A COMBINED FINITE ELEMENT-BOUNDARY ELEMENT MODEL FOR THE IN-WATER BEHAVIOR OF A HYDRAULICALLY DRIVEN PROJECTOR

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1. INTRODUCTION

This report describes a three-dimensional in-water analysis of a low frequency projector that utilizes a hydraulic mechanism to drive two opposing flexural disks. Initial testing of the projector showed a significant deviation from the flat frequency response predicted by an axisymmetric fluid-structure model. During testing it was suspected that this problem was caused by hydraulic oil inside the projector loading the radiating plates and causing asymmetric higher order modes to be excited. Because the internal fluid loading cannot be accurately included in a two-dimensional model, a three-dimensional model of the projector was constructed and used to determine the in-water behavior of the projector for various levels of internal hydraulic fluid. Results of the analysis are given here along with a description of the procedure used for combining a finite element model of the structure with a boundary element approach for modeling the fluid loading. In the construction of the finite element models the dimensions of the projector have been normalized and therefore all of the frequency results presented in this report are shifted relative to the normal operating frequency range of the projector.

2. BACKGROUND

A photograph of a prototype design for the hydraulically driven projector is shown in Figure 1. Figure 2 shows two simple cross-sectional schematics of the final projector design. The primary components of the hydraulic power supply are an electric motor powering a hydraulic pressure pump. Most of the components making up the hydraulic system are part of a manifold inside of the projector. An external heat exchanger is used to cool the hydraulic fluid, and the cavity formed by the projector housing and flexural disks is used as a reservoir for the hydraulic fluid.

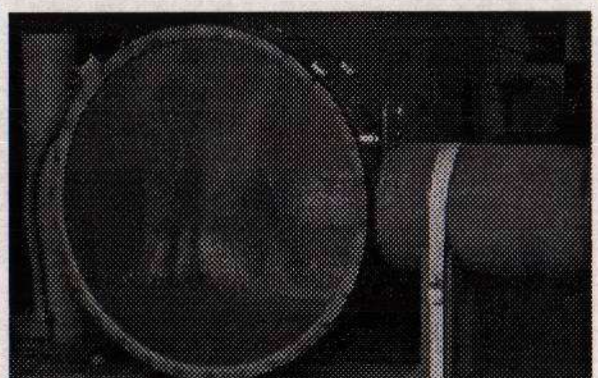

Figure 1 Photograph of the hydraulically driven projector (a prototype model).

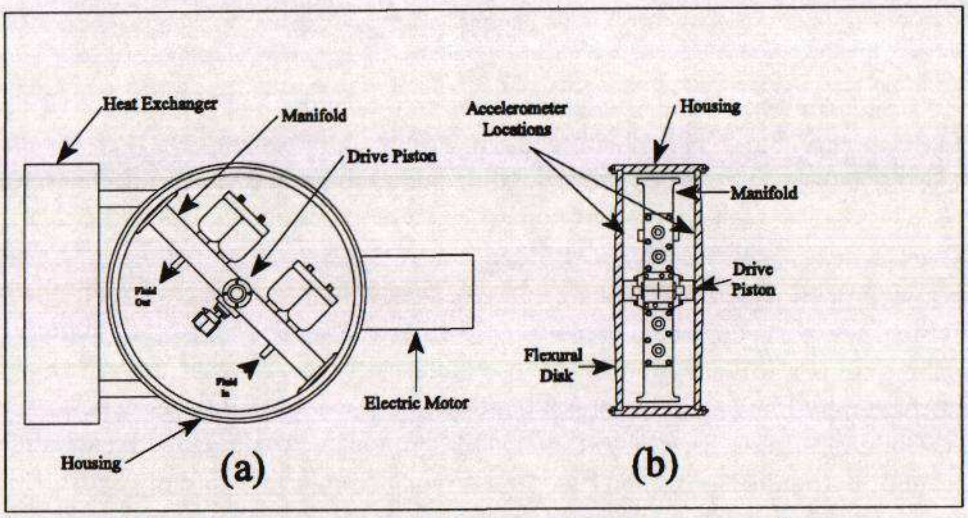

Figure 2 (a) A simple schematic showing a broadside view of the projector without the flexural disks. (b) Simple schematic showing an end-on cut-away view of the projector.

