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Effects of Deck-Mounted Components on the Sloshing Response of a Pool-Type LMFBR

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Abstract

A numerical study of the sloshing response of a reactor tank with deck-mounted components is presented. The effects of the deck-mounted components on the sloshing wave heights, wave patterns, and wave frequencies are investigated. The sloshing pressures exerted on the deck-mounted components are determined. For the case studied, the maximum sloshing pressure on the IHX or pump is 0.034 MPa (5 psi). It will produce an additional bending stress of the magnitude of 27.5 ~ 48.2 MPa (4-7 ksi) on the components and should be added to the other stresses obtained from the conventional seismic analysis for the design of deck-mounted components.

1. Introduction

A large commercial size breeder reactor tank contains a huge amount of liquid sodium and many deck-mounted components. Due to the presence of large free-surface area, the liquid sodium will participate in the sloshing motion under seismic disturbances. Of interest in the reactor design is the magnitude of the hydrodynamic pressure acting on the deck-mounted components and the maximum wave height of the free-surface. In the current practice, however, the hydrodynamic pressures and maximum wave height are still determined from a simple mechanical model [1] which was developed for calculating the dynamic response of a liquid-storage tank with no in-tank component.

Sloshing response of a reactor tank without internal component has been studied by Ma and Liu [2,3]. This paper presents the results of a finite element analysis performed on the sloshing response of a reactor tank with the presence of many deck-mounted components subjected to horizontal seismic excitation. The objective of the study is to investigate the effects of the internal components on sloshing response and to determine the sloshing loading for design of the components. The mathematical model is described in Section 2; the results are presented in Section 3; the conclusions are given in Section 4.

2. Description of the Mathematical Model

The finite element model used in the study is shown in Fig. 1 which represents the fluid in the upper part of a commercial-size LMFBR reactor tank that will participate in sloshing. The fluid in the lower part of the tank is completely trapped; it does not participate in sloshing motion and therefore is omitted. The component at the center of the tank represents an upper internal structure (UIS); the other six off-center components represent three intermediate heat exchangers (IHXs) and three pumps, which will normally appear in a large pool type of reactor. The tank and components are assumed to be rigid. The fluid is simulated with displacement-based continuum elements. Only linear sloshing is considered. The input motion is at the tank base, which is a 10 s acceleration time history having a maximum acceleration of 1 g. After 10 s, the seismic ground motion is assumed to have terminated. However, the analysis of sloshing motion is carried out to 50 s, since sloshing is a long-duration motion. For comparison purpose, a similar analysis is also performed on a reactor tank which has a UIS but no off-center components. The mathematical model of that reactor is shown in Fig. 2.

3. Sloshing Response

The computed free-surface wave patterns of the two cases studied at instant of t = 15 s are shown in Figs. 3 and 4. As can be seen, the sloshing wave height of the tank with UIS only (see Fig. 3) has a cosθ distribution in the circumferential direction of the tank. The circumferential wave patterns of the tank with UIS and other components (see Fig. 4) is, however, quite different. It no longer has a distinct cosθ distribution in the circumferential direction of the tank, and the free surface exhibits many peaks, i.e., up-and-down wave patterns when the coolant sloshes. This is clearly demonstrated in Fig. 4. Also, the presence of the internal components, i.e., IHXs and pumps affects the mode shapes and values of sloshing frequencies significantly. In the case of no off-center component, the sloshing response is dominated by two sloshing modes, i.e., the first radial mode (antisymmetric) and the first tangential mode. The modal shapes of these two modes are shown in Fig. 5 in which H and L indicate the high and low lines of the free-surface, and 0 represents a zero line. The free-surface wave height in the radial antisymmetric mode is primarily caused by fluid flowing in the radial direction of the tank, whereas the wave height in the tangential mode is mainly caused by fluid flowing in the circumferential direction of the tank. The radial antisymmetric mode has a sloshing frequency of 0.28 Hz. The frequency of the first tangential mode is found to be 0.74 Hz.

Figure 6 shows the areas of the free surface which are dominated by the two sloshing modes. It shows that the sloshing motion of coolant adjacent to the tank wall is dominated by the radial antisymmetric mode of the radial fluid flow, and the sloshing response adjacent to the UIS is dominated by the tangential mode of the tangential fluid flow. It is interesting to note that the first sloshing frequency of a rectangular tank with fluid depth of 6.09 m (20 ft) and tank width of 8.84 m (29 ft) (equal to the radial distance between the UIS and the tank wall) is 0.29 Hz which is very close to that of the radial antisymmetric mode.

In the case of the tank with off-center components, the sloshing response is dominated by four sloshing modes. They are the radial antisymmetric (0.46 Hz) and tangential (0.72 Hz) modes of the fluid which lies between the UIS and the off-center components, and the tangential (0.90 Hz) and radial antisymmetric (0.96 Hz) modes of the fluid between the off-center components and the tank. The distribution of these four modes on the free-surface is shown in Fig. 7. The first two modes are similar to those of the case without off-center component as previously mentioned. The frequency of the radial antisymmetric mode, however, is increased from 0.28 Hz to 0.46 Hz. The increase of frequency is attributed to the decrease of the effective width of an equivalent rectangular tank. For the case studied, it decreases from 8.84 m (29 ft, i.e., the radial distance between the UIS and the tank) to 4.87 m (16 ft, i.e, the radial distance between the UIS and the off-center components). The classical fundamental sloshing frequency of a rectangular tank with 6.09 m (20 ft) depth and 4.87 m (16 ft) width is 0.40 Hz. The frequency of the tangential mode, however, is not affected by the off-center components. This is because the tangential fluid flow mainly occurs in the area adjacent to the UIS as previously mentioned. The third (0.9 Hz) and fourth (0.96 Hz) sloshing modes are caused by the fluid flowing between the off-center components and the tank wall. Again, it is interesting to note that if the distance between off-center component and tank wall, i.e., 0.91 m (36 in.), is used as the effective tank width, the classical sloshing frequency is 0.93 Hz.

