Development of a hi-fi loudspeaker enclosure by using modal analysis

A modal analysis system, based on the Dual-Channel Signal Analyzer Type 2032 or 2034, can be used for optimizing the design of structural dynamic systems. By measuring the compliance at a set of points on a structure, the modal parameters can be found, and a complete dynamic model of the system can be produced. This allows discovery of potential vibration problems at an early stage in the design. And the effect of subsequent mass, stiffness, and damping modifications, designed to solve any problems, can be investigated.

This application note presents a study of how the Brüel & Kjær modal analysis system was used to solve a colouration problem existing in the prototype design of a high quality loudspeaker system.

Modal analysis of a hi-fi loudspeaker. The Dual-Channel Signal Analyzer Type 2032/2034 is used to measure the compliance between the driving point and a number of response points; then a computer aids the extraction of the mode shapes.

Introduction

The objective of a modern high-fidelity loudspeaker is to "reproduce" natural sound images over a spacially large area. Technically speaking, a speaker must exhibit a flat frequency response over a wide range, and exhibit an even and smooth directional pattern, for the audible frequencies, in a reasonably large listening room.

As a single speaker can never fulfil this goal, the modern loudspeaker is a rather complex system consisting of a set of dynamic speakers (drive units), a crossover network, and an enclosure. Building a system from high-quality individual elements does not guarantee a high quality result. A good loudspeaker should extract the best performance from each component, while ensuring optimum system compatibility. In particular, interaction with the listening room should be of prime consideration.

The hi-fi loudspeaker comprises three fundamental parts, each having different objectives:

- **Drive units.** These provide the acoustic energy. The required frequency range is shared between a set of dynamic speakers: large membranes for the low-frequency range, and small membranes for the high-frequencies.
- **Cross-over network.** This directs the part of the signal, with energy in a certain frequency band, to the appropriate drive unit.
- **Enclosure.** This is to provide a dynamically rigid structural support for the drive units, and to provide the appropriate acoustic loading for the drive units to obtain a good frequency response.

This application note discusses how to solve the enclosure vibration problems, by using the tools of structural dynamic analysis.

Enclosure problems

An ideal enclosure would be infinitely rigid. It would secure the drive units in a fixed position, and be acoustically transparent. However, real enclosures are elastic structures having specific dynamic characteristics. The reaction forces of the drive units, and the sound pressure, excite the enclosure, causing it to vibrate. The structural vibrations are transmitted to the air, contributing to the total sound image. Panel vibration can produce a significant contribution to the sound, being of the same order of magnitude as the direct drive-unit sound, at panel resonance frequencies. The panel sound is generally uncontrolled, interfering destructively with the direct sound, causing magnitude and phase errors in the frequency response, and causing the radiation pattern to deteriorate.

Counter-measures can be taken against cabinet vibration. These include increasing the mass and/or stiffness of the panels to move the resonance frequencies, decreasing the compliance, and damping the panels to reduce resonance amplification.

The enclosed air volume exhibits resonances (standing wave modes), which are excited by the internal sound pressure, and radiated through the drive-unit membranes and the panels, unless counteracted by internal damping and shielding.

Enclosure design is a compromise between quality, price, size, mass, materials, vibration treatment, and appearance.