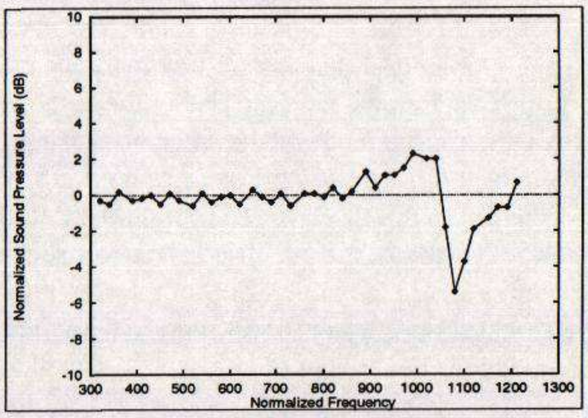

Figure 3 Acoustic output as measured by a hydrophone versus normalized frequency for the projector.

Accelerometers mounted on the inside faces of the disks (at the locations indicated in Figure 2b) are used in a feedback loop to control the projector's volume velocity. The accelerometers are also used to monitor the acoustic output of the projector. The hydraulic drive mechanism used for the projector is nonlinear. The feedback system for the projector (the accelerometers and the associated electronics) is designed to linearize the response of the projector and to allow for control of the acoustic output. During initial testing of the projector, however, it was found that the acoustic output versus frequency deviated significantly from the anticipated flat response. This is shown in Figure 3 where the acoustic output as measured by a hydrophone is plotted versus a normalized frequency. Note that there is a significant drop in the acoustic output near the upper end of the band. During testing it was suspected that this problem was caused by the hydraulic fluid loading the radiating plates and causing the higher order asymmetric modes to be excited. This behavior was observed for various amounts of hydraulic fluid. The effect is smaller for lower fluid levels; however, the fluid level could not be reduced to the point where the effect was eliminated.

3. MODELING

A combined finite element-boundary element modeling technique [1] is necessary because of the complexity of the projector. This method can, in principal, be used to analyze any structure that can be discretized. However, when more detail is added to the model, the finite element mesh becomes more elaborate resulting in larger matrices which could jeopardize the integrity of the solution. Therefore, only details that significantly affect the results are modeled. Another important modeling consideration is to describe properly the interfaces between different parts of the structure, i.e., parts defined as separate pieces of the same or different material. A two-dimensional model is adequate to address these issues. However, because of the asymmetry of the projector when hydraulic fluid is present, a three-dimensional model is necessary when including the internal fluid. Five three-dimensional models were developed, each representing a different level of hydraulic fluid. The fluid levels range from no fluid (empty) to a fluid level covering half of the flexural disk. Each of these models was run at a discrete set of frequencies. The normalized results are presented and compared with experimental results. A brief description of the combined boundary element-finite element method is given followed by the two-dimensional and three-dimensional analysis of the projector.

3.1 Finite Element-Boundary Element Method

The combined finite element-boundary element modeling technique [1] can be used to analyze fluid-loaded transducers to obtain the displacements of the structure at various frequencies. The acoustic field effects can be calculated using the numerical code CHIEF [2] (Combined Helmholtz Integral Equation Formulation). With this boundary element code, the pressure at any point in the fluid can be found provided that the velocity is known everywhere on the surface of the structure. The in-vacuo structure problem can be solved by finite element techniques [3], however, the complete structure/fluid problem requires a coupling of the finite element description of the structure with the boundary element model since the structural response is dependent on the acoustic loading.