The maximum wave heights at various locations for the cases without and with off-center components are shown in Figs. 8 and 9, respectively. It is noted that the maximum wave heights shown in Figs. 8 and 9 are not occurring at the same time. For the case without off-center components, the maximum wave height is 172 cm (68 in.). It occurs at the fluid-tank wall interface at $\theta = 0°$. The maximum wave height at fluid-UIS interface is 116 cm (46 in.). The maximum wave height for the case with off-center components is 101 cm (40 in.) which occurs at the off-center component, and is primarily caused by the radial fluid flow between the UIS and the off-center components. The maximum wave heights at various locations for the case with off-center components are generally smaller than those of the case without off-center components.

The calculated fluid pressure history of free-surface fluid element 1 (at fluid-tank wall interface at $\theta = 0°$) for the case with off-center components is shown in Fig. 10. As can be seen, the pressure in the first ten second period of time consists of both impulsive and convective (sloshing) pressures. After ten seconds only the sloshing pressure remains active. The impulsive pressure vanishes because of the termination of the ground disturbance. Since the objective of this study is to find the maximum sloshing pressure acting on the submerged in-tank components, the calculation continues to 50 seconds of time. The maximum sloshing pressure of fluid element 1 is found to be 0.0055 MPa (0.8 psi) which occurs at 25 s after the start of the ground motion or 15 s after the cease of the ground motion.

The maximum sloshing pressures at tank top and midheight for the case with off-center components are shown in Fig. 11. Again, those maximum sloshing pressures are not occurring at the same time. As can be seen in Fig. 11, the maximum sloshing pressure acting on the components is 0.0275 MPa (4.0 psi). The off-center components are subjected to two different types of sloshing modes, one side with a frequency of 0.46 Hz and the other side with a frequency of 0.9 Hz. Since both sloshing modes have a $\cos\theta$ distribution, it is reasonable to assume that the sloshing pressure acting on the component will have $\cos\theta$ distribution at certain instances (see Fig. 12). In other words, one side of the component will be subjected to a compressive loading, while the other side will be subjected to a tensile loading. This is the worst loading condition for a component subject to seismic sloshing. To obtain a conservative estimate, we use the maximum sloshing pressure of 0.034 MPa (5 psi) to calculate the maximum stresses on the component. Furthermore, it is assumed that this maximum pressure is uniformly distributed along the submerged length of the component. If the component is represented by a stick model which is usually the case in the conventional component analysis, the resultant force f per unit length acting on the component (see Fig. 12) is

$$f = \int_0^{2\pi} P \cdot \cos^2\theta \, r \, d\theta \qquad (1)$$

or

$$F = \pi \cdot P \cdot r \qquad (2)$$

where p is the maximum sloshing pressure and r is the radius of the component. The total force F acting on the component is given by

$$F = f \cdot \ell \qquad (3)$$

where ℓ is the submerged length of the component plus the maximum wave height.

The bending stress at the support of a component due to the sloshing loads described above is 24.1 MPa (3.5 ksi). The component is assumed to have a diameter of 3.04 m (10 ft), thickness of 5.08 cm (2 in.), a length of 10.66 m (35 ft) and a submerged length of 6.09 m (20 ft). If the component has a thickness of 2.54 cm (1 in.), the bending stress would be increased to 48.2 MPa (7 ksi) due to sloshing.

4. Conclusions

From the results of this study, it can be concluded that:

1. The presence of off-center components can significantly change the dynamic characteristics of the sloshing motion. The sloshing frequencies of a tank with off-center components are considerably higher than those of a tank without off-center component.

2. The sloshing wave height is considerably reduced due to the presence of off-center components. The prediction of maximum wave height based on a simplified mechanical model without in-tank components such as Housner's equation is too conservative. Therefore, it should not be used in the reactor design.

3. The seismic stress due to sloshing could be significant; it should be added to the conventional seismic analysis for the deck-mounted components. For the case studied, the maximum sloshing pressure on the off-center components is 0.034 MPa (5 psi). It has a $\cos\theta$ distribution along the circumferential direction of the component, which can produce an additional stress of the magnitude of 27.5 - 48.2 MPa (4-7 ksi) on the deck-mounted components.

