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UNCOUPLING APPROXIMATION IN FLUID-STRUCTURE INTERACTION PROBLEMS WITH CAVITATION

Weidlinger Associates, Consulting Engineers
110 East 59th Street
New York, New York 10022

28 February 1980

Topical Report for Period 1 December 1978—28 February 1980

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number):

Linear and nonlinear methods are presented for the decoupling of fluid-structure interaction problems in which cavitation occurs. These methods are tested against a one-dimensional case with a known solution. On this basis the nonlinear approach is recommended for use in multi-dimensional problems and an algorithm for its implementation is given.

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1. INTRODUCTION

If a structure has complex internal components, the capacity of presently available computers rarely allows the use of the complete fluid equations when dynamic interaction of the structure with fluid is investigated. In most cases, it is necessary to uncouple the equations of motion of the fluid from those of the structure by assuming approximate differential (or integro-differential) relations between fluid pressure and velocity on the wet surface of the structure.

For submerged structures, cavitation often does not occur or is negligible. Many uncoupling schemes have been developed and applied for such cases, Ref. [1]. When, however, a surface ship is exposed to typical underwater shock loadings, it may no longer be possible to neglect cavitation.

In this report, procedures are developed for modifying presently used uncoupling schemes to include cavitation. These permit structural response to be calculated if the free field velocities and pressures are known. A one-dimensional problem is considered in detail and linear and nonlinear interaction approximations are developed. The results are compared with exact solutions. An extension of the methods to two-dimensional problems is then outlined, leading to a non-linear interactive approximation to be used in the practical numerical solution of large scale fluid-structure problems.

2. FORMULATION OF THE ONE DIMENSIONAL PROBLEM

To study the proposed methods, consider, the one dimensional problem illustrated in Fig. 1. A model of a surface ship, consisting of a rigid mass m per unit area with an average floating depth h is subjected to an exponential pressure wave with incident gauge pressure p_o, decay time τ and cutoff time T.*) It is desired to obtain the velocity response of the mass, v(t), as a function of time t.

3. FREE FIELD PRESSURES AND VELOCITIES

The constitutive relation for the fluid is assumed to be the bilinear one illustrated in Fig. 2, which does not permit tension in the fluid. Cavitation occurs when the total pressure p_T first reaches zero at a density $\rho = \rho_o$. Small deformations are assumed, so that

$$|\rho - \rho_o| << \rho_o \tag{1}$$

In the absence of the mass in Fig. 1, free field pressure p_F**) and particle velocities u_F would result in the half space. Using the cavitation model of Fig. 2 these free field values may readily be obtained using the interactive solution of Bleich and Sandler, Ref. [2]. It is only necessary to set m = 0 in the programs they developed.

---

*) The cutoff time T is intended to exercise the interactive model under the sudden reduction in pressure associated with surface reflection of the incident wave. Of course, in a 1-D problem, the surface reflection cannot be represented as such; it is included in the incident wave.

**) Unless otherwise noted, live pressure will be used in this report, i.e., total pressure less the atmospheric and hydrostatic pressure, $p_A + \rho_o gh$.

4. EXACT RESPONSE OF MASS

The exact velocity of the mass, and total pressure exerted on its bottom surface, may be obtained by slight modifications of the program of Bleich and Sandler, Ref. [2], to permit non-zero depth h and finite cutoff time T. These exact solutions will be used to evaluate the validity of the approximations described in the sequel.

5. INTERACTIVE APPROXIMATIONS

Consider the free field pressures and particle velocities of Section 3. Let $\bar{p}_F$ and $\bar{u}_F$ denote values*) at a depth h. If the rigid mass is replaced by a body of water of depth h, as shown in Fig. 3a, these values may be taken as a first approximation to the pressure acting on the mass and its velocity response to that pressure. The actual values, denoted by $\bar{p}$ and v, occur when the mass is actually present as shown in Fig. 3b. The quantities $\bar{p}_F$, $\bar{p}$, $\bar{u}_F$ and v are related by

$$\bar{p} - \bar{p}_F = F\{\bar{u}_F - v\} \tag{2}$$

in which F is an appropriately chosen functional. Equation (2) is a special case of a general interactive approach (currently being developed by Weidlinger Associates, Ref. [3], and summarized in Appendix 1) to uncouple the motion of a structure from that of nonlinear medium with which it is in contact. In this report the approximation of F is studied.

A. Linear Interactive Approximation

The simplest functional F is that corresponding to the linear (acoustic) approximation*)

$$\bar{p} - \bar{p}_F = \rho_o c(\bar{u}_F - v) \tag{3}$$

*) Note that $\bar{p}_F$ and $\bar{u}_F$ include cavitation effects in the free field.