The finite element-boundary element discretization of an excited structure in water can be written as:

$$\{[K] - \omega^2[M] + j\omega[X][Z][X^T]\}\tilde{u} = \tilde{f} \tag{1}$$

where K refers to the stiffness matrix, M the mass matrix, $\tilde{u}$ the generalized displacement vector, $\tilde{f}$ the consistent applied force vector, X the compatibility matrix, Z the mutual coupling (radiation impedance) matrix and ω the driving frequency in radians. Every matrix except Z can be generated by the finite element code. The impedance Z which describes the fluid-loading effects on a vibrating structure can be generated by CHIEF. CHIEF is a "patch" code which means that the surface pressures and normal velocities are constant over each element or patch. To combine the Z matrix from CHIEF with the nodal description from the finite element code, a matrix X is needed to transform from a surface element (patch) discretization to a nodal discretization. Each column of the X matrix contains the nodal consistent forces resulting from a unit pressure applied on the corresponding surface element.

Each of the matrices in Equation 1 can be computed and written to a file, and a computer program external to both the finite element and boundary element codes can calculate the nodal displacements and the normal velocities of the structure. It is also possible to modify the finite element source code to calculate the compatibility matrix X, read in the impedance matrix Z and perform the solution internal to the finite element code. The second implementation is generally more efficient, but is possible only if the finite element source code is available.

3.2 Two-Dimensional Analysis
The schematics shown in Figure 2 illustrate the complexity of the projector and the many components that must be considered for inclusion in a finite element model. Only those structures that affect the behavior of the flexural disks are necessary for this analysis. Because the drive pistons and disks form a balanced system about a vertical plane, many components do not have to be included in the finite element mesh. The internal hydraulic system is mounted to a manifold centered in the housing. It is assumed that the manifold and the attached components will not affect the behavior of the disk. The electric motor is attached to the center plane and so will also not be included in the model. The heat exchanger is also eliminated because it is shock mounted.

Figure 4 is a cut-away view of the simplified structure. Note that this schematic is not to scale. Many dimensions are exaggerated for the purpose of illustrating features that are important considerations in modeling. The flexural disks are constructed of aluminum, the housing and clamp ring of steel and the compliant pad of polyurethane. Note that the compliant pad is in contact with, but not attached to the flexural disk. The clamp ring has the sole purpose of keeping the flexural disk on the housing and does not

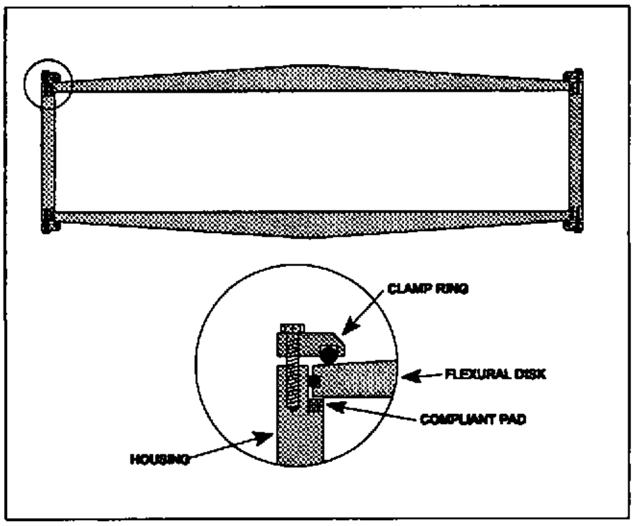

Figure 4 Schematic of the projector without any internal structure. This drawing is not to scale. Many dimensions are exaggerated to illustrate the interfaces between different parts of the structure.

provide a water seal. Figure 5 is an illustration of a two-dimensional axisymmetric model with the axis of rotation located at the center of the plate (through node 101) and a plane of symmetry (perpendicular to the axis of rotation) bisecting the housing. The drive piston shown in Figure 2 is represented in the model by a constant force applied to the center of the disk (node 101 in Figure 5).