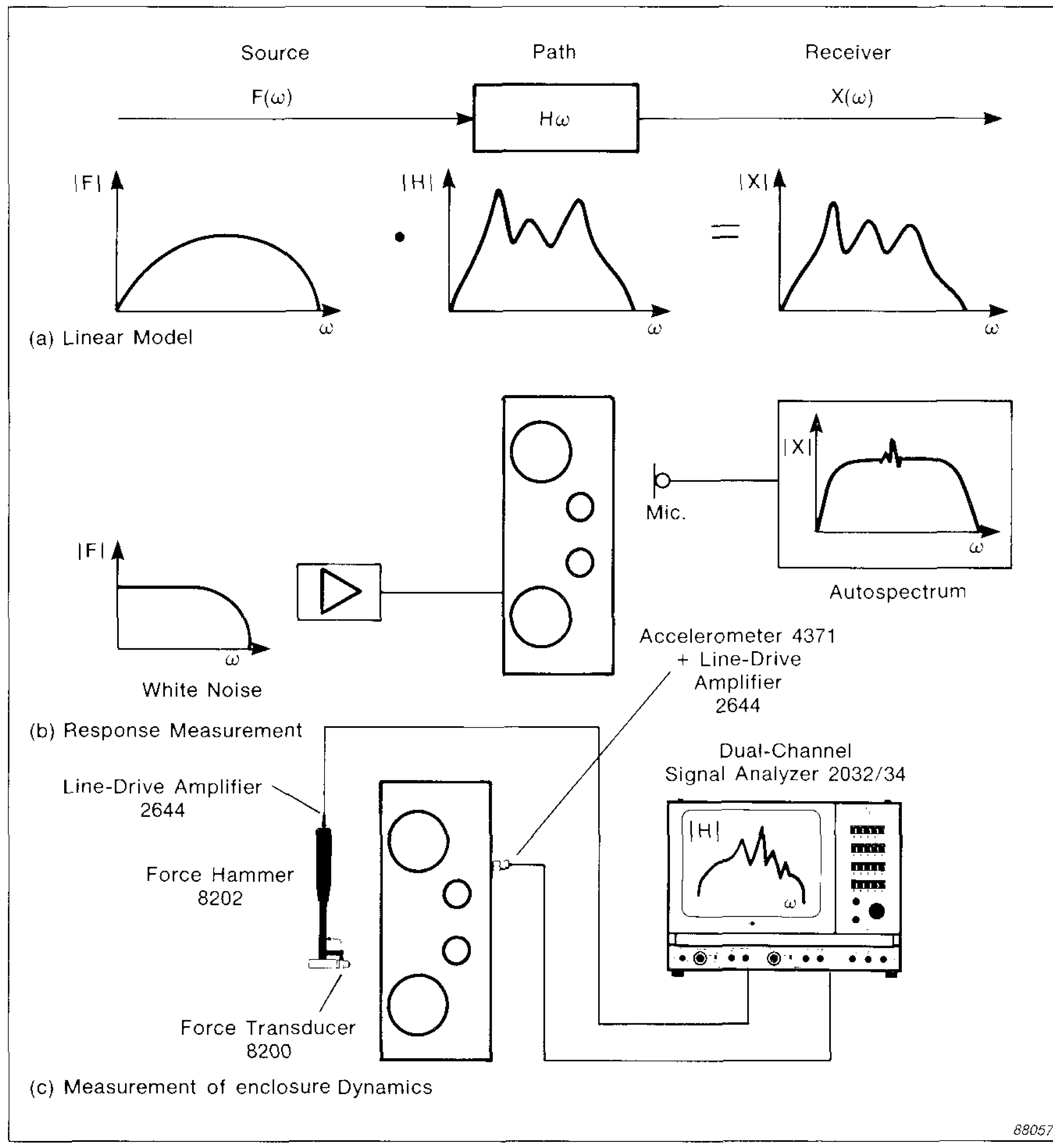

Fig. 1. Modelling and testing methods used to investigate the loudspeaker's colouration problem.

Enclosure vibration analysis in terms of structural dynamics

From now onwards we'll disregard the direct radiated sound, and concentrate on the undesired sound caused by the enclosure vibration. There are three elements to consider with every dynamics problem: the source, the path, and the receiver. Either one can be the cause of the problem, or the key to the solution. See Figure 1a.

A loudspeaker enclosure can be characterised in the way described above. In this case:

- The receiver is the listener. If significant enclosure vibration is present, a *box-sound* will be perceived, the sound will be dependant on the listening position, and the quality of the stereo image will be dramatically degraded. If this is the case, not much can be done. If the listener doesn't like the sound, then he/she won't buy the loudspeaker.

