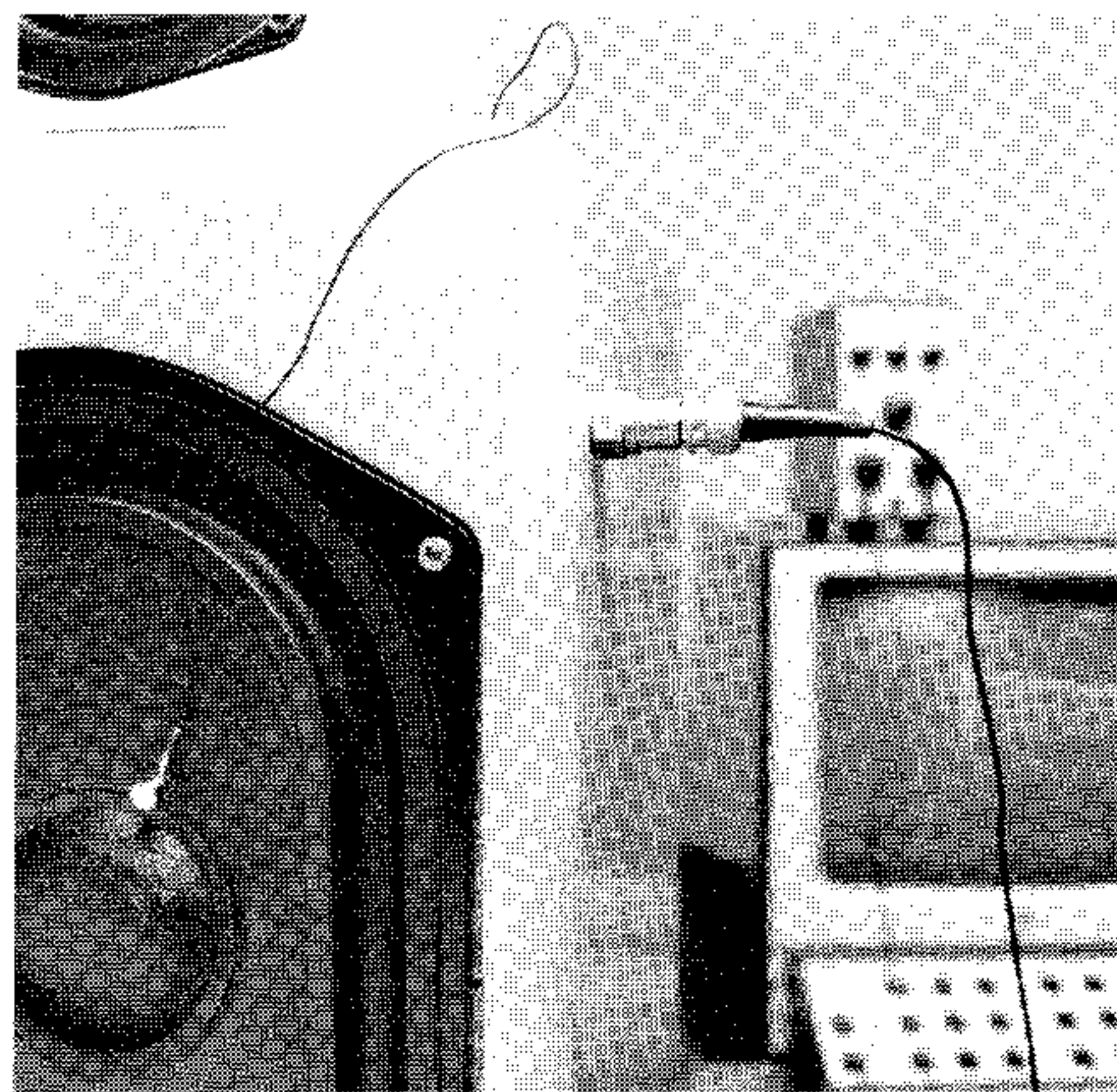


Fig. 9. Investigating the vibration performance of the subwoofer cabinet by examining the transfer function between the diaphragm motion and the cabinet vibration

