ACOUSTIC-STRUCTURAL INTERACTION WITH MSC/NASTRAN: A REVIEW

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1. ABSTRACT

In this paper an attempt to review the acusto-structural interaction analysis capability of the MSC/NASTRAN is made. The pressure formulation and the velocity potential approach, are considered together with a complete assessment of the acoustic analogy from different point of view. Several numerical results are presented showing the comparison between theoretical and numerical applications. The effect of changing finite elements, and some specific parameters of the formulation are shown for both 2D and 3D models, giving some final considerations on the applicability and reliability, both for the theory and its numerical implementations.

2. INTRODUCTION

In the last ten years, a large numbers of paper, involving the capability to solve some specific scalar field problem using the F.E.M. (Finite Element Method) and using the capability of the MSC/NASTRAN have been presented (ref. [1],[2],[4],[5],[6],[9],[12]). On the basis of the fluid structure analogy, which will be later presented after, it was attempted to solve some of the historical problems of the commercial aircraft, like the prediction of the interior noise, and eventually, its control. The goal of this work is to make some considerations about the F.E. simulations of the fluid-structure interaction , specifically for the acousto-structural coupling. In all problems involving submerged structures, scattering of sound waves, piping systems, and also interior noise, the starting equation is the classical wave equation :

$$(1) \qquad \nabla^2 p = \frac{\ddot{p}}{(c*c)}$$

with p is the unknown fluid pressure in the medium
c is the speed of sound
∇ is the gradient operator

The boundary condition which we are dealing with is :

$$(2) \qquad p_{,n} = - d_f * (\ddot{q}_n)$$

where dots denote time partial derivative

- $,n$ — partial derivative with respect to the variable n
- n — the unit outward normal vector
- q_n — the normal structural displacement
- d_f — the fluid density

The analogy between the NAVIER-STOKES elasticity equations, and the common scalar field equation (1) (rif. [4]), is such that the NASTRAN can solve the wave equation. It is no need to remember that the application of the analogy, is such that for all problems involving a fluid contained inside a rigid close wall yields to the following F.E. matrix formulation of the (1) :

$$(3) \qquad [\, Ma \,] \{ \ddot{p} \} + [\, Ka \,] \{ p \} = \{ 0 \}$$

where [Ma] = generalized fluid mass matrix
[Ka] = generalized fluid stiffness matrix

in which the dissipation terms have been neglected. In such a case, the differences between formulations of coupled solutions presented in the following paragraphs, vanish because the modal representation of the isolated fluid is already in the optimal matricial form. In this case the only informations, that NASTRAN needs, are those regarding the analogy. It should be remembered that the way in which the analogy is established is the following . The fluid, more generally the scalar field, is considered like a 'structure' in way to obtain the resolution of the (1). This is possible if one gives the proper values to the common elasticity costants, like E,G,v. This time the constants have not specific physical sense, but the goal is only to build the equation (1). In elasticity application the stress-strain relationships are represented by a 6x6 (or 3x3 in 2D case) symmetrical matrix, whose general term is Gij. It is not difficult to show (ref.[4],[5],[6]) that for the F.E. simulation of the scalar field the matrix have to be the following (except for a costant) :

$$(4)\quad 2D: \begin{bmatrix} 1 & -1 & 0 \\ -1 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad 3D: \begin{bmatrix} 1 & -1 & -1 & 0 & 0 & 0 \\ -1 & 1 & -1 & 0 & 0 & 0 \\ -1 & -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

With the proper values of E,G,v in MAT1 cards one can obtain the previous matrices,or more simply using a MAT9 cards.

3. FLUID-STRUCTURE ANALOGY FORMULATIONS

The previously illustrated acoustic analogy, has lead to write,to test and to apply a common approach for the coupled problem of an acoustic field that interacts with a vibrating structure (ref.[1],[2],[5],[10]).It is interesting to present a possible review of the different forms in which the coupling can be established for both 2D and 3D models. It'should be remembered that the first condition for the application of the analogy is that the displacement in the F.E. model of the acoustic field must be written in one of these three ways :

1) T1=T2=R1=R2=R3=0 2) T1=T3=R1=R2=R3=0 3) T2=T3=R1=R2=R3=0

where Ti = displacements along i-direction
Ri = rotations around i-axis

It is well known that the only unconstrained d.o.f. represents the scalar unknown,p, whatever form of the analogy we are using.

<u>FORM 1 : Ref.[4] Unsymmetrical formulation A</u>

<u>Equation</u> : $\underline{\nabla} * \underline{\nabla}\, p = \dfrac{1}{c*c}\,(\ddot{p})$

<u>Material properties</u> : (2D model) E = 1.0E-5
(MAT1 cards) G = 1.0
v = - 0.999995
(3D model) E = 1.0E20
G = 1.0
v = 5.0E19

<u>Density</u> (RHO in MATi CARDS) : d = 1 / (c*c)