5. Acknowledgments

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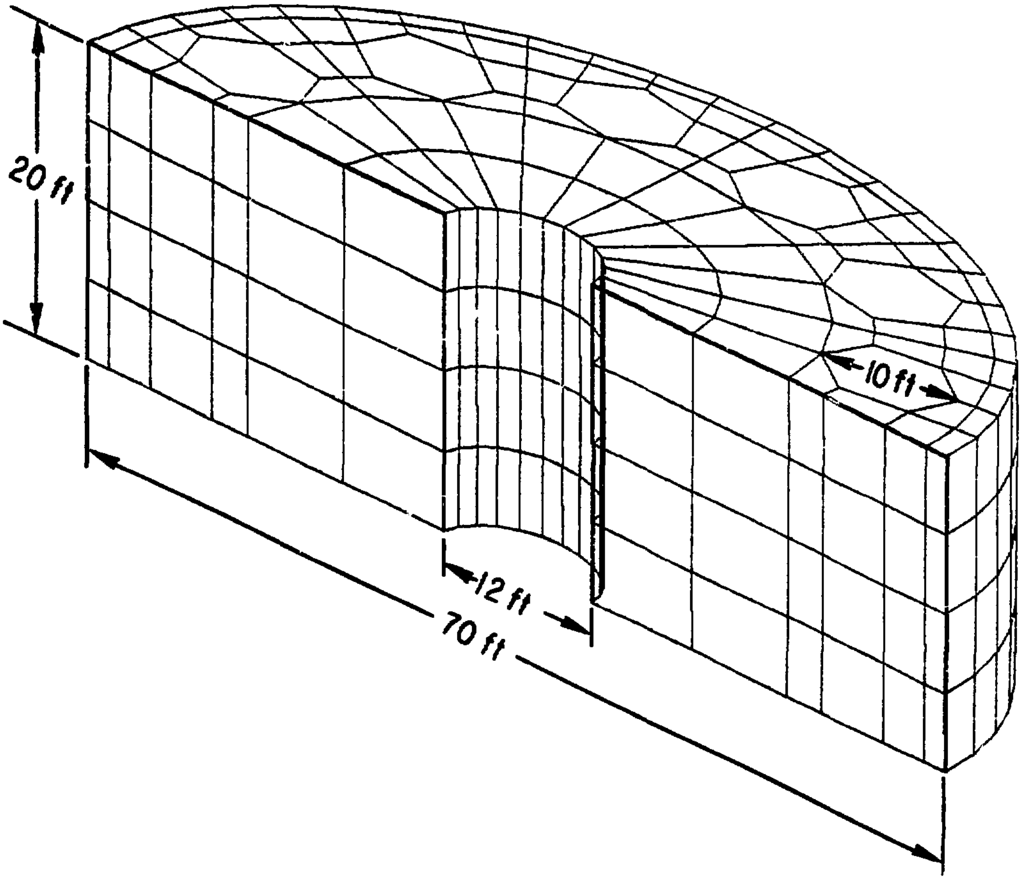
[3] LIU, W. K., MA, D. C., "Coupling Effect Between Liquid Sloshing and Flexible Fluid-Fill Systems," Nuclear Engineering and Design, Vol. 72, pp. 345-357 (1982).

