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ANALYSES OF THE TRANSMISSION OF SOUND INTO THE PASSENGER COMPARTMENT OF A PROPELLER AIRCRAFT USING THE FINITE ELEMENT METHOD

Peter Göransson and Fredrik Davidsson
The Aeronautical Research Institute of Sweden (FFA)
P.O. Box 11021, S-161 11 Bromma, Sweden

Abstract

To control the sound transmission through the double wall construction of a propeller aircraft is a very difficult, however desireable, task. The arrangements found in most modern aircraft might not always be the best possible to reduce the transmitted low frequency sound from the propeller outside the fuselage. In fact there have been situations where the stiff, light panels facing the passenger compartment act as resonators, thus enlarging the vibration levels from the outer skin.

The parameters that, among other, govern the function of the double wall in terms of sound transmission are weight of the inner (trim) panels, attachment of the trim panels to the frames of the fuselage structure, the type of insulation material in the space between the walls etc. Despite the low frequency and, hence the long wave length in the air, it seems like the double wall airspace could act as a reducing shield for the sound transmitted from the propeller. However, in order to achieve this the fastening of the trim panels have to be carefully designed and even more so, the thermal insulation material have to be choosen so as to give an additional reduction of the transmitted sound. This latter effect is however, strongly dependent on the design of the panels, i.e., if they act as a true double wall or not.

This paper will give a discussion of an analysis performed for a cross section of an aircraft. The main purpose of the analysis is to study the double wall construction from an analytical point of view to see if the phenomena found in experiments might be reproduced. For this reason a comparison between the eigen values and eigen modes of the plane cross section will be calculated, with and without the inner trim panels. Special attention will be given to the effects of different attachment of the trim panels to the frames and also of the weight and stiffness of the trim panels. The calculated modes will then be used to calculate the sound levels arising from an external pressure field acting on the outer shell.

The analysis is performed with the FE-system ASKA-Acoustics which is a joint development project between FFA and SAAB-SCANIA AB. The interaction between the structural parts and the fluid in the different cavities is modelled with a symmetric coupling formulation with both pressure and displacement potential as fluid degrees of freedom. The acoustic field is modelled with special acoustic finite elements and the coupling to the structure is handled with interface elements.

I. INTRODUCTION

The ever increasing interest in propeller driven aircraft poses difficult problems in the struggle to obtain sound pressure levels which compare favourably with those found in modern jet aircraft. Not only is the propeller a hardly understood source of noise, but its spectrum is of an extremely cumbersome nature. The distinct peaks at low frequencies, starting with the first blade passage frequency and continuing with the harmonics, forces the acoustician to control pure tones which have acoustic wave lengths in comparison with the dimensions of the aircraft itself. The response of the aircraft structure and interior is mainly governed by global modes, some of which couple the structure to the acoustic field strongly. In this state of complexity the finite element method has been used quite extensively resulting in a wider understanding of these difficult matters,(1).

In this paper, acoustic finite elements are used to analyse the transmission of sound through the double shell represented by the fuselage skin and the composite trim panels. In particular the scope is to show the relative effects of changes in the trim panels material data and installation. Similar work has been published recently by Pope et al(1). In that paper an aircraft interior noise prediction model was discussed. The fundamental difference in approach between Ref. (1) and the current paper is that here the transmission analysis is based upon a coupled acoustic-structure FE formulation,(2), while in the former the uncoupled modes are used. Earlier analyses have shown that this coupling is sometimes very strong, thus causing large frequency shifts compared to the in vacuo resonance frequencies for the structure.(2,3)

The analyses are performed with the FE system ASKA-Acoustics,(4), which is a joint development project between FFA and Saaba-Scania AB.