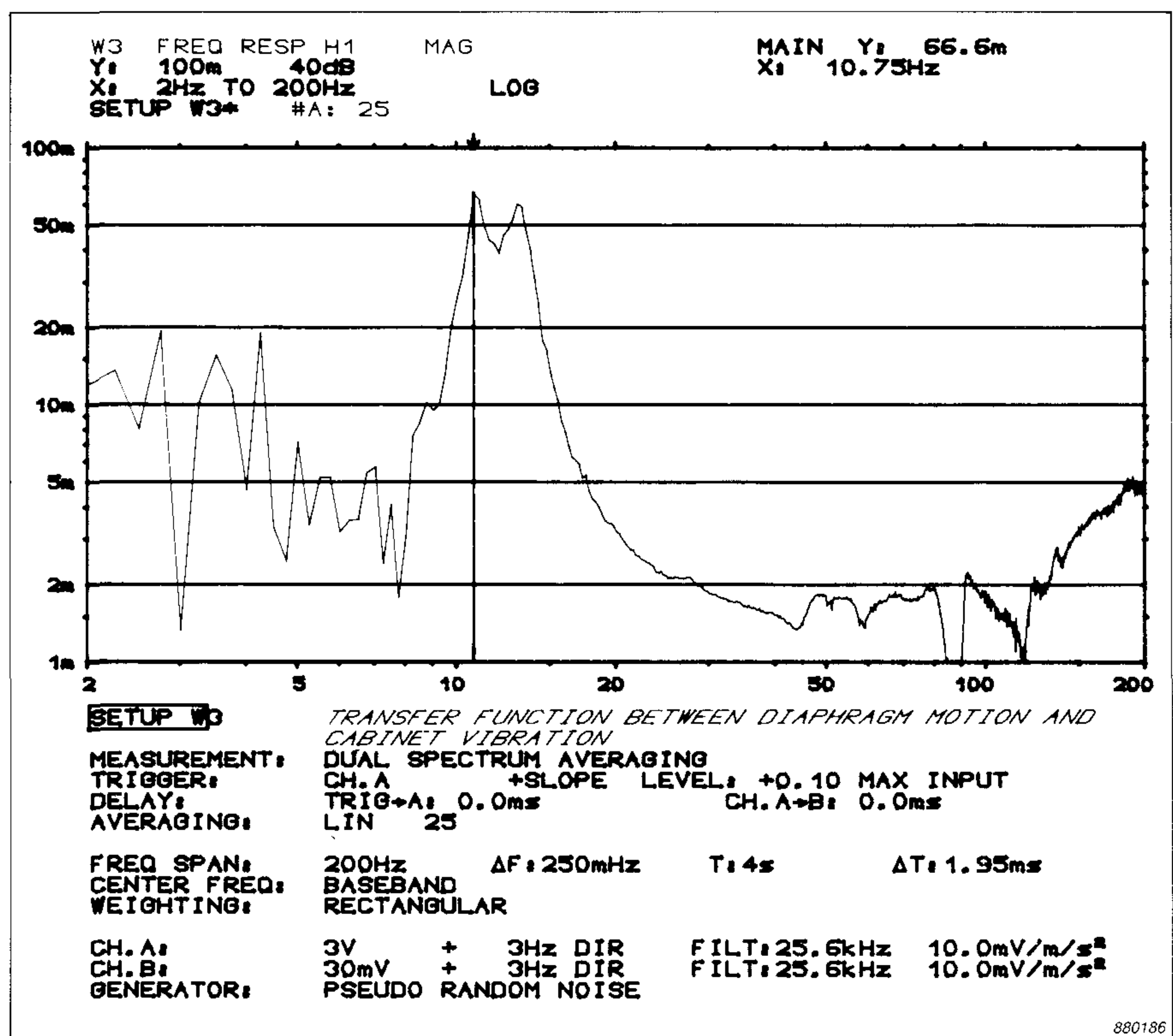


Fig. 8. The transfer function between the motion of the diaphragm and the motion of the subwoofer cabinet with the loudspeaker under operating conditions

to a chosen frequency which theoretically was only really limited by the maximum excursion capabilities of the driver and the electrical power available from the subwoofer's power amplifier. In this case 25 Hz seemed low enough. The effect of the bass-EQ is shown in Fig. 10.

The great advantage of the 2034 in this type of electronics design work is that the effect of a modification can be seen within seconds and an instant comparison can be made to the previous version. The designer can use more of his efforts and time in design work and not getting tangled up in measurements and analysis.