FIGURE CAPTIONS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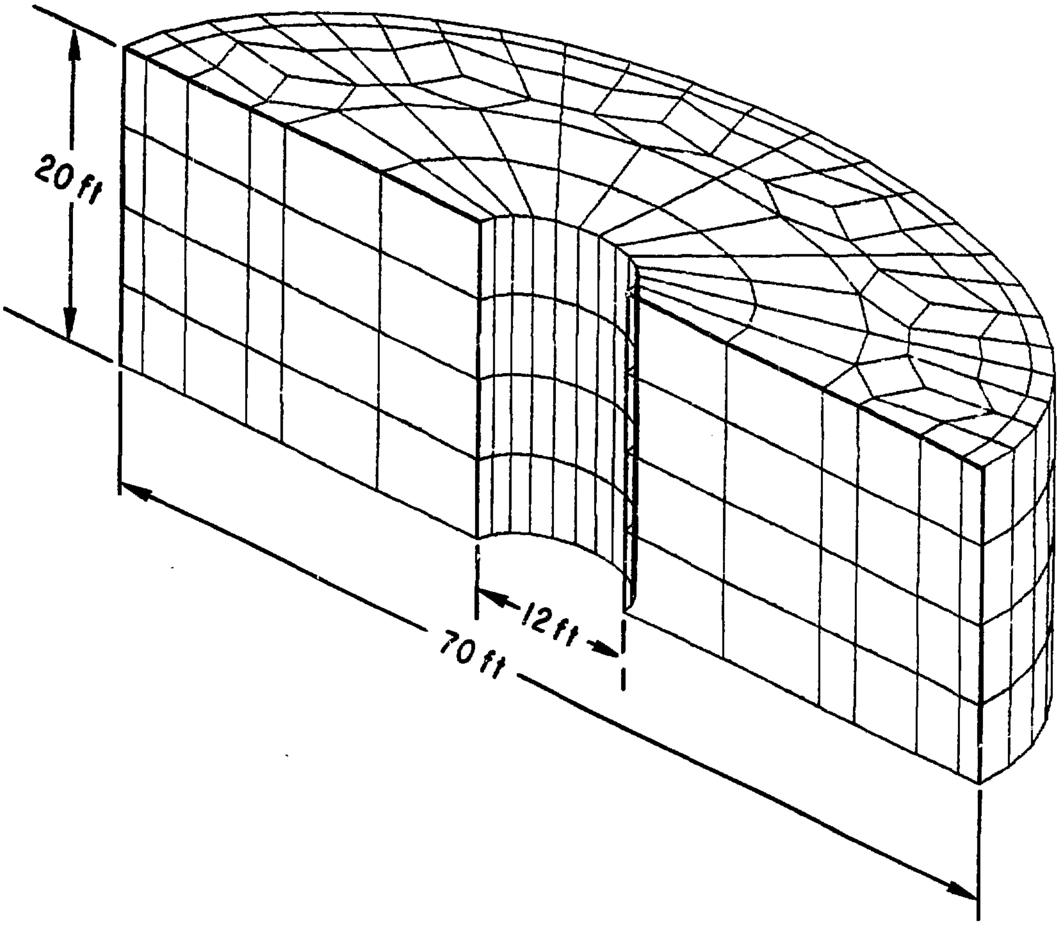
70 ft
10 ft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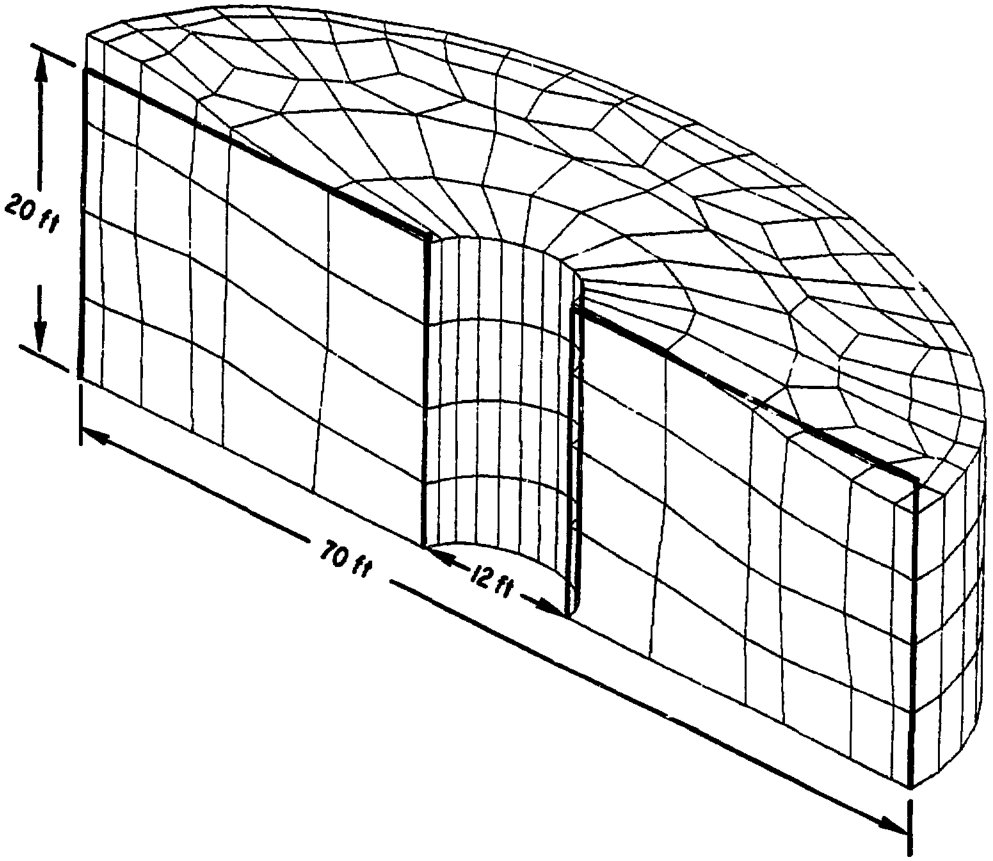