- The vibration source is, in our opinion, the internal sound pressure inside the enclosure, plus to a lesser extent, the reaction forces of the drive units. This point is a little controversial, as it is a common opinion that the reaction forces are dominant. The position of the drive units greatly affects the influence of the reaction forces.

- The dynamic energy is transmitted from the source through the enclosure's structure to the receiver. The sensitivity of the cabinet to vibration is described by its compliance (response/force). This is affected by the cabinet's mass, stiffness and damping distribution.

The most efficient way of modelling the structural dynamics of the problem is to use modal analysis. This involves exciting the test structure, with a measurable force, in the frequency range of interest. The resulting dynamic response is measured, and the frequency response is calculated by using a Dual-Channel Analyzer Type 2032 or 2034. The modal analysis system uses a process called curve fitting to compare the measured frequency response function with a theoretical model. From this model, the modal parameters, which give a statistically best curve fit, are extracted.

Development of a prototype enclosure for a quality hi-fi loudspeaker: Audionord Dali 18.

Test object

The Dali 18 is a new high quality loudspeaker. The design is a three-way system comprising two 8 in woofers, one 4,5 in mid-range, and one 1 in moving-coil direct-radiation tweeter. The cross-over network is a third-order linear-directivity filter with asymmetric slopes. The enclosure is a bass reflex design of 90 litre volume, and is constructed from heavy chipboard and fiberboard, with a number of rib stiffeners. The selling price is approximately $800 on the US market.

Subjective evaluation

Measurements on the prototype had shown that the design goals had apparently been fulfilled. The next step was to subjectively evaluate the speaker. The listening panel concluded that the speaker was coloured in the 600 Hz region. The designer realized that the problem was caused by an enclosure resonance, and that a trial-and-error approach to the solution would be too time consuming and would produce dubious results. Consequently, he decided to attack the roots of the problem from a knowledge of the dynamic behaviour of the loudspeaker, obtained by using modal analysis.

The objective of the measurements was to determine the inherent dynamic properties of the enclosure alone. A number of frequency response measurements were made at randomly chosen positions to gain an initial impression. Figure 1c shows the instrumentation used for the introductory measurements. For convenience, hammer excitation was used. The results indicated high compliance in the troublesome frequency range (Figure 4 shows a frequency response measurement before and after enclosure modifications). To obtain a more comprehensive knowledge of the dynamic behaviour of the enclosure, a full modal test was made.

Modal test of the enclosure

Measurement positions: structural degrees of freedom.

The modal test produces a dynamic description of a discrete set of defined points and directions, termed *degrees-of-freedom*. The points on the enclosure panels were defined approximately equidistantly in a 0,1 m mesh. The measuring direction, for each point, is perpendicular to the surface.

Driving point: choice of excitation and reference point.

To produce enough force at high frequencies, a vibration exciter was used in place of the impact hammer. The Dual-Channel Signal Analyzer Type 2032/2034 supplied the vibration exciter with a random signal having a flat spectrum across the selected frequency range (0 to 1600 Hz). The vibration exciter was attached to the loudspeaker enclosure at a reference point on the side panel, in this case point #13, as the pre-analysis indicated high compliance here.