Troubleshooting

Active filters can become quite complex affairs compared to their passive counterparts. Some of the filters did not work correctly first time. The 2034 showed quite clearly that the roll-offs were not correct; instead of 24 dB/octave they were sometimes only 18 or 12 dB/octave. Roll-offs could be read directly from the screen of the analyzer by using the *delta cursor* facility. The filters employed two second order filters in cascade, it was a simple matter to follow the build-up of the total filter characteristic at the appropriate points on the board and identify the faulty section. In this way obscure

How FFT analyzers such as 2034 compute transfer functions

The analyzer simultaneously “captures” a segment of the time history of the input and output of a system. The *system* could be a crossover network, loudspeaker or room. The system input can be *any* signal containing sufficient energy in the frequency range of interest. The 2034 has a built-in generator designed to produce a range of test signals for this purpose.

The two time histories are converted into a digital format and fed into an

FFT algorithm which produces spectra of these two signals. Basically, the ratio of the output spectrum to the input spectrum provides the frequency response function after averaging. The *Fourier Transform* of the frequency response function gives the *Impulse Response Function* of the system.

The important point is that the frequency response function is a *property*

of the system and is independent of the types of signals used.

The 2034 can measure the far-field response of a loudspeaker in an ordinary room by using impulses as the excitation. As long as the first reflection of the pulse from the room is not included in the spectrum calculations then the resultant frequency response is valid. We can “window” the first impulse and reject the rest using the *transient window* facility of the 2034.

faults such as broken copper tracks and defect capacitors were found in a matter of minutes.