II. IDEALISATION OF AIRCRAFT FUSELAGE

In the analyses performed in this paper the behaviour of the fuselage wall and the trim panel is simplified to a plane, two dimensional dynamic fluid-structure model. The aircraft is modelled as a true double shell with isolated air cavities in the interior and in the double wall space. This is to some extent a crude model since in the aircraft the trim panels are mounted to the frames of the fuselage. Of course such a three dimensional attachment is not possible to cover in a plane model, but this will be simulated by means of mechanical connections between the fuselage and the trim panel.

The fuselage structure and the trim panel are modelled with beams which have been given section properties equivalent to a slice of the real aircraft. Hence, in, e.g., the moment of inertia of the fuselage beams, mass and stiffness from the skin and the longerons are included. For the trim panel the stiffness and the mass are given values according to manufacturers and measurements that have been performed.

The material data used for the beam section properties of the trim panel are shown in table 1, for the four different design cases studied in this paper. It should be pointed out that the mechanical connections are comparatively stiff and so are the floor part of the trim shell which supports seats, etc.

Case	Trim panel properties wall ρ [kg/m^3]	floor ρ [kg/m^3]	Mechanical coupling
1	767	2800	yes
2	278	"	yes
3	767	"	no
4	278	"	no

Density of trim panels

Wall: $E = 12\cdot10^9$ N/m^2, $I = 1.9\cdot10^{-9}$ m^4

Floor: $E = 7\cdot10^{10}$ N/m^2, $I = 11\cdot10^{-7}$ m^4

TABLE 1 Properties for trim panel in the different cases studied

The first case, case 1, in the analysis is to be considered as the basic design. Here the fuselage and the trim panel are in mechanical contact and the density of the trim panel is high. This case will serve as the reference for comparisons. Case 2 is similar to case 1, the difference being a lighter trim panel. However, case 3 is of a quite different type since here the trim panels are uncoupled to the fuselage except for the fluid-structure interaction. This represents some kind of ideal mechanical vibration isolation and is of an extreme design. The last case, case 4, differs from case 3 in the density of the trim panel which is the same as in case 2.

These four cases were analysed for eigen frequencies and eigen modes, in the range 80-110 Hz. For the same cases a response calculation was performed with a pressure field having a maximum pressure of 130 dB SPL at 90 Hz, see figure 3a. This frequency corresponds to the fundamental tone of a four bladed propeller at cruising conditions. The pressure field is purely real, i.e., effects of propeller phasing are not included.

It is believed that this ideal model will serve as a reliable tool for the study of mechanisms and qualitative effects on the sound transmission at low frequencies.

III. EIGENVALUE ANALYSIS

The eigen frequencies for the four different cases in table 1 are shown in table 2.

Case	Eigen frequencies				
1	81	85	87	95	109
2	86	102	104		
3	92	94	105		
4	81	95	100		
without trim panel	88	110			

TABLE 2 Calculated eigen frequencies

In this table the results of an analysis of the fuselage without the trim panels are included for comparison. As may be seen there are more modes in the interesting region when the trim is taken into account. A change in the density of the trim panels shifts the frequencies of the modes dominated by the inner shell quite a lot as expected. The eigen modes around 90 Hz for the two extremes, i.e., case 1 and 4, are shown in figure 1 and 2 respectively. The lower frequencies, 87 Hz for case 1 and 81 Hz for case 4, have similarities in the pressure field while the structure in case 1 does not move as much as in case 4. However, for the frequencies above 90 Hz, i.e., 95 Hz for both cases the pressure patterns are different due to differences in vibration shapes of the trim panel. In fact, as may be seen in figures 1a and 2a, the air is vibrating in two different modes. The nodal line (zero pressure) goes from wall to wall in case 1 and from top to floor in case 4. Similar changes in modal patterns for the fluid due to changes in the coupling to the structure might also be observed for the other cases in table 2.

IV. RESPONSE ANALYSIS FOR UNDAMPED AIRCRAFT

The pressure field discussed above was applied to the outside of the fuselage for the four different cases, without damping in the system. The primary objective is to study the transmission through the double wall system into the passenger compartment inside the trim panel. Hence, the results discussed in this chapter might be seen as effects of different approaches to the design problem. The focus will be on the obtained SPL in the interior and to some extent vibrations of the structures.