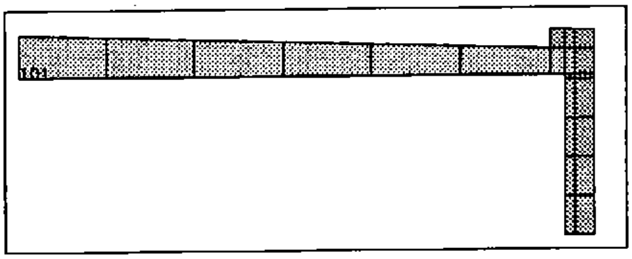

Figure 5 Two-dimensional finite element model of the projector.

This model was developed and exercised to obtain the behavior of the interfaces described above under various constraints in order to best simulate the disk behavior. All of the two-dimensional analyses that are discussed in this section are results from an in-vacuo eigenvalue solution.

The interfaces existing between the polyurethane, the steel and the aluminum were investigated in detail. The most reasonable boundary condition was a rigid connection between the base of the pad and the steel housing. This rigid connection guarantees that at this interface the two materials will move together. A slip condition is prescribed at the side of the pad and the housing and between the disk and the pad. A slip condition is a boundary condition that, for example, allows the disk and pad to move independently in the longitudinal direction, but forces them to move together in the transverse direction thus eliminating the nonphysical situation in which the two structures cross one another. The first in-vacuo flexural (breathing) mode occurs at 846 Hz, which is in agreement with the experimental result.

The effects of the clamp ring and the tapering of the disk were also examined. It turns out that the clamp ring and the upper portion of the housing have virtually no effect on the behavior of the flexural disk. Figure 6 is a two-dimensional finite element mesh of the projector with some of the structure eliminated as discussed above. The change from a tapered plate to a straight plate causes a significant change in the modal frequency and therefore the tapering remains in the final two-dimensional model. A material sensitivity analysis was also performed and it was concluded that the material properties of the polyurethane ring are critical in computing the modal frequency.

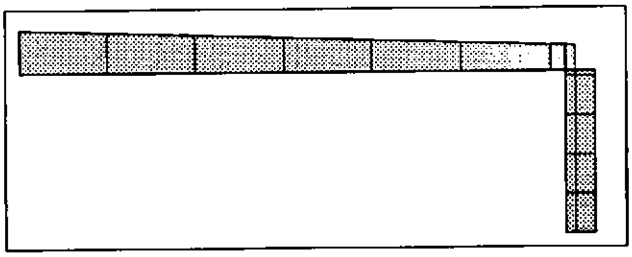

Figure 6 Final two-dimensional finite element model of the projector with the clamp ring removed.

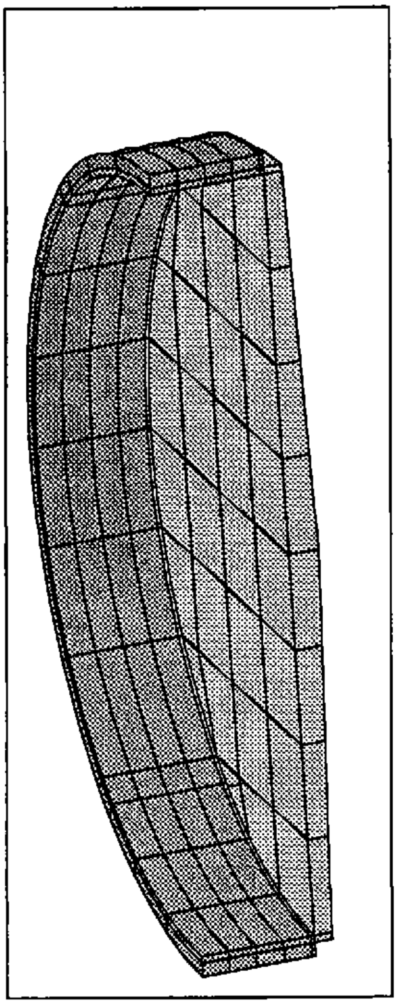

Figure 7 Three-dimensional finite element model with no internal fluid (empty).