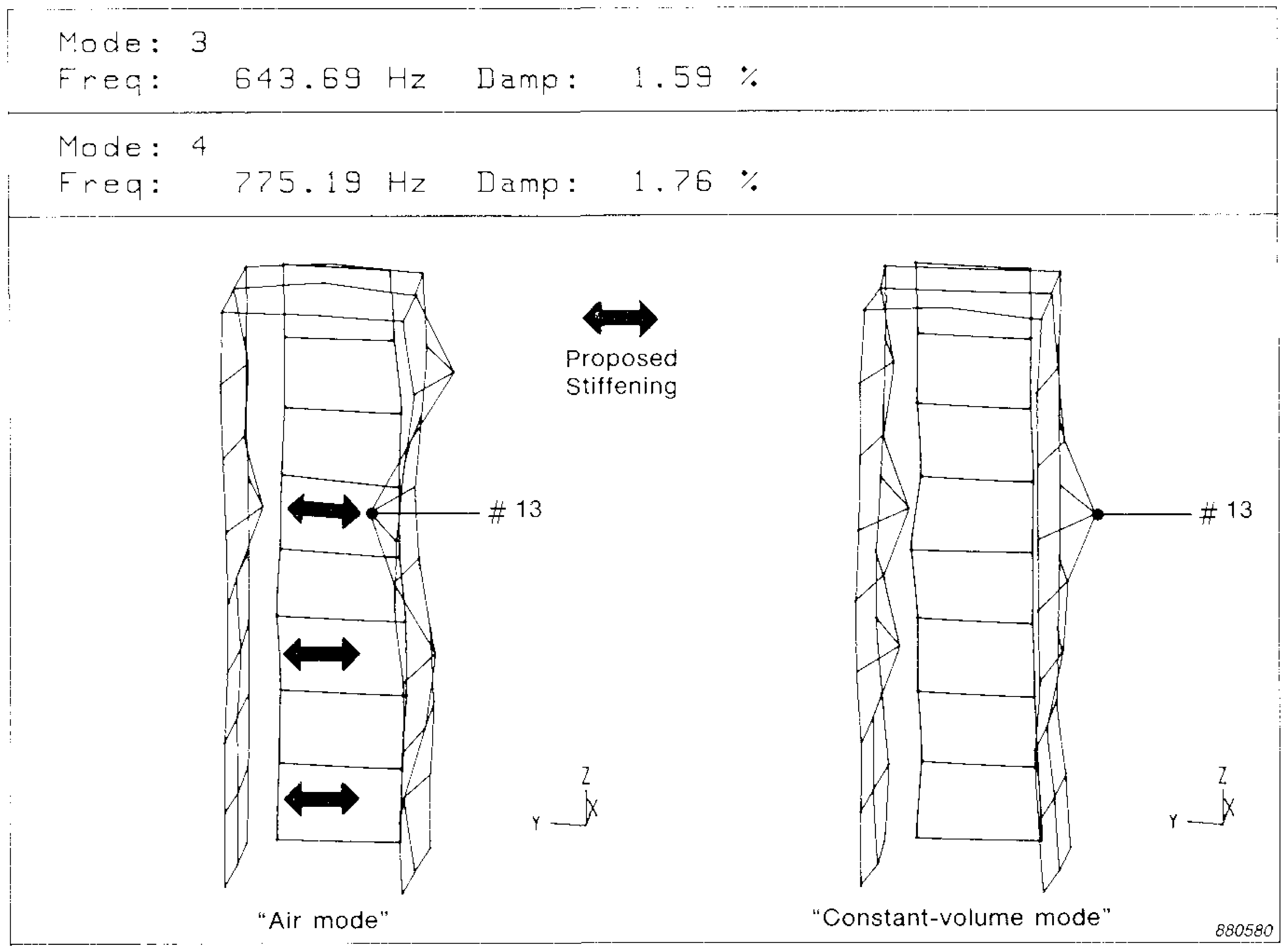

Fig. 2. Examples of estimated mode shapes, model frequencies and dampings for the loudspeaker enclosure.

Frequency response measurements: determining the compliance over the structure.

A force transducer, mounted at the reference position, measured the force. The vibration exciter was connected to the force transducer by a flexible rod (stinger) to prevent any structural constraints. The response signal was produced by an accelerometer, which was mounted on the panels by using bees-wax. For each measurement, the accelerometer was moved to a new DOF. The force and acceleration signals were supplied to the dual-channel analyzer via charge amplifiers. A frequency response measurement H1, representing the compliance between the reference point and each measurement point, was produced by the Type 2032/2034 analyzer. Each frequency response measurement was transferred to magnetic disk by a computer running a modal analysis software-package WT9100.