Hooke relations (stress-strains) :

$$2D : \begin{bmatrix} 1 & -1 & 0 \\ -1 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad 3D : \begin{bmatrix} 1 & -1 & -1 & 0 & 0 & 0 \\ -1 & 1 & -1 & 0 & 0 & 0 \\ -1 & -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Boundary condition for the coupling:
with the used notation is

$$p_{,n} = - d_f \, (\ddot{q}_n)$$

also

$$p_{,n} = \nabla p \cdot \underline{n}$$

The application of the analogy is such that , if T1 is the only unconstrained d.o.f. :

$$p_{,n} = s_{xx} \cdot n_x + s_{xy} \cdot n_y + s_{xz} \cdot n_z = Tx$$

where Tx is a superficial tensile load and s_{ij} are the stresses. The last equation can be written as

$$Tx = \frac{Fa}{A} \quad \text{to obtain} \quad Fa = - d_f \cdot A \cdot (\ddot{q}_n)$$

The Fa is the F.E. simulation of the boundary condition and represents the effect of the structure on the fluid.The reversal is expressed by a force Fb, such that : Fb = p·A

The F.E. final form of the coupled model is the following :

$$\begin{bmatrix} Ms & 0 \\ -d_f A^T & Ma \end{bmatrix} \{ \ddot{x} \} + \begin{bmatrix} Ks & A \\ 0 & Ka \end{bmatrix} \{ x \} = \{ F \}$$

where $\{ x \} = \{ q , p \}^T$
[A] = areas matrix
[Ks] = structural stiffness matrix
[Ms] = structural mass matrix
{ x } = unknown vector
{ F } = known vector

FORM 2 : Ref.[1] Unsymmetrical formulation B

Equation :

$$\frac{1}{d_f} \left(\underline{\nabla} * \underline{\nabla} p \right) = \frac{1}{c*c*d_f} \left(\ddot{p} \right)$$

Material properties : They have to be such that the Hooke relations are verified

Density (RHO in MATi CARDS) : $d = 1 / (d_f * c * c)$

Hooke relations (stress-strains) :

$$2D : \frac{1}{d_f} * \begin{bmatrix} 1 & -1 & 0 \\ -1 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad 3D : \frac{1}{d_f} * \begin{bmatrix} 1 & -1 & -1 & 0 & 0 & 0 \\ -1 & 1 & -1 & 0 & 0 & 0 \\ -1 & -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Boundary condition for the coupling :
following the same previous considerations

$$Fa = - A \cdot (\ddot{q}_n) \qquad Fb = p \cdot A$$

The F.E. final form of the coupled system is the following:

$$\begin{bmatrix} Ms & 0 \\ -A^T & Ma \end{bmatrix} \{ \ddot{x} \} + \begin{bmatrix} Ks & A \\ 0 & Ka \end{bmatrix} \{ x \} = \{ F \}$$

FORM 3 : Ref.[5] Unsymmetrical formulation C

Equation :

$$(d_f * c * c) \left(\underline{\nabla} * \underline{\nabla} p \right) = d_f \left(\ddot{p} \right)$$

Material properties : They have to be such that the Hooke relations are verified

Density (RHO in MATi CARDS) : $d = 1 / (d_f)$

Hooke relations (stress-strain) :

$$2D: (c*c*d_f) \begin{bmatrix} 1 & -1 & 0 \\ -1 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad 3D: (c*c*d_f) \begin{bmatrix} 1 & -1 & -1 & 0 & 0 & 0 \\ -1 & 1 & -1 & 0 & 0 & 0 \\ -1 & -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Boundary condition for the coupling:

again following the previous considerations

$$F_a = - A \cdot (\ddot{q}_n) \cdot (d_f \cdot c^2) \qquad F_b = p \cdot A$$

The F.E. final form of the coupled system is the following:

$$\begin{bmatrix} M_s & 0 \\ -A^T (d_f\, c^2) & M_a \end{bmatrix} \{ \ddot{x} \} + \begin{bmatrix} K_s & A \\ 0 & K_a \end{bmatrix} \{ x \} = \{ F \}$$

FORM 4 : Ref.[6] Symmetrical formulation

Equation :

$$\frac{1}{d_f} (\underline{\nabla} * \underline{\nabla}\, p) = \frac{1}{c*c*d_f} (\ddot{p})$$

Material properties :

$$E = \alpha\, \beta$$
$$G = \beta$$
$$v = (\alpha/2 - 1)$$

The values of α and β will be specified later.

Density (RHO in MATi CARDS) : $d = \beta / (c*c)$

Hooke relations (stress-strain) :

$$\text{2D:}\ \beta * \begin{bmatrix} 1 & -1 & 0 \\ -1 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad \text{3D :}\ \beta * \begin{bmatrix} 1 & -1 & -1 & 0 & 0 & 0 \\ -1 & 1 & -1 & 0 & 0 & 0 \\ -1 & -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Boundary condition for the coupled system:

still following the previous approach one obtains

$$\begin{bmatrix} M_s & 0 \\ -d_f\, \beta\, A^T & M_a \end{bmatrix} \{ \ddot{x} \} + \begin{bmatrix} K_s & A \\ 0 & K_a \end{bmatrix} \{ x \} = \{ F \}$$