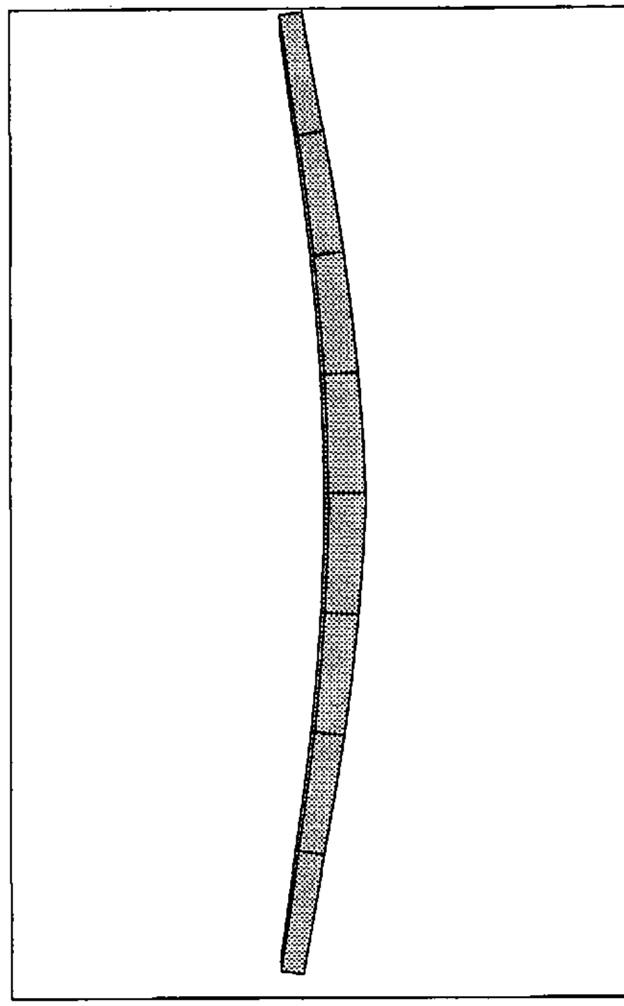

Figure 8 Cut-away view of the in-air breathing mode of the flexural disk with no internal fluid loading.

3.3 Three-Dimensional Analysis

The boundary conditions and final structure (after elimination of details) are determined using a 2-D model because it is computationally much faster than a 3-D model. However, since the 2-D model is axisymmetric, only "donuts" of internal fluid can be described which is not a realistic representation of the fluid. It is therefore necessary to develop a 3-D model to properly incorporate the internal fluid. Figure 7 is the finite element mesh of the projector with no internal fluid. This model has two planes of symmetry with a driving force at the center of the flexural disk to simulate the piston. The boundary conditions in the 3-D model are analogous to those used in the 2-D model. A cut-away view of the fundamental in-air (breathing) mode of the flexural disk is shown in Figure 8. The modal frequencies resulting from the 2-D and 3-D models of this mode agree to within 10 Hz. Having demonstrated that the 3-D model and the boundary conditions are defined correctly, the internal fluid elements are added as shown in Figures 9a-9d. A harmonic analysis is performed at each fluid level, including the case with no internal fluid, using the coupled finite element-boundary element method described above. The operating frequency range of this projector is between 300 and 1200 Hz on a normalized frequency scale. Two resonances were found in this frequency range and will be discussed separately in this section of the report.

The first in-water resonance in the operational frequency range of the projector is examined in order to demonstrate the accuracy of the finite element model. This resonance is found to occur at a frequency of 410 Hz which is in good agreement with the experimental result. Note that this is a 52 percent reduction in frequency compared to the in-vacuo result. This resonance is not apparent in the experimental results shown in Figure 3 due to the feedback circuit providing volume velocity control for the projector. The internal fluid is found to have little effect on the resonance frequency. Clearly the external fluid loading is the dominant effect for this resonance. Table 1 summarizes the results for the various fluid levels.

Internal Fluid Level	Normalized Frequency
Empty	410
1st	410
2nd	400
3rd	390
half-full	370

Table 1 In-water resonance frequencies for five fluid levels.