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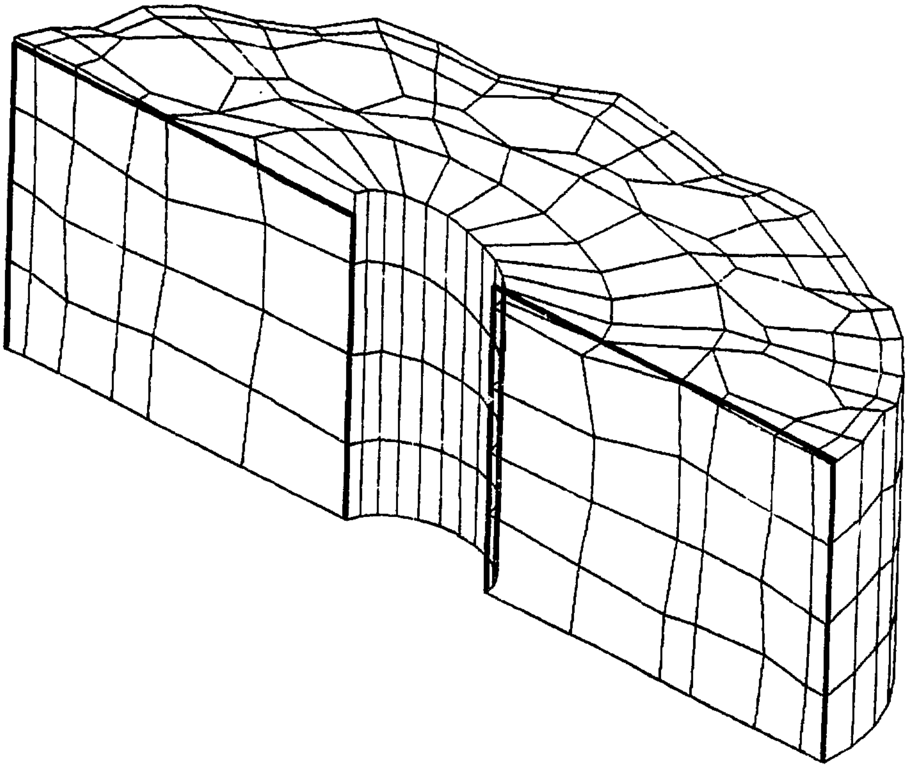
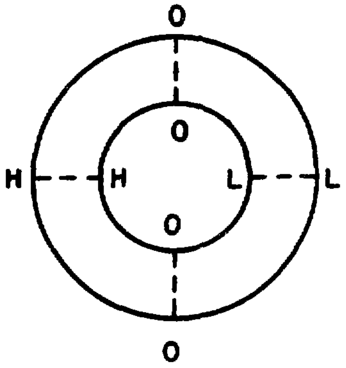
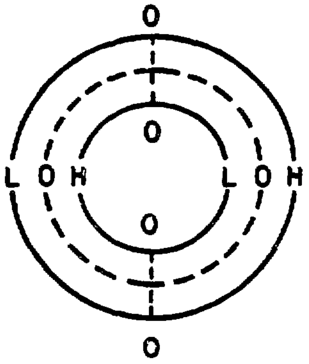