Introducing a new variable z ,it can be established that

$$p = \dot{z}$$

and integrating the previous differential equations with the new unknown vector

$$\{ y \} = \{ q , z \}^T$$

and establishing that $\beta = - 1/d_f$ it is possible to obtain

$$\begin{bmatrix} Ms & 0 \\ 0 & Ma \end{bmatrix} \{ \ddot{y} \} + \begin{bmatrix} 0 & A \\ A^T & 0 \end{bmatrix} \{ \dot{y} \} \begin{bmatrix} Ks & A \\ 0 & Ka \end{bmatrix} \{ y \} = \{ F \}$$

In this case the output NASTRAN velocities will be the unknown pressure.The material properties have to be calculated by the previous value of β and the following values of α :

2D model : $\alpha = 1.0$ E-5 3D model : $\alpha = 1.0$ E+20

3. APPLICATION TO 2D AND 3D MODELS

It should be noted that the first three forms of the F.S.I are the same, in fact the only variations are for the material properties (MAT1 or MAT9 cards) .The only formulation that presents an important different characteristic is the fourth,because the matrices are all symmetrical, and the analogy is established between the velocities (not the displacements) and the pressures. In fact the unknown, this time, is a velocity potential gradient.At this point, it was choiced to develop for the following applications only the formulations (1) and (4), that was distinguished simply like

UNSYMMETRICAL FORMULATION and SYMMETRICAL FORMULATION

Also,it is should be noted that in the unsymmetrical formulation,the NASTRAN solution is such that, in the same run, the user can obtain pressures and pressure gradients.If the symmetrical formulation is used,in order to obtain the pressure variations and their distribution, it is necessary to post-process NASTRAN output data.In the following,the characteristics of the cylindrical model,used for the tests,are given while the discussion is presented in the next paragraph.

METALLIC CYLINDER SIMPLY SUPPORTED WITH AIR IN THE INTERIOR

STRUCTURE

radius.................: 36 inches,914.4 mm
lenght.................: 160 inches,4064. mm
thickness..............: 0.032 inches,0.808 mm.
Young's modulus........: 10.5E6 lb/in*in , 7382.35 kp/mm*mm
Poisson's modulus......: 0.3
density................: 1.146E-7 lb s*s/(in**4)
2.85E-10 kp s*s/(mm**4)

FLUID

density................: 1.146E-7 lb s*s/(in**4)
1.25E-13 kp s*s/(mm**4)
bulk modulus...........: 20.55794 lb /(in*in)
0.1445 kp /(mm*mm)
speed of sound.........: 13394 in / s
340197 mm / s

INFINITE CYLINDER (2D)

MODEL WITHOUT EDGE NODES

	GRID	ELEMENTS
STRUCTURE	21	20 BAR
FLUID	169	160 QUAD/4 , 20 TRIA3

MODEL WITH EDGE NODES

	GRID	ELEMENTS
STRUCTURE	41	40 BAR
FLUID	497	160 QUAD/8 , 20 TRIA/6

FINITE CYLINDER (3D)

MODEL WITHOUT EDGE NODES

	GRID	ELEMENTS
STRUCTURE	252	220 QUAD/4
FLUID	2028	1540 HEXA , 240 PENTA

MODEL WITH EDGE NODES

	GRID	ELEMENTS
STRUCTURE	723	220 QUAD/4
FLUID	7823	1540 HEXA/20,240 PENTA/15

4. RESULTS

Using the equations presented in the previous paragraphs and the described coupled models,some computations have been carried out in order to obtain a comparison among

A.1) Analogy formulation
A.2) Numerical vs. theoretical results
A.3) CPU computer time (for a SOL 26 of MSC/NASTRAN)

A.1 Analogy formulation

The numerical comparison has showed no differences between the unsymmetrical formulation and the unsymmetrical one.This has been tested and verified both for the modal analysis of the isolated fluid and for the dynamic response of the coupled models.

A.2 Numerical vs. theoretical results

The choice of cylindrical model has not been casual.The problems involving above-mentioned coupled models have a theoretical representation that uses BESSEL's functions (rif.1),and therefore a such test case for the F.E. simulation of the coupling is the most suitable. For both 2D and 3D models,the spectral dynamic responses of four points is reported whose cylindrical coordinates are

Point 1 :	Structural	x = L/2 ;	r=R ;	phi = 0
Point 2 :	Acoustic	x = L/2 ;	r=R ;	phi = 0
Point 3 :	Acoustic	x = L/2 ;	r=R/2 ;	phi = 0
Point 4 :	Acoustic	x = L/2 ;	r=0 ;	phi = 0

(the x axis no exists in 2D models)

The point 1 is excited by a white noise frequency spectrum load.The reported plots show that the structural response is always obtained with a good accuracy with respect to the theoretical model in both 2D and 3D models (fig. 1).Also the acoustic response of the point 2 has the same good theoretical-numerical comparison for both 2D and 3D models (figg.2 and 6).The F.E. solution shows some numerical oscillation around the theoretical values, for the acoustic points,3 and 4,wherethe effect of some acoustic high frequency mode is relevant.Such problem is more evident in the case of models with edge nodes are augmented (figg.3, 4, 7, 8).The effect can be attributed to the inadequate shape functions used in the F.E. code for such elements.