In the absence of cavitation, Eq. (3) would be exact, with the increments on the left and right hand side of (3) referred to as radiated pressure and velocity, respectively. From (3), the resultant pressure acting on the mass is

$$\bar{p} = \bar{p}_F + \rho_o c \bar{u}_F - \rho_o c v \tag{4}$$

so that the equation of motion of the mass,

$$m\dot{v} = \bar{p} \tag{5}$$

becomes

$$m\dot{v} + \rho_o c v = \bar{p}_F + \rho_o c \bar{u}_F \tag{6}$$

It is readily seen that the fluid reaction to the motion of the mass in the linear approximation (3) is equivalent to that of a linear viscous dashpot with damping coefficient $\rho_o c$ attached to the mass, as illustrated in Fig. 4.

After free field values on the right hand side of (6) are obtained as described in Section 3, Eq. (6) may be integrated to give v(t), which can then be compared to the exact response described in Section 4.

B. Nonlinear Interactive Approximation

The linear approximation of Eq. (3) will be in error when cavitation occurs. It will be most seriously in error when cavitation is present at or near the depth h because then separation takes place and the dashpot in the model of Fig. 4 should not be acting. In this stage the mass should be almost freely decelerating under the action of only gravity and atmospheric pressure.

Equation (6) should be replaced, while cavitation occurs at the bottom of the mass, by

$$\dot{v} = -\frac{p_A + mg}{m} \tag{7}$$

When the mass again makes contact with the water, Eq. (6) may again be used.

The considerations outlined above suggest that a better choice for the functional F to be used in Eq. (2) would be defined by the following approach:

<u>Initial Shock</u> - Use Eq. (6) until such time t_1 as the condition

$$\bar{p}_T(t_1) \equiv \bar{p}(t_1) + p_A + mg = 0 \tag{8}$$

is satisfied, i.e., when the total pressure first drops to zero.

<u>Separation and Fall</u> - Use Eq. (7) until such time t_2 as the separation distance returns to zero, i.e., until the condition

$$\int_{t_1}^{t_2} (v - \bar{u}_F)\,dt = 0 \tag{9}$$

is satisfied.

<u>Closure</u> - Return to Eq. (6) for as long as $\bar{p}_T(t) > 0$. If Eq. (8) is again satisfied, a new separation and fall phase begins.

Again the response v(t) will be compared with the exact results described in Section 4.

6. NUMERICAL EXAMPLE

A comparison between the two approximate interactive approximations and the exact solution was made for the following material and geometric parameters:

$mg = 7$ psi

$g = 32.2$ ft/sec^2

$h = 16$ ft

$p_o = 114$ psi

$\tau = 4$ ms

$T = 2.2$ ms

$\rho_o = 1.94$ slugs/ft^3

$p_A = 14.7$ psi

$c = 5000$ ft/sec

The solutions for the response in all cases were obtained by an Euler forward integration scheme. This low order scheme was intentionally used because it corresponds to the scheme that must be used, for practical reasons, in the multidimensional case, Appendix 2.

As discussed in Sections 3 and 4, the exact free field pressures and particle velocities, and the exact velocity response of the mass were obtained using the above parameters. In Figs. 5 and 6, the cavitation fields with and without the mass present, respectively, are shown. It is seen that both the extent and duration of the cavitation are affected significantly by the presence of the mass.

In Fig. 7, the histories of live pressure at the depth h with and without the mass, denoted by $\bar{p}$ and $\bar{p}_F$, respectively, are exhibited. Note that the three phases discussed in Section 5B are clearly delineated for the solid curve $\bar{p}$. The initial shock, with pressure doubling, is followed by a long cavitation period in which the total pressure $\bar{p}_T = 0$, and then by the closure shock.

Figure 8 shows the free-field particle velocity at depth h, $\bar{u}_F$, and the velocity of the mass, v, as functions of time. Again the three stages are clearly evident when the mass is present. The constant slope of the plot of v during the cavitation phase is essentially that of free deceleration given by Eq. (7).

Using the free field histories at depth h, $\bar{p}_F$ and $\bar{u}_F$, the velocity of the mass was obtained with a) the linear interaction approximation of Eq. (6) (and denoted by v_L) and b) the nonlinear interaction described in Section 5B (and denoted by v_{NL}). These were then compared with the exact response v, previously plotted in Fig. 8. This comparison is illustrated in Fig. 9. It is seen that the linear approximation is excellent initially but becomes increasingly poorer as the long cavitation phase continues. During this phase, c should be set equal to zero in Eq. (6), i.e., Eq. (7) of the nonlinear approximation should be used. It is seen that the nonlinear interaction approximation predicts response which is in excellent agreement with exact results through all three phases of loading. Therefore, this procedure is chosen for use in multidimensional situations as described in the following section and in Appendix 2.