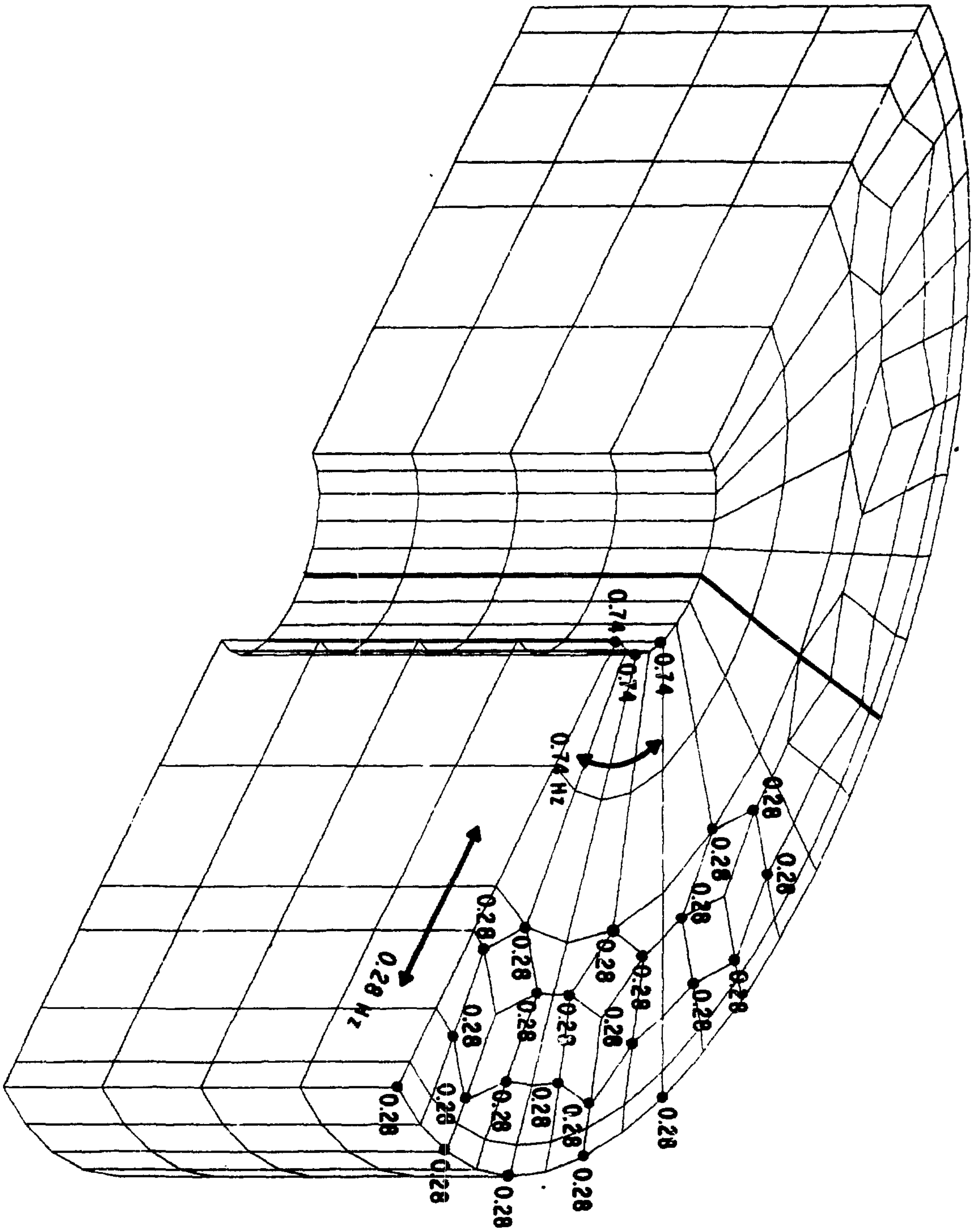


MODE 1

TANGENTIAL MODE



RADIAL
ANTISYMMETRIC MODE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0.74
0.74
0.74 Hz
0.28 Hz
0.28
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0.28
0.28
0.28
0.28
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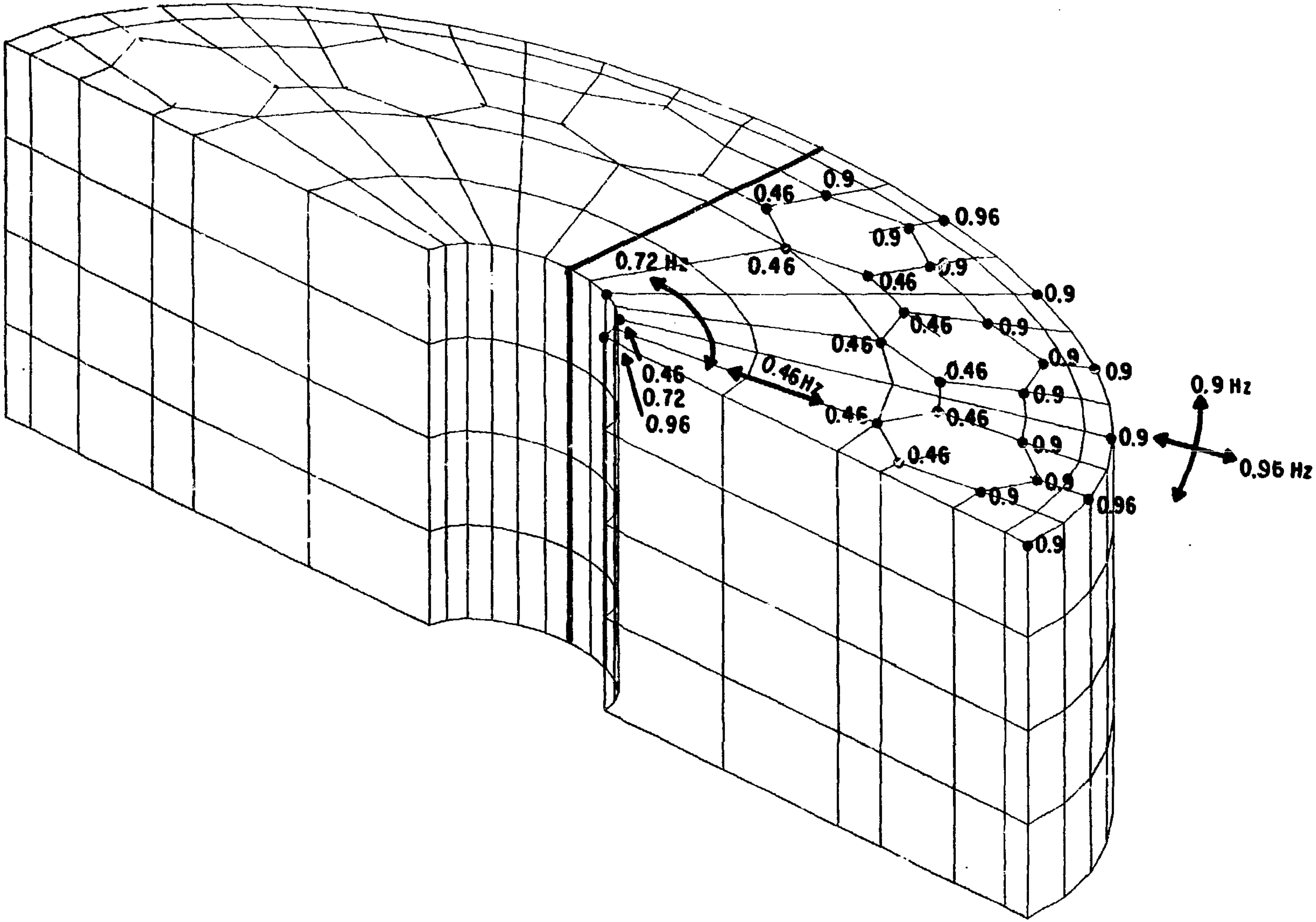
0.28