A.3 CPU Computer time

The figures 5,9,10 show some important remarks about the CPU time for the execution of SOL 26 of MSC/NASTRAN having used like independent variable the requested frequency number (FREQ1 cards).For both 2D and 3D models it is evident that the unsymmetrical formulation (with or without edge nodes) runs always more 'slowly' than the symmetrical one.The difference is reduced using is edge nodes elements, because the dimensions of the matrices overcome the effects of the simmetry or unsymmetry (fixing all other conditions). This effect is measured by the alpha parameter defined like

$$\alpha = (T1 - T2) / T1$$

where T1 : CPU NASTRAN time for unsymmetrical formulation
T2 : CPU NASTRAN time for symmetrical formulation

The results for the 3D model with edge nodes solid elements are not so far available because the costs for obtaining them are outside the goals and the needs of this paper.

5. CONCLUSIONS

From this work the following final considerations can be drawn,regarding all the problems in which a fluid interacts with a surrounding structure:

- The shape functions used by F.E. code are not always adequate for the simulation of acoustic field.
- A simple increase of the mesh leads to unacceptable time computer costs, with particular regard to the actual hardware and software.

As a consequence of this a future goal for a total standardization and reliability of the coupled fluid-structure finite element procedure,could be the implementation of an 'acoustic oriented' element that uses proper shape functions, and fits the necessary requirements for an and a more general use

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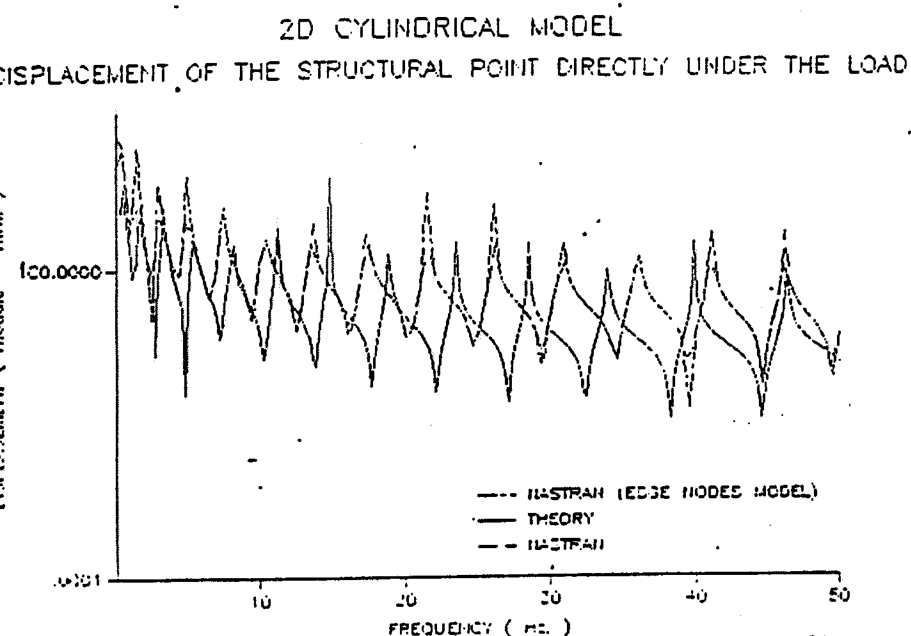