Parameter estimation: curve-fitting the measured frequency response.

After completing the frequency response measurements (84 in total), the modal parameters (that is the modal frequency, damping and associated mode shapes) are extracted by the modal software. This is achieved by curve-fitting the frequency response data. The curve-fitter chosen is a "global" curve-fitter, which finds the modes representing the complete data set, in a least squares sense. This curve-fitting method works well with structures such as enclosures because it emphasizes "global" modes, and suppresses local modes, which can sometimes obscure the global modes.

Results

Two of the estimated modes, plus their modal frequencies and dampings, are shown in Figure 2. Computer animation (slow motion simulation) of the mode shapes reveals that all modes behave as normal modes – each part of the structure moves either in-phase or 180° out-of-phase with the other parts, and all the parts pass through zero simultaneously.

The modal parameters constitute the parameters in the mathematical "modal model", which can be used in computer programs to enable us to predict what happens to the dynamic properties of a system (resonances, mode shapes, sensitivity etc.), when the system is physically modified.

Enclosure modifications: Applying additional rib stiffeners.

Any of the modal parameters, mass, stiffness, and damping, can be modified to affect the structural dynamics. The modal analysis system can simulate the effects of potential modifications, before they are implemented.

By studying the mode shapes, with the response model borne in mind, we can see that it is mode no. 3 that is the most likely cause of the colouration.

This is evident because the mode shape exhibits what is called an *air mode*, that is it breathes and changes volume. In this enclosure, only the bass sound is present, as the mid-range and tweeter units are encased in their own enclosures. Consequently, only wavelengths which are long, relative to physical dimensions of the cabinet, are present. Assuming equal pressure fluctuations throughout the cabinet, only an air mode can be excited by the internal sound pressure fluctuations. Fortunately, air modes are easily modified by bracing the parts of the structure that move in opposite phase. From the appearance of the mode shape, it would seem reasonable to place a stiffener between the air-mode's anti-phase points, illustrated in Figure 2. Reasoning along this path leads to a number of stiffness modifications, shown in Figure 3.