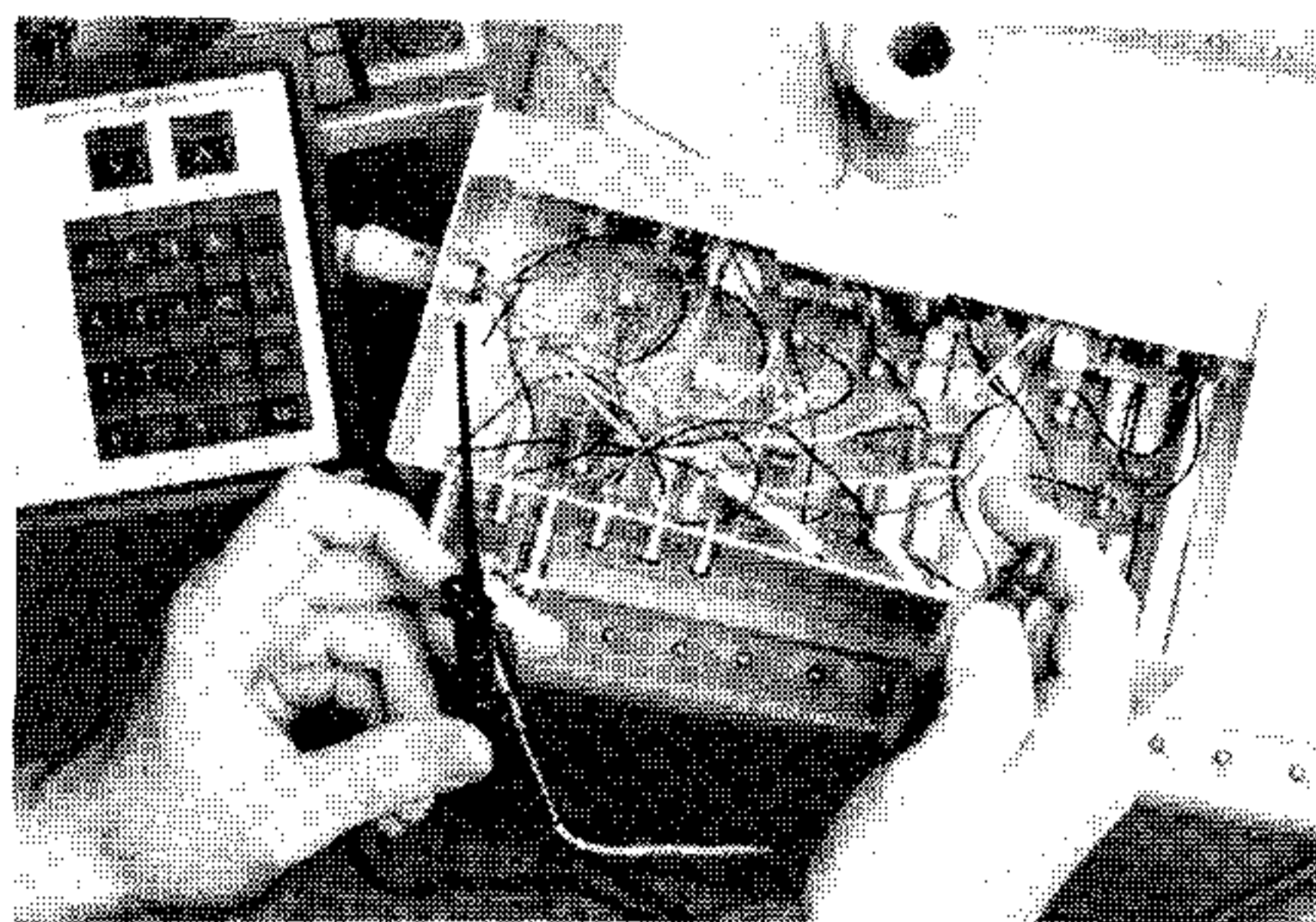


Fig. 11. There's a fault in here somewhere — but where?

Testing the finished product

The finished loudspeakers were tested in the laboratory and then in a typical domestic set-up. Near- and far-field measurements were made in a matter of seconds.

When the loudspeakers were tested in the domestic room the microphone was placed in the listening position and a pseudo-random noise signal applied. In this way the *total* system response of electronics, loudspeakers and room could be examined. It was no surprise to find that the room, which wasn't considered to be particularly acoustically "bad", (reverberation time of 0,6 seconds) quite convincingly ruined the relatively smooth response of the loudspeakers on their own as is seen in Fig. 12. Such measurements can be used to optimize the properties of the listening room.

Incidentally, from a subjective point of view the loudspeakers sounded excellent. The bass-EQ system helped to provide a bass response which was extended and well controlled. The stereo imagery was excellent.

...and there's more

Only a part of the total capabilities of the 2034 were used in this project. The *sound intensity* feature of the analyzer could have been used to investigate the cabinet vibration along with the *modal analysis* capability. Sound intensity could also have been used to measure the sound power output of the loudspeakers. Room acoustics investigations can also be performed using the analyzer's *Hilbert Transform* and *correlation functions*.