0.9
0.46
0.96
0.9
0.72 Hz
0.46
0.9
0.46
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0.46
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0.46
0.9
0.46
0.9
0.9
0.9 Hz
0.46
0.72
0.96
0.46Hz
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0.46
0.9
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0.96 Hz
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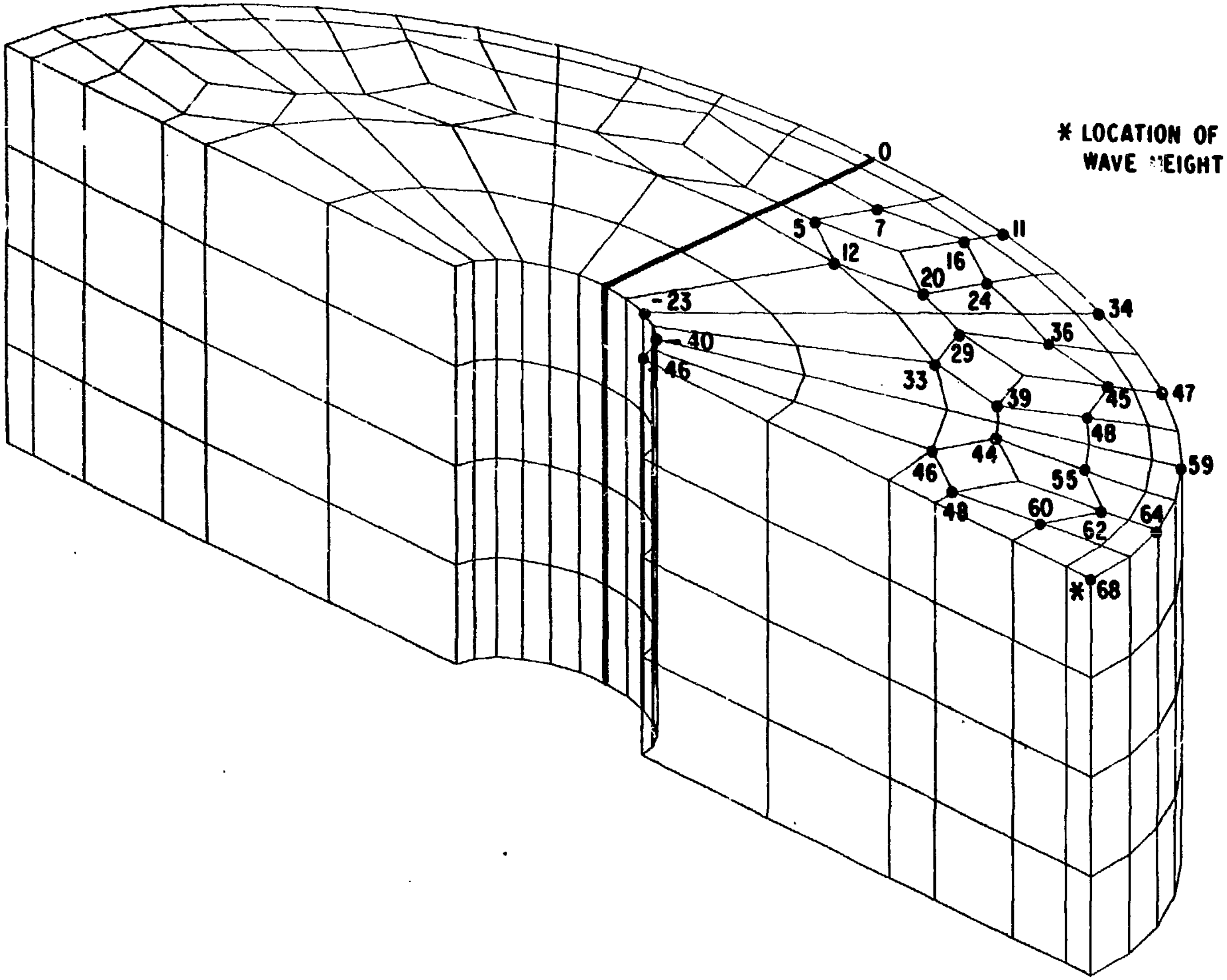
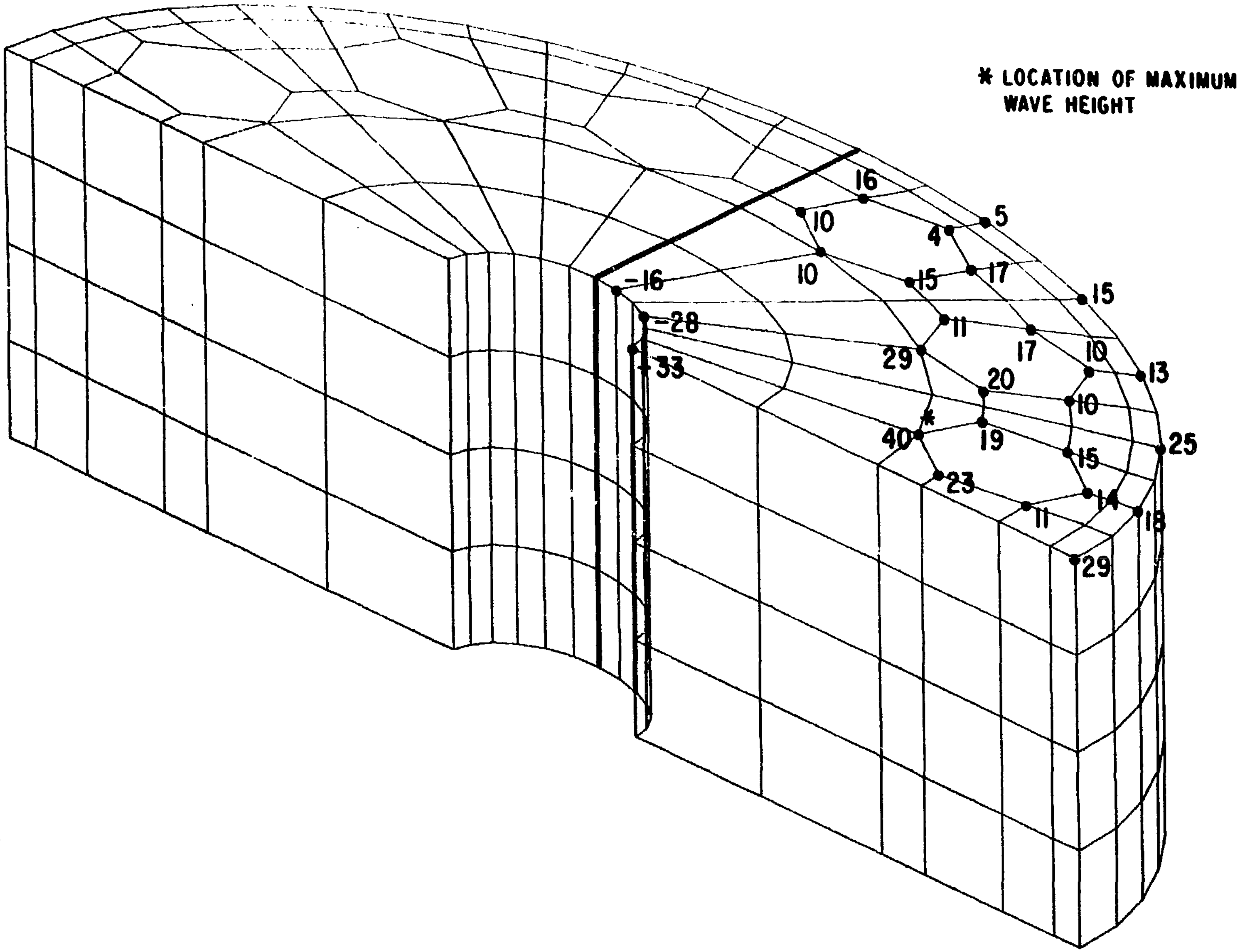
0.9
0.96
0.9