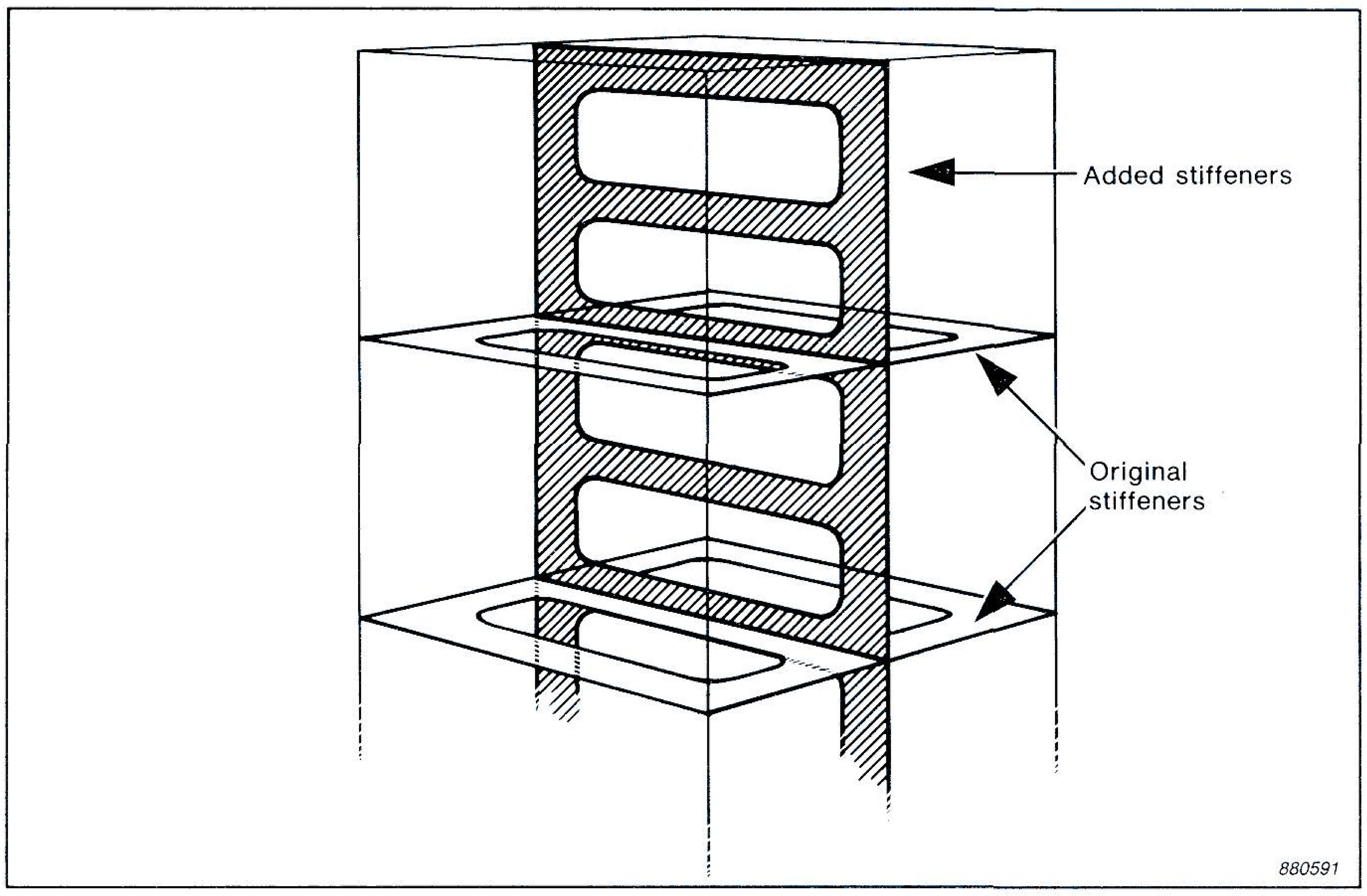

Fig. 3. Application of rib-stiffeners to the enclosure.

Has the colouration problem been solved?

After the loudspeaker enclosure was modified, it was re-tested for verification purposes. Initially, frequency response measurements were made at suitable points to see if the resonant behaviour had decreased. The first measurements showed that further modifications were needed. In total, three modifications were completed.

Figure 4 shows a driving point compliance measurement, before and after modification. The compliance in the critical frequency range has been attenuated by approximately 20 dB. Note that the modification effecting the compliance at mode 3 does not effect the compliance of the constant volume modes 1, 4 and 5.