fig. 1

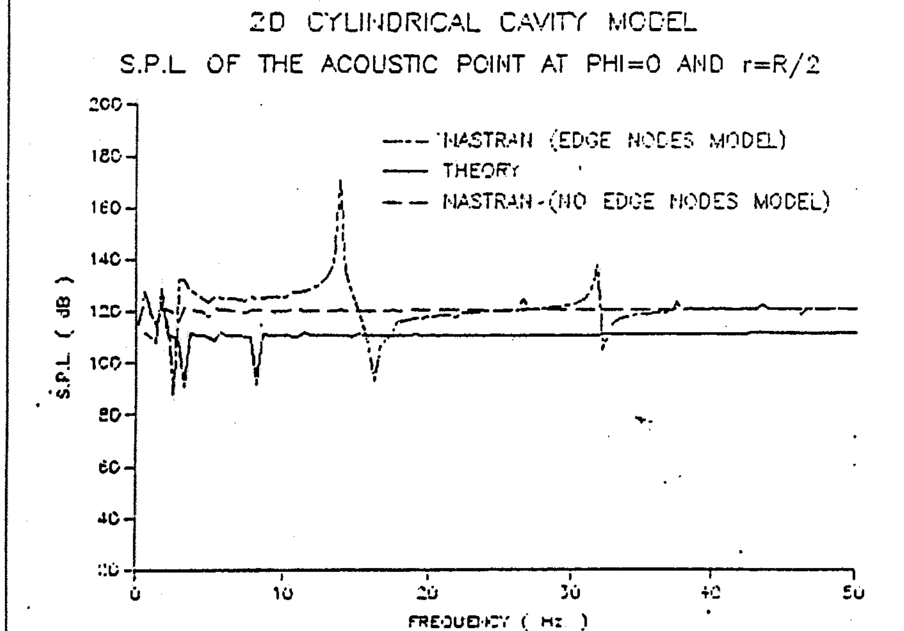


fig. 3

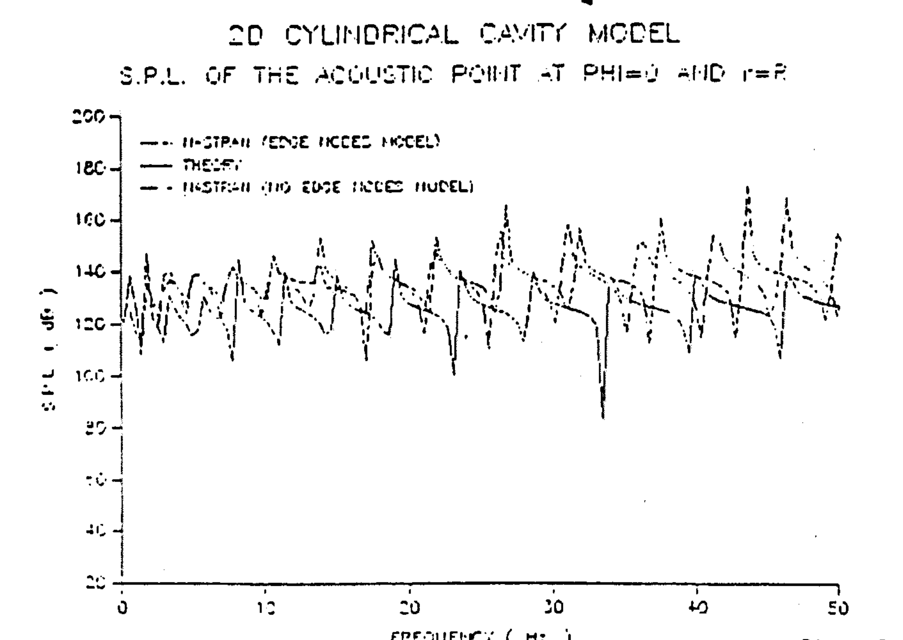


fig. 2

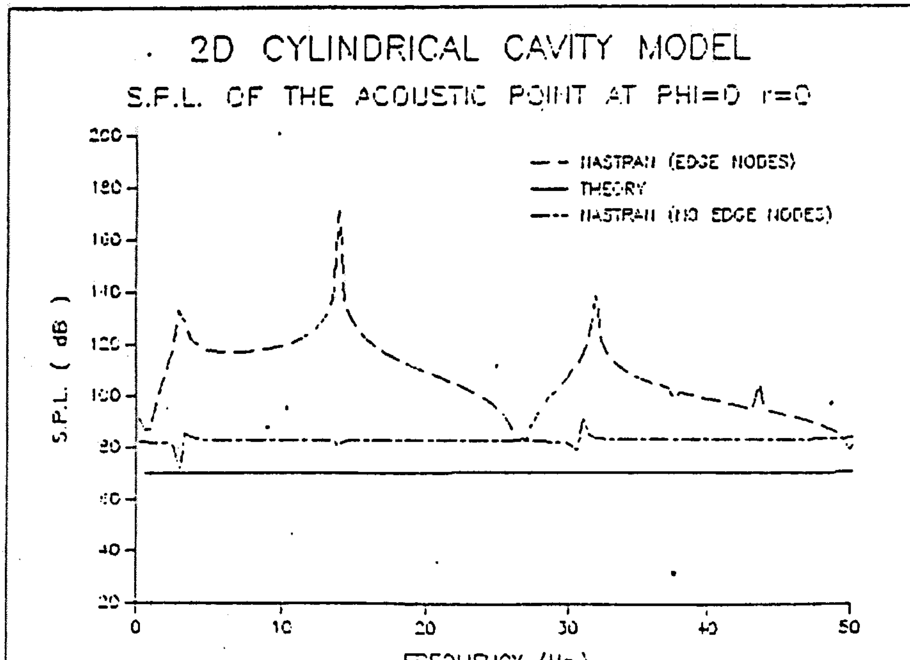


fig. 4

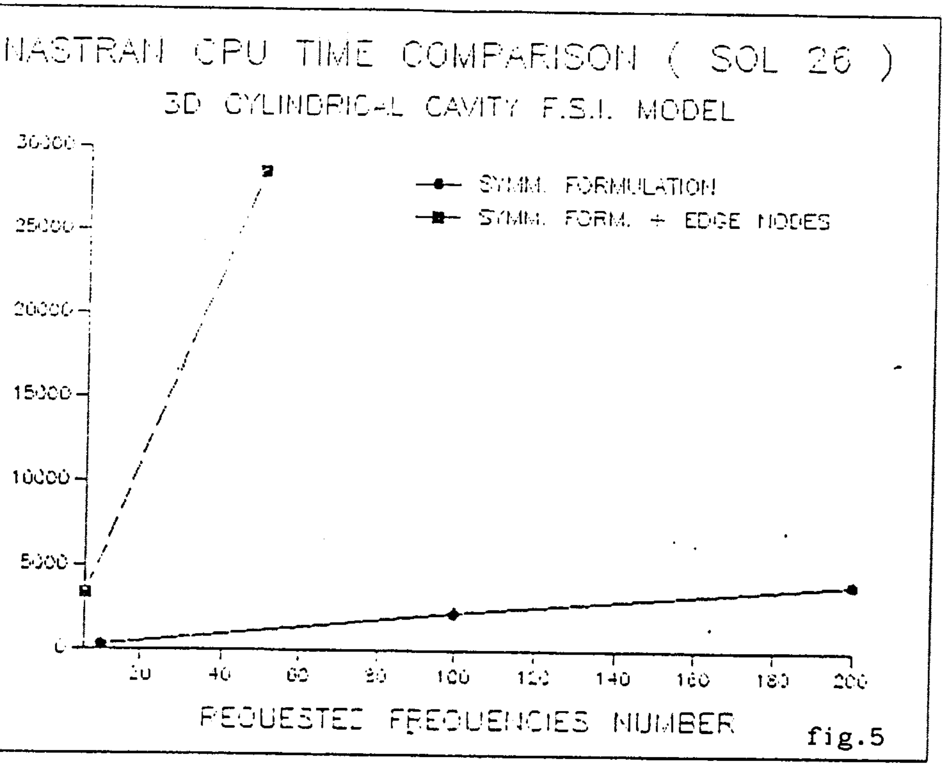

NASTRAN CPU TIME COMPARISON (SOL 26)
3D CYLINDRICAL CAVITY F.S.I. MODEL
SYMM. FORMULATION
SYMM. FORM. + EDGE NODES
30000
25000
20000
15000
10000
5000
0
20
40
60
80
100
120
140
160
180
200
REQUESTED FREQUENCIES NUMBER