Case 1

The maximum pressure level in the interior is about 122 dB and the presssure field resembles the modal pattern in figure 1b, as may be seen in figure 3a. The structural vibration, though seems to be a mix between the modes below and above 90 Hz. The fuselage has a smaller amplitude than the lighter, stiffer trim panel which excits the air.

Case 2

Decreasing the weeight of the trim panel is advantageous as may be seen in figure 3b. The maximum pressure is 119 dB, a decrease mainly due to the shift in eigenfrequencies. The pressure pattern is very different in nature as compared to case 1.

Case 3

Removing the mechanical contact between the fuselage and the trim panel moves one eigen frequency closer to the excitation, see table 2. This results in an increase for the maximum pressure level up to 123 dB compared to case 1 where the maximum was 122 dB. Despite the prevention of transmission of energy through mechanical components the levels go up, a rather astonishing fact. In this case the trim panel is vibrating in a shape which is similar to the 92 Hz mode, and also the acoustic modal pattern at this frequency is seen, see figure 4a.

Case 4

A decrease in the density from the above case results in a drastic lowering of the maximum pressure level down to 117 dB. The vibration levels in this case are also small over a large portion of the trim panel. It is also interesting to see that the pressure pattern is different from the one observed in case 3. As may be seen from figure 4b, the nodal line is transverse from wall to wall and more complex in nature.

Discussion

Through a variation of mechanical contact conditions and the density of the trim panel, large changes in the SPL in the interior of the aircraft are seen from the calculations performed. The best configuration seems to be an ideally isolated trim panel with rather low density. Quite contrary to common practice the high density panel seems to be the worst of the studied cases. Of course the background of these results is found in the location of the eigen frequencies of the different cases that have been studied.

V. RESPONSE ANALYSIS INCLUDING THERMAL INSULATION

To investigate the effect, if any, of the thermal insulation, an analysis was performed for the best design, i.e., case 4. The space between the fuselage and the trim was filled with a porous absorbent, the effects of which, were included in the analysis. Previous calculations and experiments have shown the possible existence of low frequency resonance effects of a porous material,(5). The effects, which are dependent on the mass density of the material, have a narrow bandwidth. This analysis was therefore intended to show whether there is any significant influence in such a complex situation as discussed in this paper. The material choosen have a mass density of 19 kg/m^3 and a flow resistance of $2 \cdot 10^4$ Ns/m^3. The density have been choosen to provide an optimal effect at 90 Hz and from figure 5 it may be seen that indeed, the pressure levels are generally lower by about 3 dB. As may be seen from figure 5 the pattern of the pressure field has not changed as compared to figure 4b. The real and imaginary parts of the displacement are also shown in figure 5. Most of the structural response is in phase with the excitation.

VI. CONCLUDING REMARKS

The analyses of an aircraft cross section discussed in this paper show that the transmission of low frequency sound is strongly dependent on the dynamics of the fuselage-air-trim-air system. The maximum SPL may vary from 123 down to 118 dB in the extreme cases where only attachment and density of the trim panel are changed. The results also show that a porous absorbent in the air space may give an additional decrease down to a maximum of 114 dB by carefully tuning the mass density of the porous material.