* LOCATION OF MAXIMUM WAVE HEIGHT



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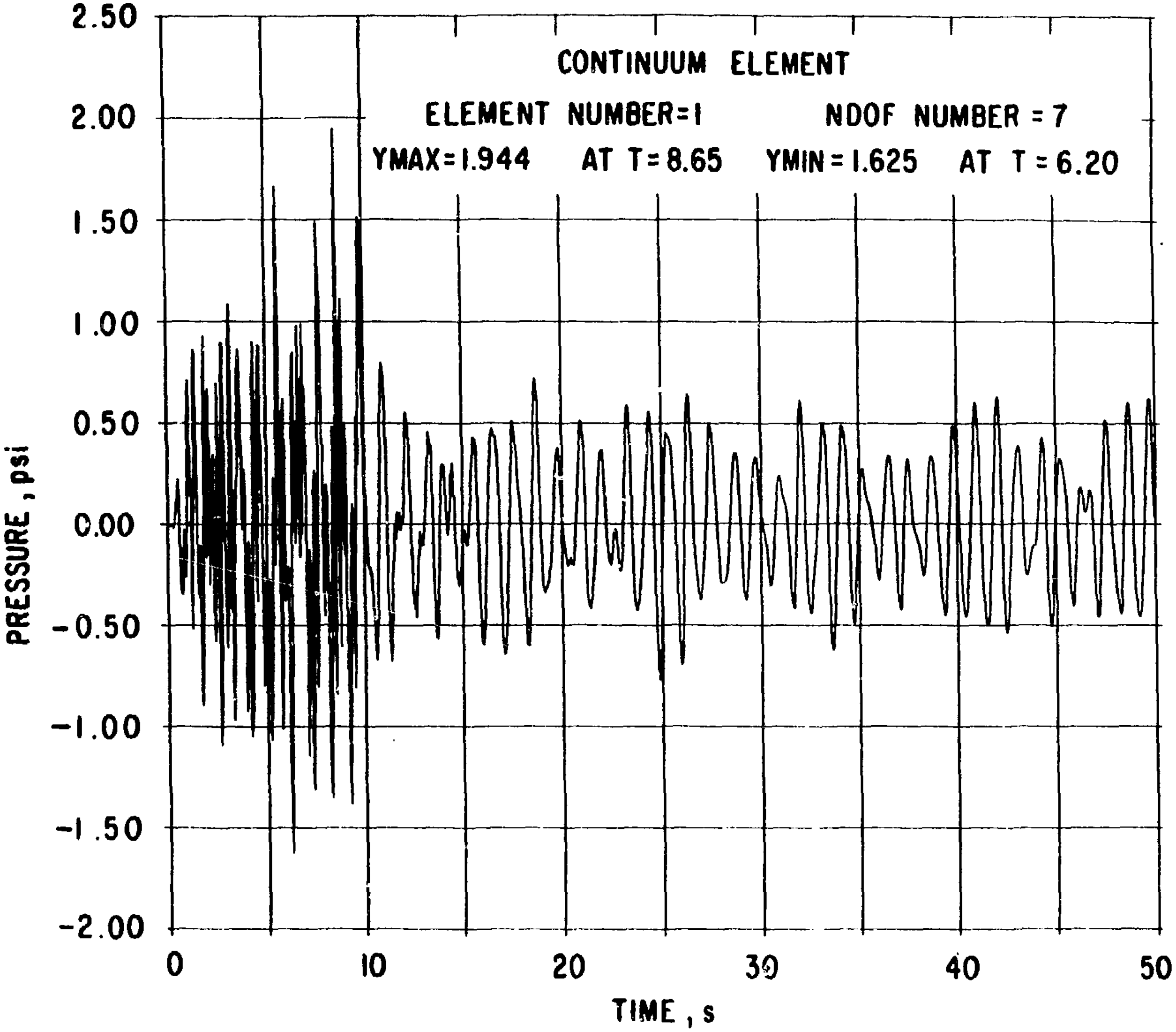
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NDOF NUMBER = 7
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YMIN=1.625 AT T=6.20
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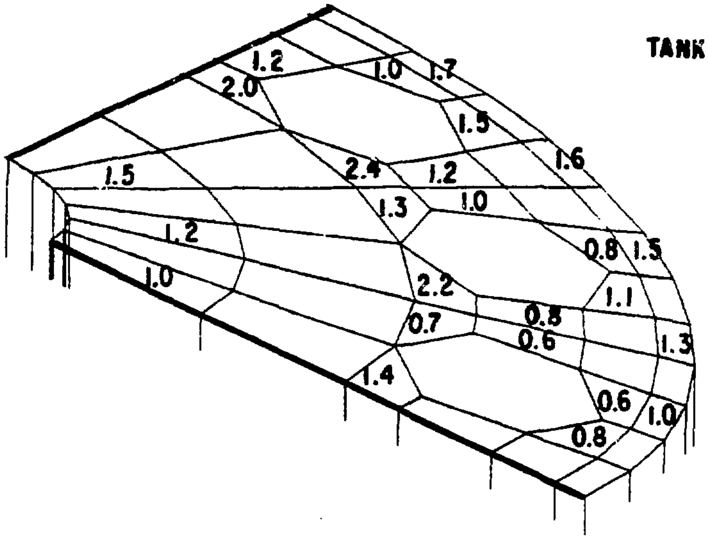
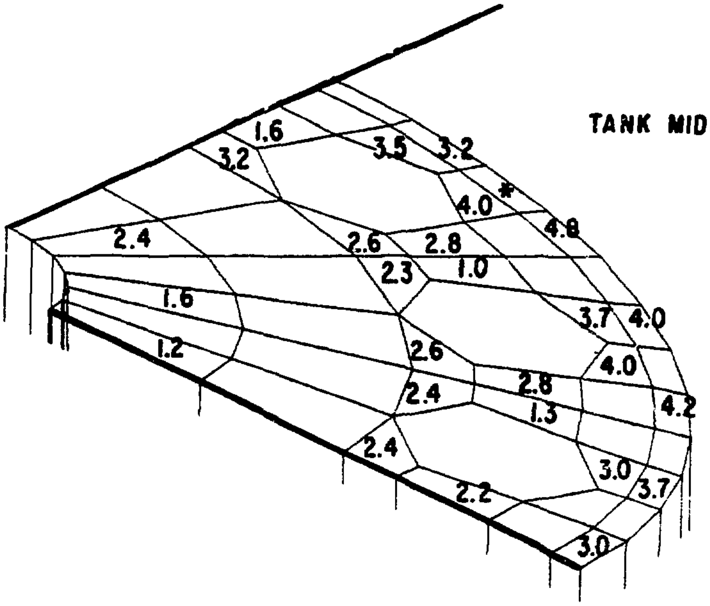
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
PRESSURE , psi
0
10
20
30
40
50
TIME , s

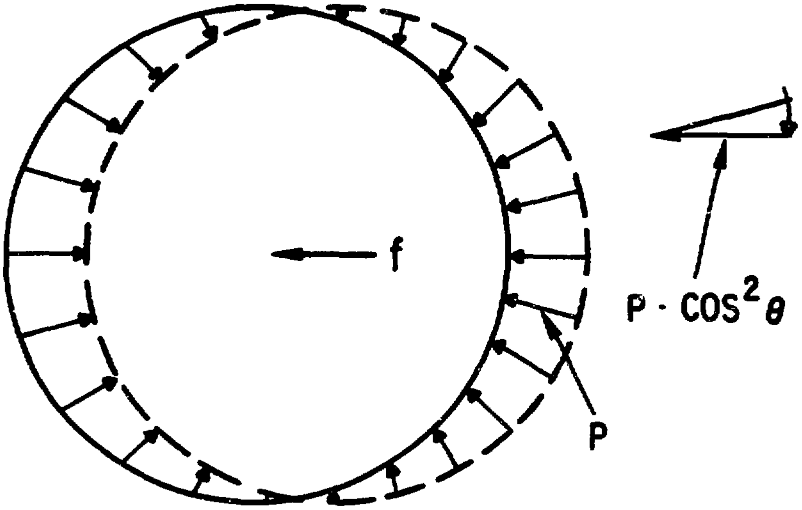


TANK TOP



TANK MIDHEIGHT

* MAXIMUM SLOSHING PRESSURE
ACTING ON COMPONENT


f
P · COS²θ
P