fig.5

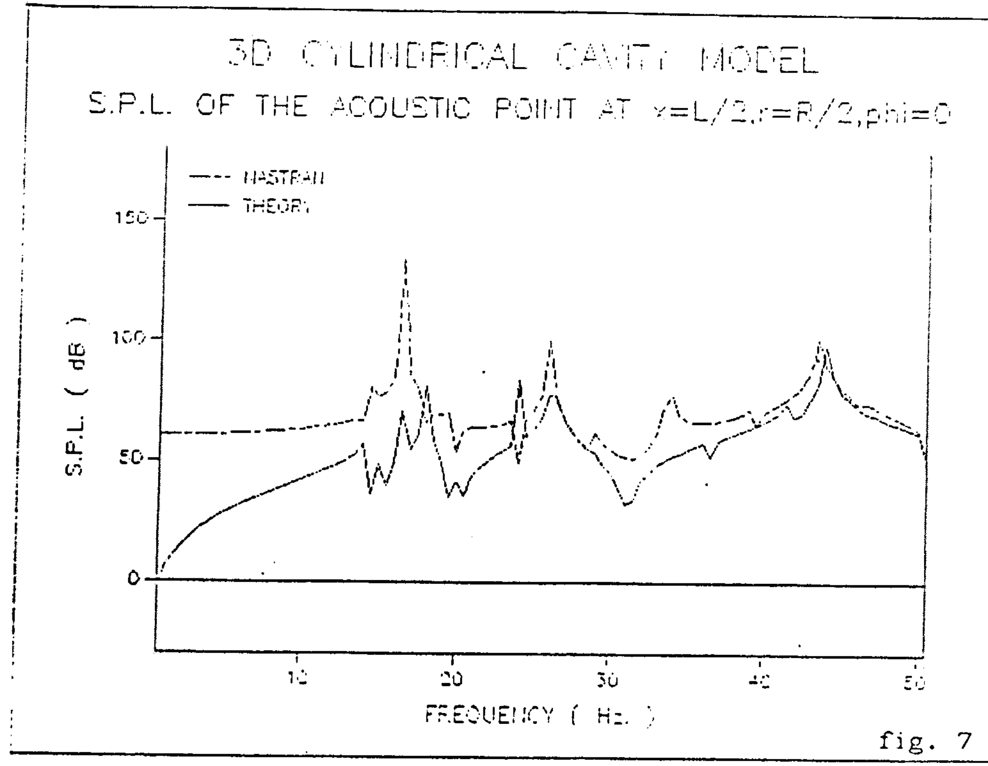
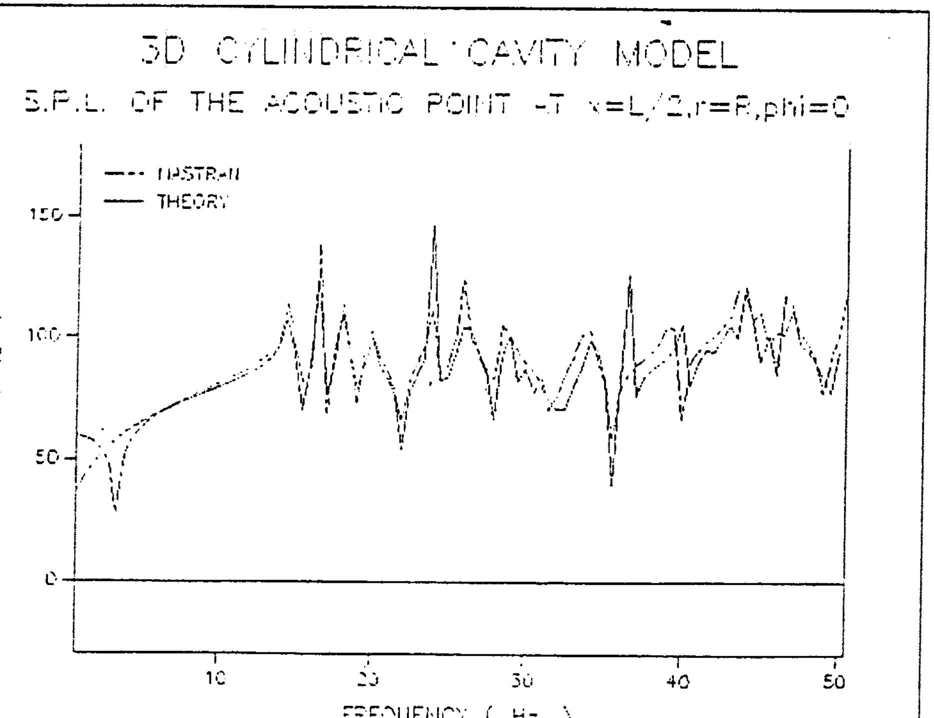
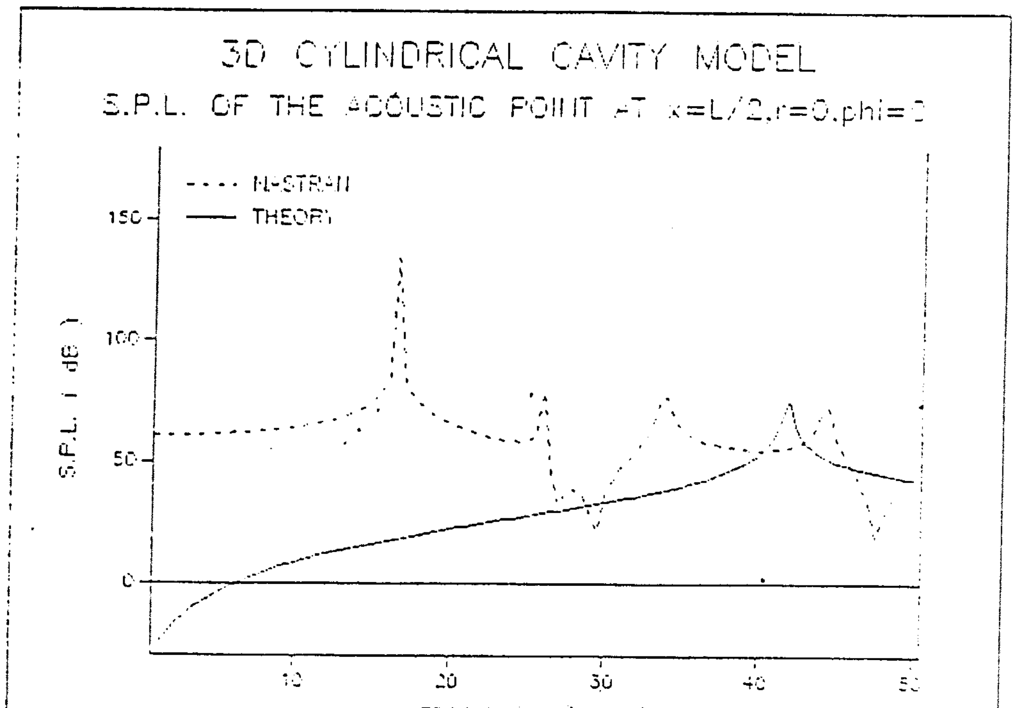

3D CYLINDRICAL CAVITY MODEL
S.P.L. OF THE ACOUSTIC POINT AT x=L/2,r=R/2,phi=0
NASTRAN
THEORY
S.P.L. (dB)
150
100
50
0
10
20
30
40
50
FREQUENCY (Hz.)

fig. 7


3D CYLINDRICAL CAVITY MODEL
S.P.L. OF THE ACOUSTIC POINT AT x=L/2,r=R,phi=0
NASTRAN
THEORY
150
100
50
0
10
20
30
40
50


3D CYLINDRICAL CAVITY MODEL
S.P.L. OF THE ACOUSTIC POINT AT x=L/2,r=0,phi=0
NASTRAN
THEORY
S.P.L. (dB)
150
100
50
0
10
20
30
40
50