VII. ACKNOWLEDGEMENTS

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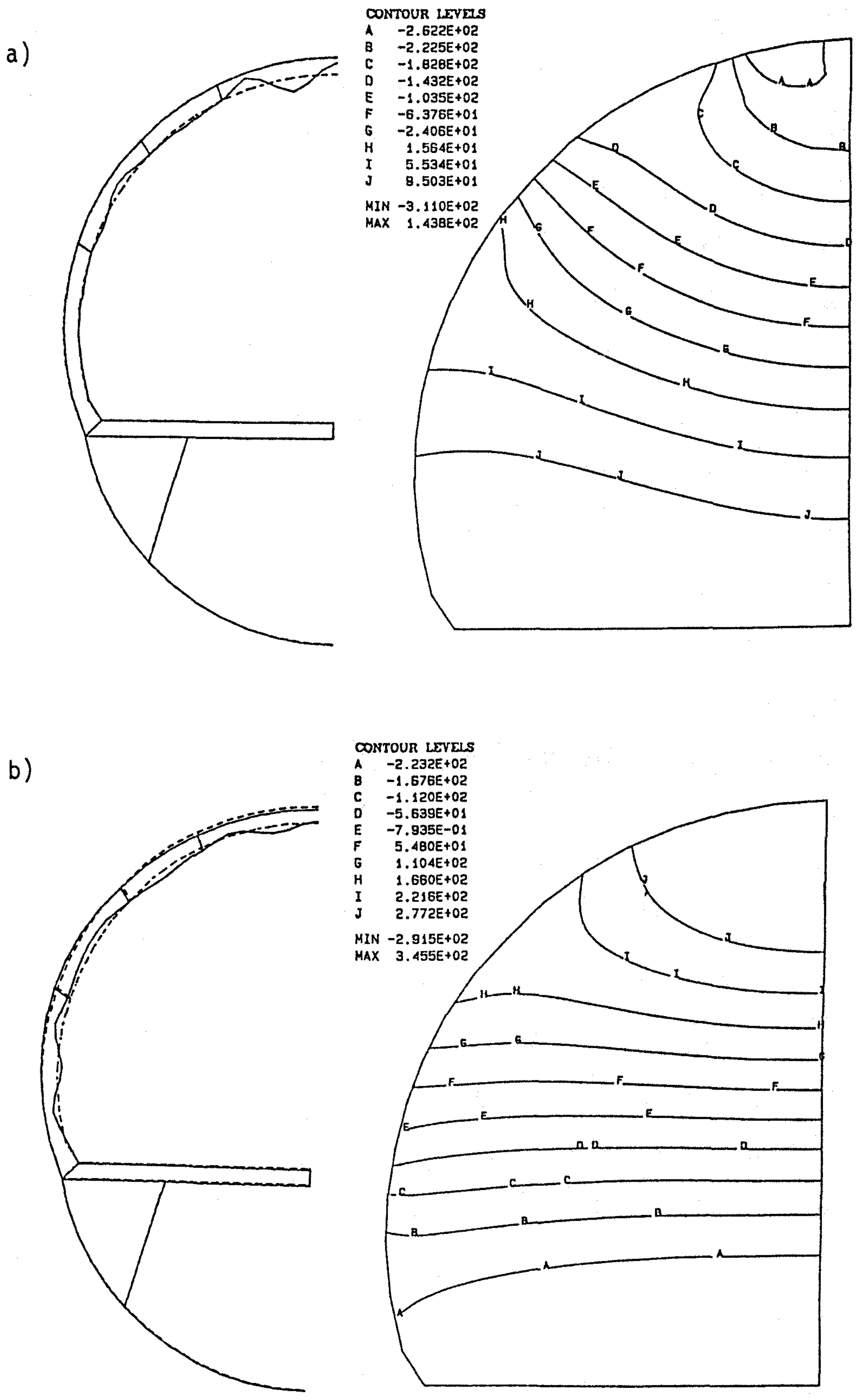