All of the displaced meshes corresponding to the various fluid levels look similar to the breathing mode shown in Figure 8. However, close examination of the displacement values reveals a slight asymmetry due to the internal fluid-loading on the bottom half of the projector.

The second resonance is outside the frequency band of interest for the first and second fluid levels. The second resonance occurs at 1150 Hz when the fluid is at the third level. Note that this resonance occurs at the same location at which the acoustic output is found experimentally to deviate from the anticipated flat response. Figure 10 is a cut-away view of the displaced flexural disk at 1150 Hz with the hydraulic fluid at the first level (Figure 9a). Although not visible in the figure, the displacement values show that there is an antisymmetric effect

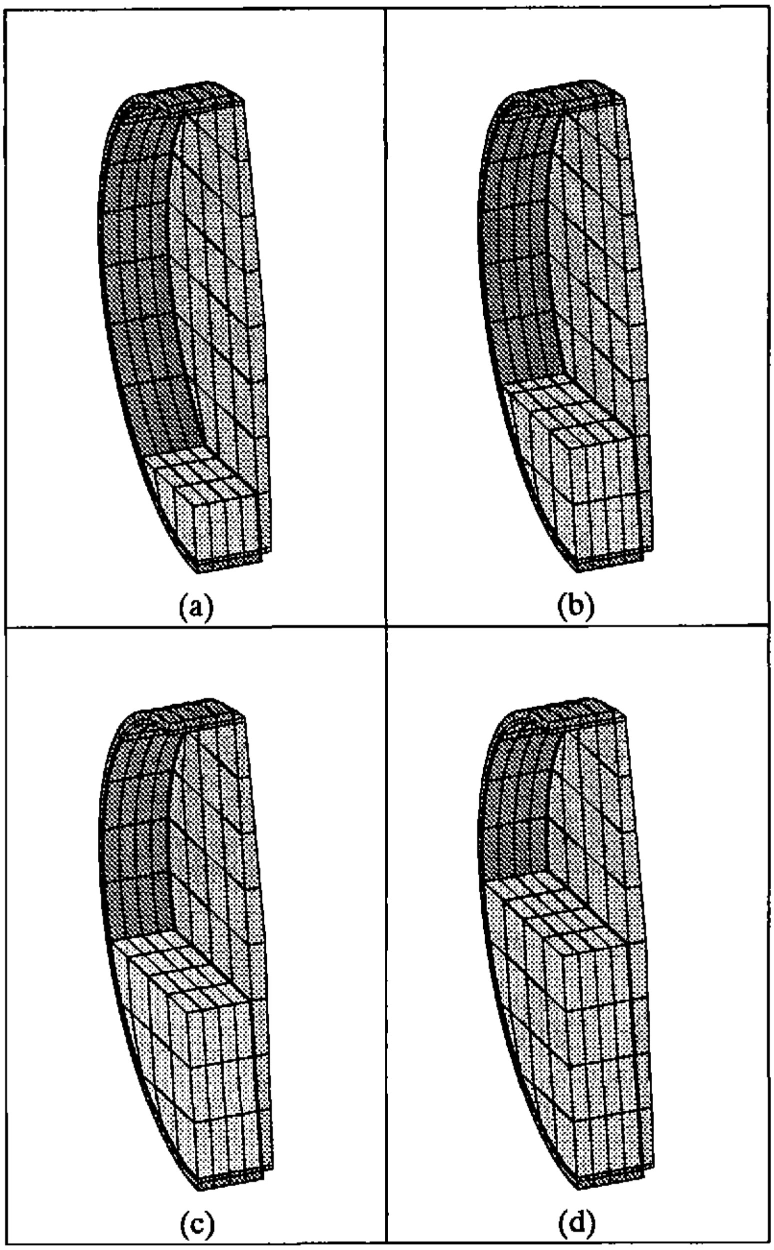

Figure 9 Three-dimensional finite element model for (a) first fluid level, (b) second fluid level, (c) third fluid level and (d) fourth fluid level.