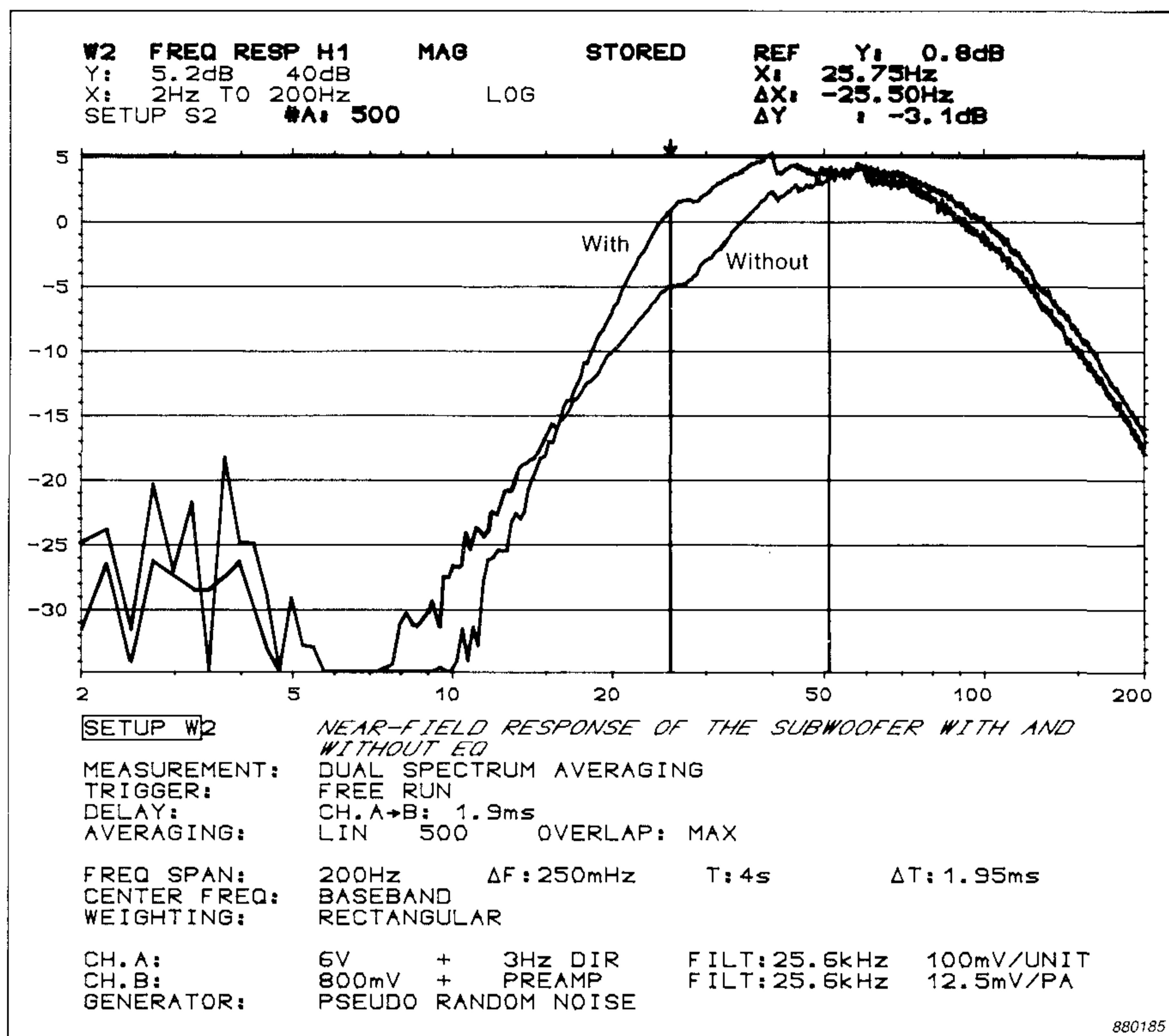


Fig. 10. The near-field response of the subwoofer with and without the bass-EQ network