FIGURE 1 Eigen modes around 90 Hz for case 1. a) 87 Hz, b) 95 Hz

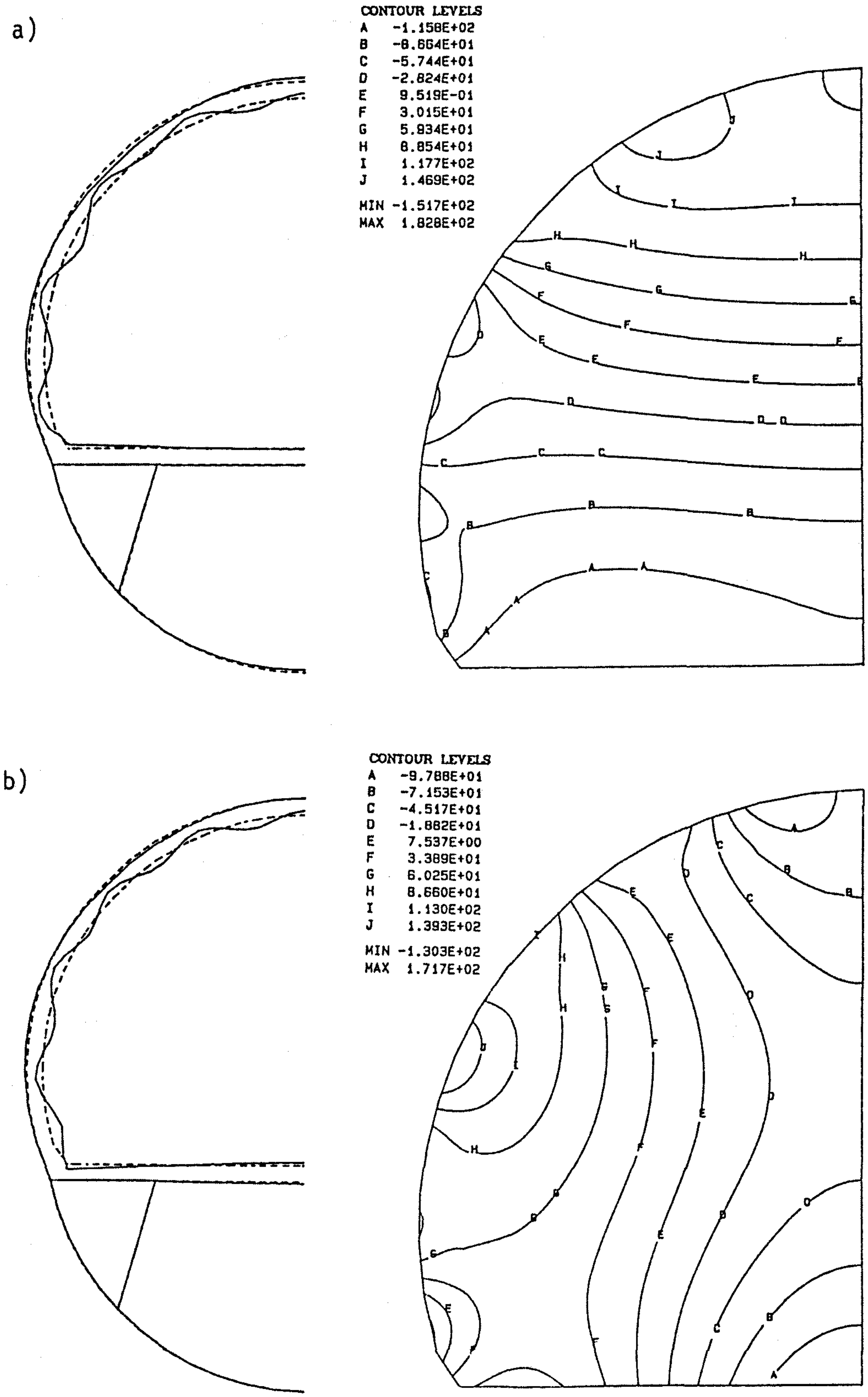

FIGURE 2 Eigen modes around 90 Hz for case 