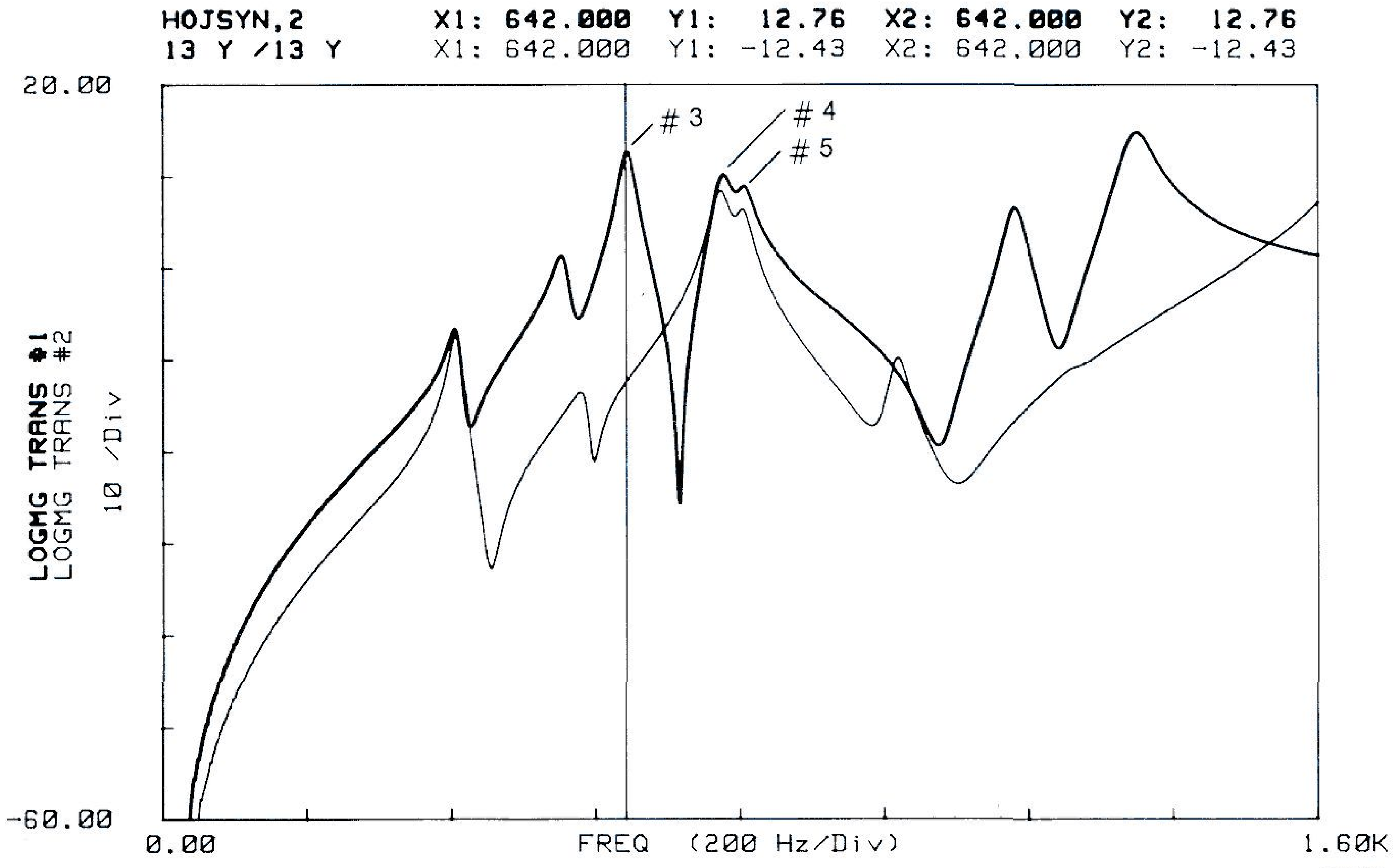

Fig. 4. Driving point compliance measurement, before (thick line) and after (thin line) structural modification.

The modal model allows modifications to be tested analytically, before they are implemented. However, a trial-and-error approach, based on a comprehensive knowledge of the enclosure dynamics found from a modal test, was considered best. This was because the forcing function, being pressure distributed over all points, plus drive-unit reactions, is complicated and, due to the lack of knowledge of the force distribution, is difficult to model.

Final results and conclusions

The last and most critical test – the subjective evaluation by a listening panel – was passed with flying colours. Science, as applied to arts such as hi-fi, is necessary, but certainly not sufficient. Mechanisms other than functions based on ideal linear models can behave in a unpredictable manner because they cannot be completely described by simplified models. However, a modal analysis system based around a Dual-Channel Analyzer Type 2032 or 2034 is ideal for investigating the measurable properties. In this application, modal analysis enabled the enclosure structure to be optimized dynamically. A modal analysis system aids comprehensive understanding of structures, and supports the designer in product and prototype development.

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