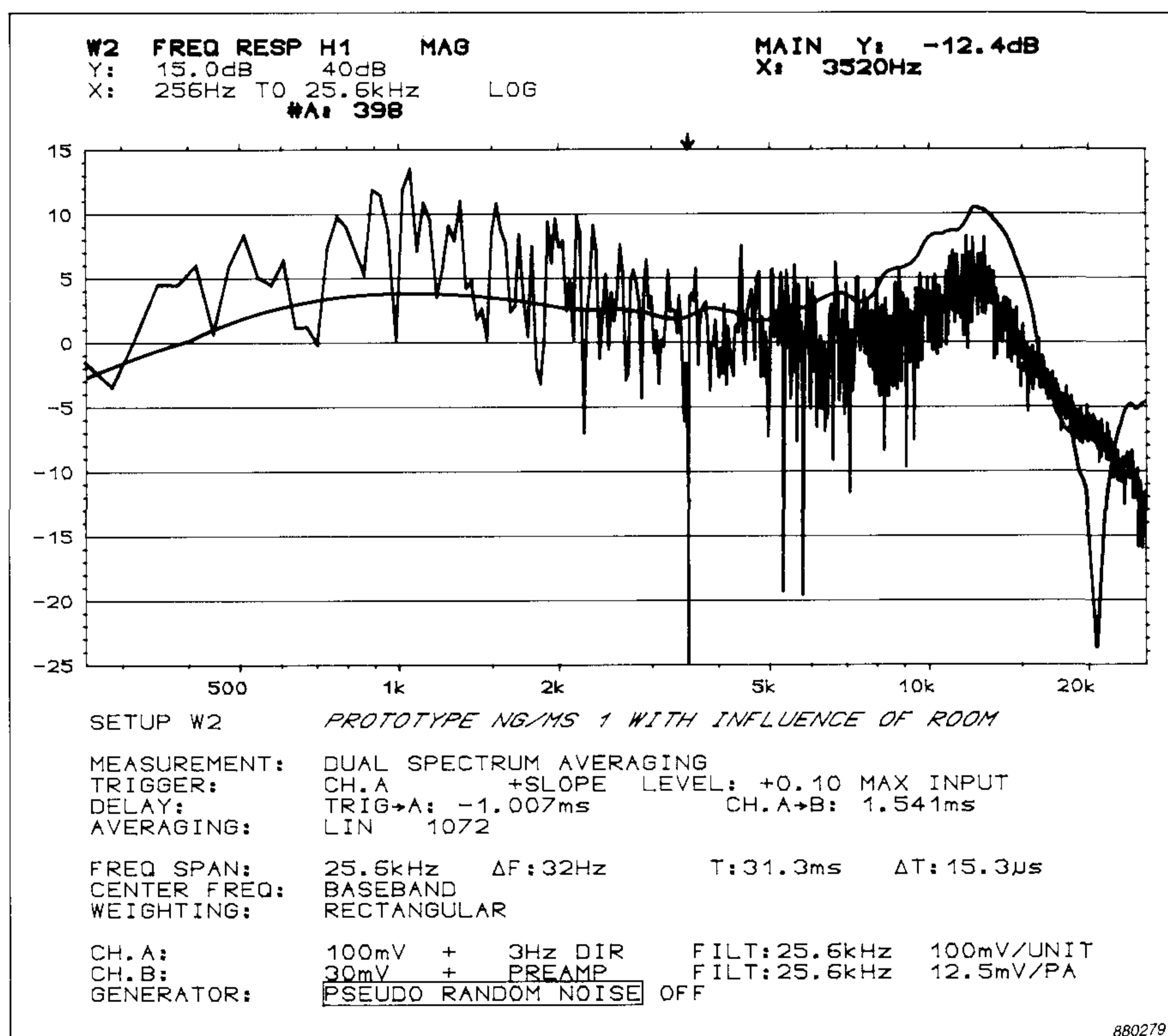


Fig. 12. The near-field frequency response of the first complete system. Superimposed on this is the far-field response measured in a domestic environment

Distortion at single frequencies was easily and quickly measured using the 2034's internal generator and examining the levels of the distortion compo-

nents in the autospectrum. Total distortion measurements are possible using the *delta/total* cursor facilities.

Conclusions

There are possibly a number of misconceptions about the use of FFT analyzers in the loudspeaker laboratory. Firstly, there is the price; FFT analyzers are no longer as expensive as they once were. The 2034 can compete on price with any good traditional set-up. Secondly, there is a belief that analogue techniques such as swept sine testing are better. This really is not true but has resulted from misconceptions about "modern" FFT techniques and their application. There's nothing a 2034 can't do that can be done by an analogue set-up, but there are so many "extras" which are possible with a 2034. Finally, it really is possible to measure frequency response functions without an anechoic chamber, and they are accurate.

The 2034 provides accurate results in a simple and fast manner. The added versatility of a 2034 in terms of documentation flexibility, optional mass data storage with the help of a digital cassette recorder or Personal Computer, means that every loudspeaker laboratory can benefit from the addition of a 2034 to the existing set-up. The "trial and error" nature of loudspeaker design lends itself particularly well to an instrument such as the 2034.

Additionally, in the quality control sections of the industry a 2034 would be the perfect tool with which to monitor the consistency of the frequency responses of drive-units and assem-

bled loudspeakers. Results can be stored onto tape or disc and recalled in the future; once a measurement is put back into the 2034 post-processing of that measurement is possible. What this means, for example, is that the impulse response of a drive-unit which left the factory some years ago can be found even though it was only the frequency response function which was actually measured at the time.

Of particular importance to OEM manufactures of drive-units for the car industry is that the 2034 is ideal for making sound-system measurements *in the car*.

The smaller loudspeaker companies of the world should certainly consider joining the larger ones in the move over to FFT techniques in loudspeaker R&D.