2. a) 81 Hz, b) 95 Hz

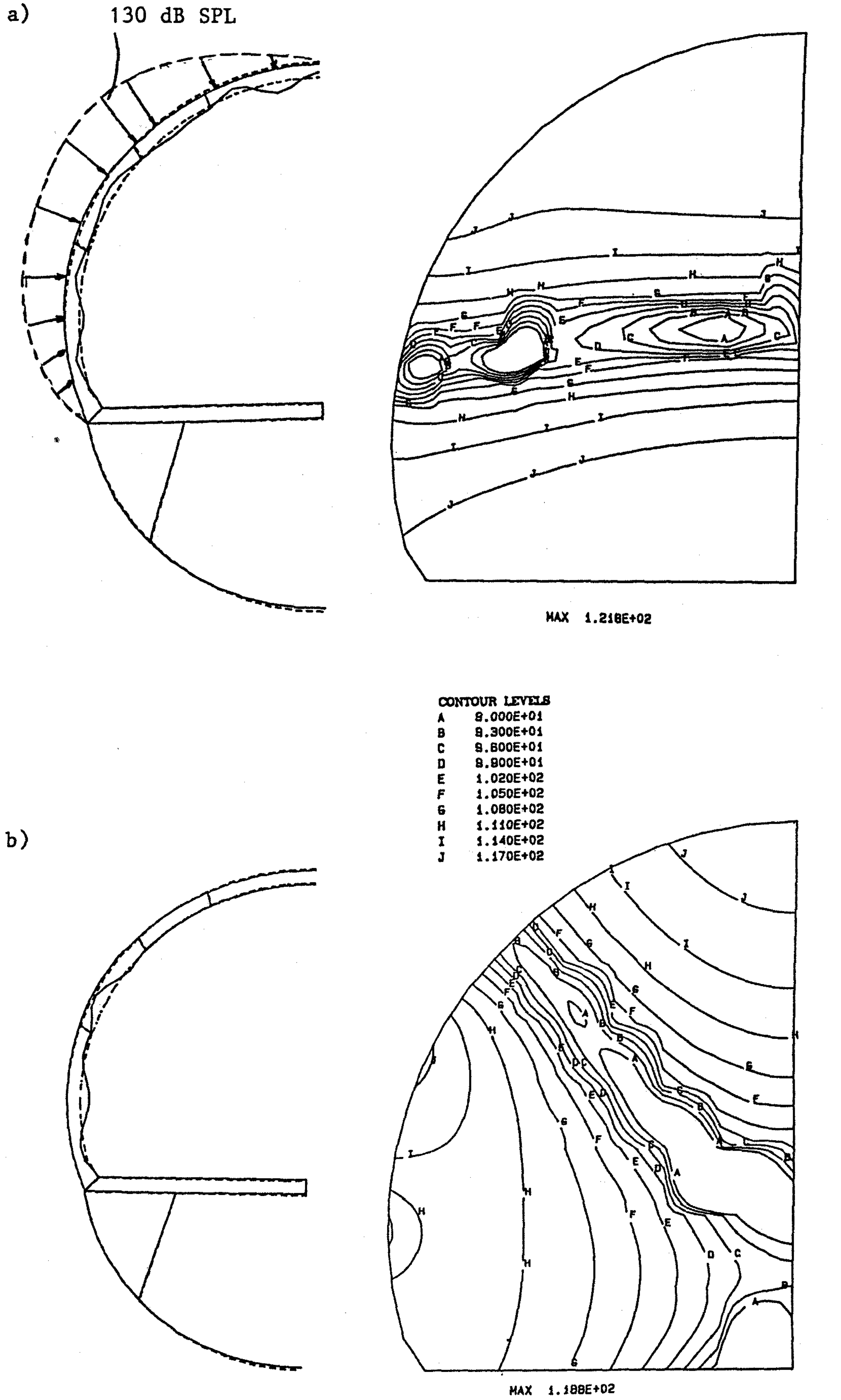

FIGURE 3 Frequency response at 90 Hz. Loading in response cases a) case 1, b) case 2