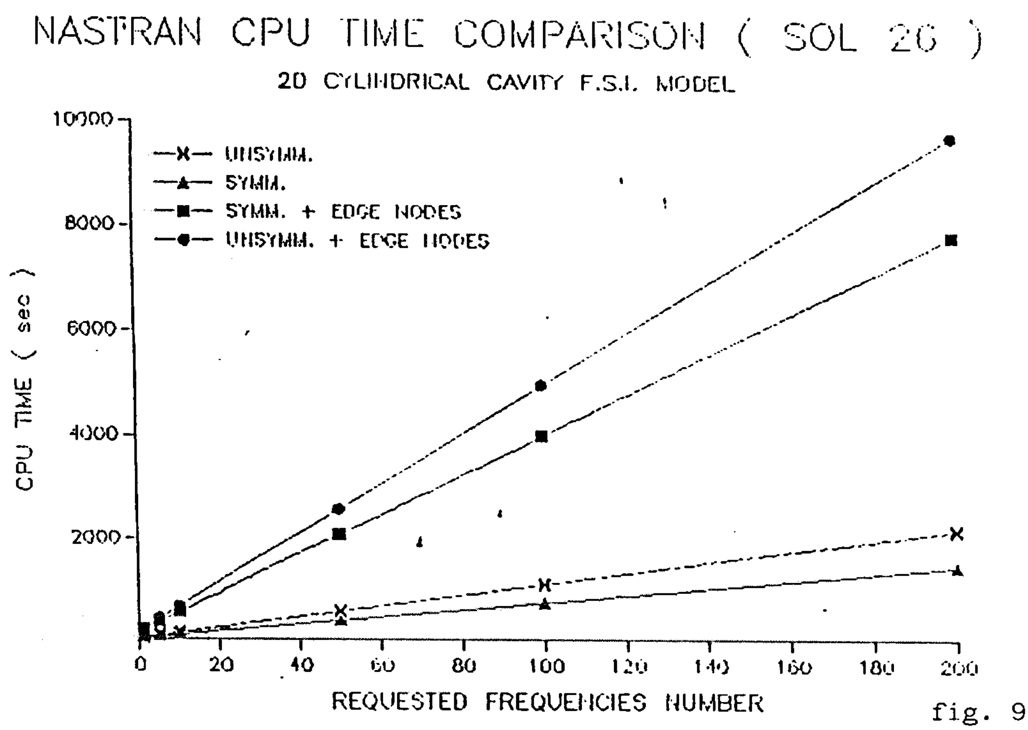

NASTRAN CPU TIME COMPARISON (SOL 26)
20 CYLINDRICAL CAVITY F.S.I. MODEL
UNSYMM.
SYMM.
SYMM. + EDGE NODES
UNSYMM. + EDGE NODES
CPU TIME (sec)
10000
8000
6000
4000
2000
0
20
40
60
80
100
120
140
160
180
200
REQUESTED FREQUENCIES NUMBER

fig. 9

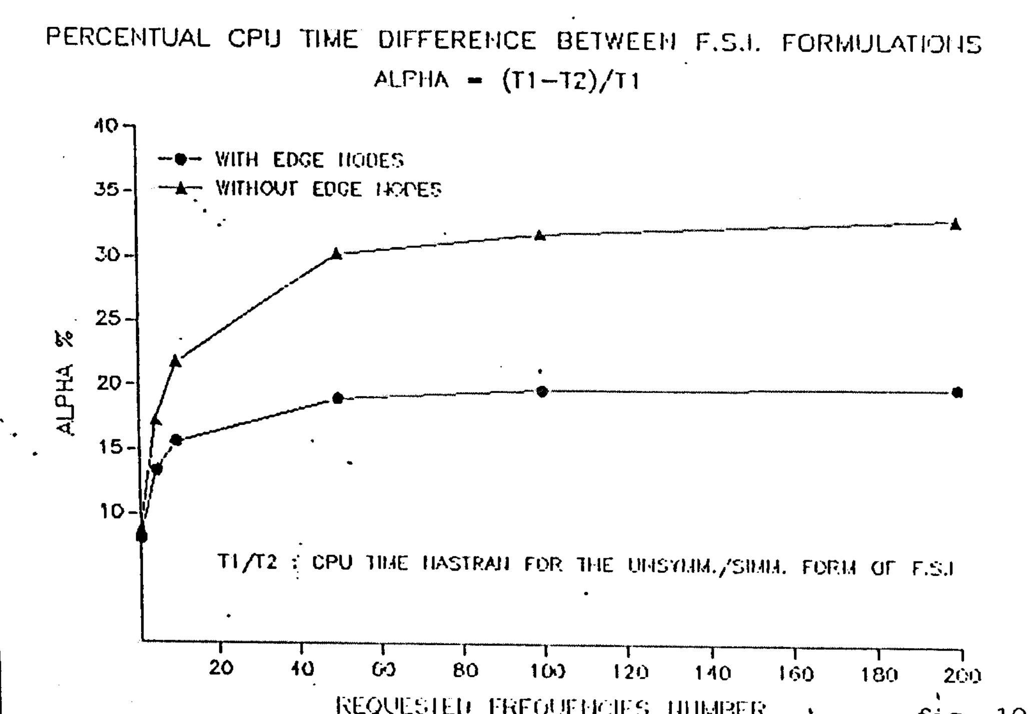

PERCENTUAL CPU TIME DIFFERENCE BETWEEN F.S.I. FORMULATIONS
ALPHA = (T1-T2)/T1
WITH EDGE NODES
WITHOUT EDGE NODES
ALPHA %
40
35
30
25
20
15
10
T1/T2 : CPU TIME NASTRAN FOR THE UNSYMM./SIMM. FORM OF F.S.I
20
40
60
80
100
120
140
160
180
200
REQUESTED FREQUENCIES NUMBER

fig. 10