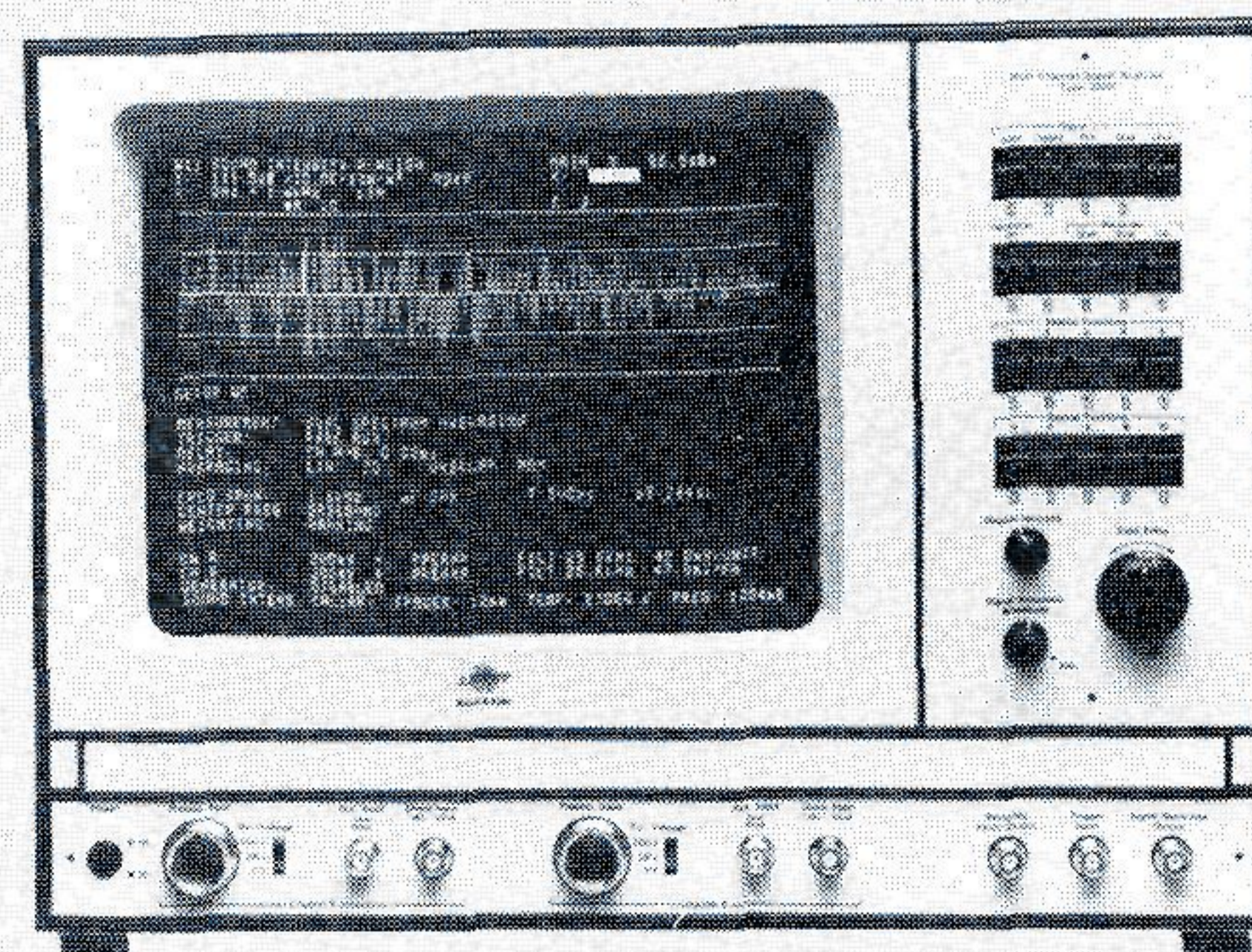


The Brüel & Kjær Dual Channel Signal Analyzer Type 2034

From the point of view of features and specifications offered the 2034 is one of the best FFT analyzers available today. In terms of its user-friendliness the 2034 is unbeatable. Here's a quick run down of some of the features on offer:

34 time, frequency and statistical domain functions; 801 line spectra in 15 frequency ranges (25,6 kHz to 1,56 Hz) including zoom; IEC/IEEE compati-

ble digital interface, large 12" CRT, 20 user definable and savable display and measurement set-ups, power supplies for microphones and line-drive accelerometers, built-in signal generator, versatile window functions, real-time frequency of 800 Hz (a faster version Type 2032 is available with a real time frequency of 5 kHz. However, high real time frequencies are not necessary in the majority of loudspeaker measurements.)



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