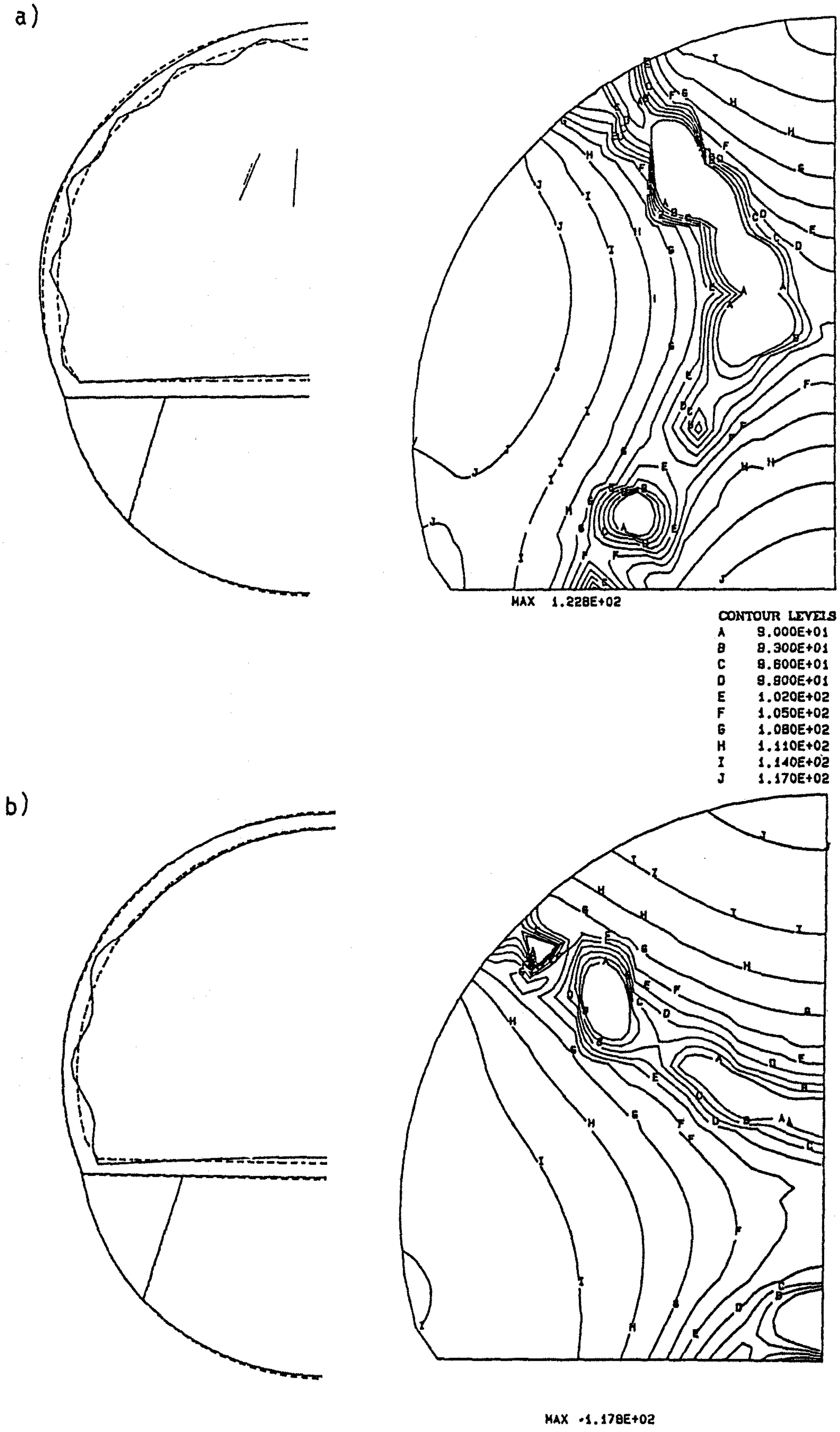

FIGURE 4 Frequency response at 90 Hz. a) case 3, b) case 4