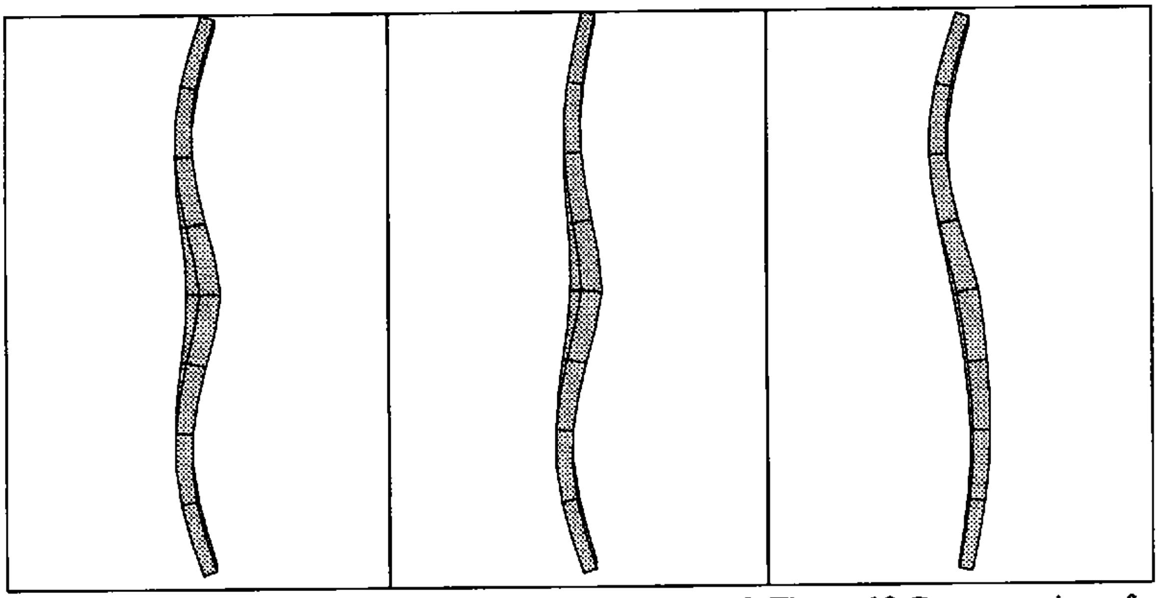

Figure 10 Cut-away view of the displaced disk when the hydraulic fluid is at the first level.

Figure 11 Cut-away view of the displaced disk when the hydraulic fluid is at the second level.

Figure 12 Cut-away view of the displaced disk when the hydraulic fluid is at the third level.

superimposed on a symmetric mode. Displacement results for frequencies in the neighborhood of 1150 Hz show that there is no resonance in this range. The displacements simply increase monotonically with increasing frequency. Figure 11 is a cut-away view of the displaced disk with the fluid at the second level (Figure 9b) at the same frequency. The behavior of the flexural disk at this fluid level is very similar to that of the first fluid level; however, there is an increase in the asymmetry of the displaced shape. A significant change in displacements occurs with the fluid at the third level (Figure 9c). The displaced shape is displayed in Figure 12 at the resonance frequency of 1150 Hz. This figure shows clearly that the flexural disk has an asymmetric shape at this frequency. Experimentally, the influence of antisymmetric modes leads to an incorrect feedback signal and a drop in the acoustic output as shown in Figure 3.

4. SUMMARY

A three-dimensional finite element model for a fluid-filled projector was developed and coupled with a boundary element model for the acoustic water loading. This combined model was exercised for five levels of internal fluid loading. The model was used as a diagnostic tool in identifying the cause of an experimentally observed reduction in the acoustic output of the projector. The model results show that increasing the amount of internal hydraulic fluid increases the asymmetry of the displaced flexural disk. The model can now be used to determine more precisely the level of hydraulic fluid at which the asymmetry causes an unacceptable drop in acoustic output. Successful verification of the model has resulted in a tool which has the capability to evaluate design changes and hence facilitate optimization of the projector's performance.

5. REFERENCES

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