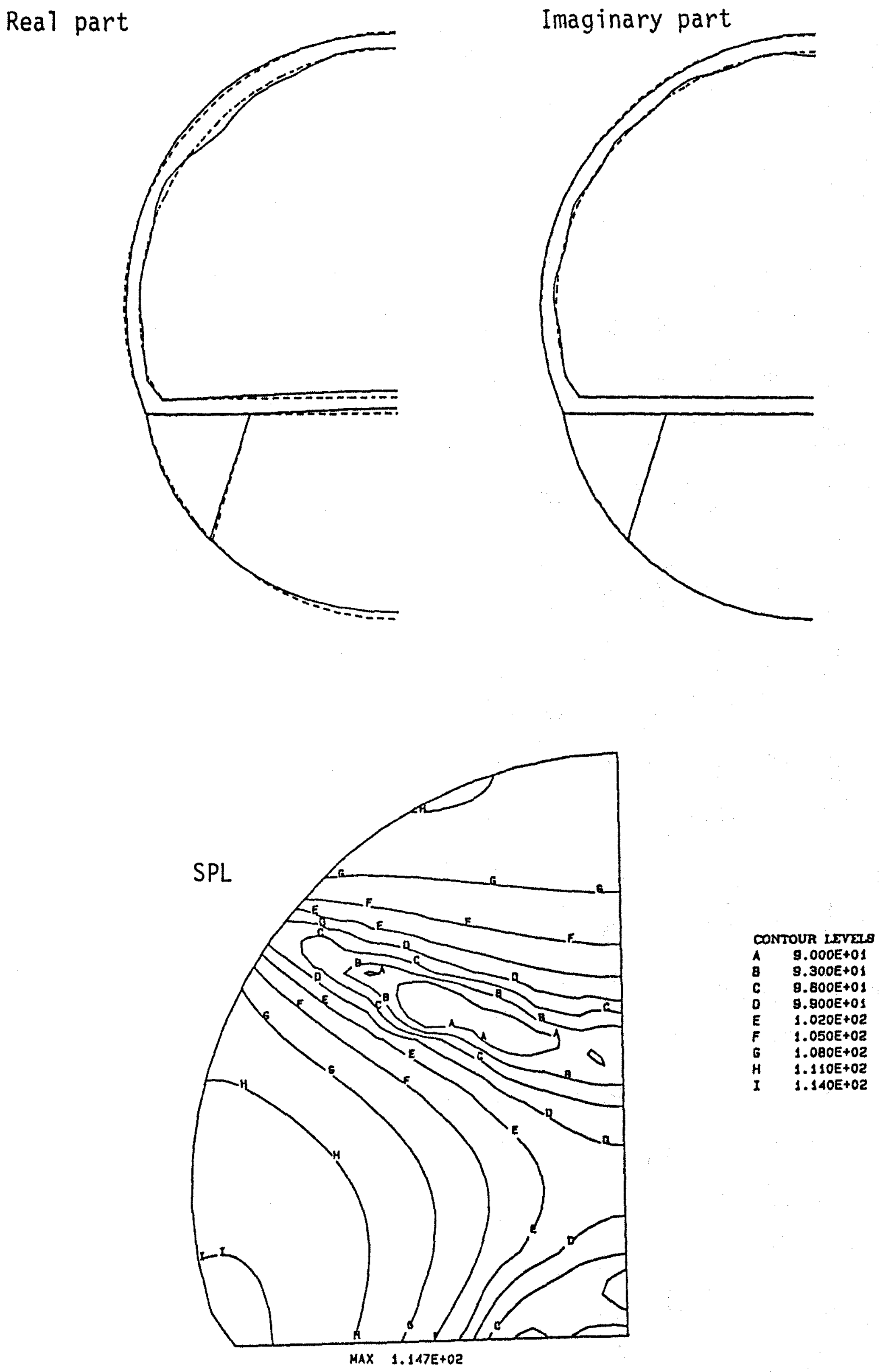

FIGURE 5 Response at 90 Hz with thermal insulation