7. EXTENSION TO TWO DIMENSIONAL EXCITATION OF NON-RIGID STRUCTURES

Consider the problem of determining the response of a non-rigid structure partially (or completely) immersed in a fluid when a cylindrical shock wave travelling through the fluid impinges on it, as illustrated in Fig. 10. Let r and z be radial and vertical coordinates, respectively, and let s denote a generic point on the wet surface of the structure.

Assume the free field pressure $p_F(r,z,t)$ and particle velocity $u_F(r,z,t)$ are known experimentally or can be obtained by analysis. Let $\bar{p}_F(s,t)$ and $\bar{u}^{\nu}_F(s,t)$ denote free field pressure and the component of the particle velocity normal to the boundary at s.

In Fig. 11, a schematic of a finite element at node i at point s, analogous to the one-dimensional model of Fig. 4, is shown, with k_i denoting the structural stiffness associated with normal motion. The response $v_i(t)$ can then be obtained using a finite element program such as SAP IV, with the wet-surface elements modified by the addition of the damping components.

The quantity $\bar{c}$ (in the dashpot constant $\rho\bar{c}$ in Fig. 11) is taken as equal to c except when the separation and fall phase occurs. During that phase $\bar{c}$ is set to zero, as indicated in Appendix 2. This holds until the separation distance returns to zero*).

If at later times, the damping is suppressed and the structural mass m_{ij} made to approach

$$u_{ij} = m_{ij} + m_{vij} \qquad (11)$$

---

*) If $\bar{c} = c$ throughout, a linear plane wave approximation, analogous to that of Ref. [4], is obtained.

in which m_{vij} are the elements of the virtual mass matrix, another interactive approximation is obtained which replaces the doubly asymptotic approximation first proposed by Geers, Ref. [5], and extensively used by him and others (see, e.g., Ref. [1]) for uncavitated fluids.

If three dimensional free field shock loadings are involved, such as would occur when tapered charges are used, the free field would probably have to be determined experimentally before the methods discussed could be applied. It does not appear feasible at present to analytically determine the free field for such explosions.

8. CONCLUSIONS

A linear and a nonlinear interactive scheme have been developed to uncouple the equations of motion of a structure from those of a cavitating fluid in which it is immersed, and through which a shock wave propagates and impinges on the structure. The method has been tested numerically on a one dimensional problem for which the exact solution is obtainable. In this case, the nonlinear interactive approximation gives especially good results, even when the cavitation phase on the wet surface of the structure is of a long duration. It will be used in subsequent multidimensional applications.

Free field pressure and particle velocities in the fluid must be known or calculated before these methods may be applied.

These interactive approximations replace the uncoupling schemes such as the plane wave approximation and the doubly asymptotic approximation extensively used when cavitation does not occur or is neglected.

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APPENDIX I

Interactive Schemes for Nonlinear Media

Consider a structure S partially or totally embedded in a nonlinear medium M. Let B be the surface common to S and M. Assume that free field input is available and could be used in a simplified structure-medium calculation in which only a coarse approximation of the structure is used. This solution gives trial boundary tractions $\underset{\sim}{t}_B^T$.

Let the correct boundary tractions for the actual structure be denoted by $\underset{\sim}{t}_B$. Due to the error $\underset{\sim}{t}_B^T - \underset{\sim}{t}_B$ in the tractions in the simplified calculation, the velocities along B are in error by an amount $\underset{\sim}{v}_B^T - \underset{\sim}{v}_B$ as determined by

$$\underset{\sim}{t}_B^T - \underset{\sim}{t}_B = \underset{\approx}{F}\{\underset{\sim}{v}_B^T - \underset{\sim}{v}_B\} \qquad \text{(A1-1)}$$

where $\underset{\approx}{F}$ is a functional which describes the response of the surrounding *material to an excitation* on boundary B. The proposed uncoupling procedure consists of finding an appropriate approximation to functional $\underset{\approx}{F}$.

For a general nonlinear structure, finite element equations will be of the form

$$\phi(\underset{\sim}{x}) = \underset{\sim}{P} \qquad \text{(A1-2)}$$

in which $\underset{\sim}{x}$ and $\underset{\sim}{P}$ are the displacement and interface force vectors, respectively, and ϕ is an operator which represents the structural characteristics. If $\underset{\sim}{t}_B^T$ and $\underset{\sim}{t}_B$ are first Piola-Kirchhoff tractions, $\underset{\sim}{P}$ depends linearly on the interface tractions $\underset{\sim}{t}_B$, i.e.,

$$\underset{\sim}{P} = \underset{\sim}{P}(\underset{\sim}{t}_B^T) - \underset{\sim}{P}(\underset{\sim}{t}_B^T - \underset{\sim}{t}_B) \qquad \text{(A1-3)}$$

Then (A1-2) may be written as

$$\phi(\underset{\sim}{x}) + \underset{\sim}{P}[\underset{\approx}{F}(\underset{\sim}{v}_B^T - \underset{\sim}{v}_B)] = \underset{\sim}{P}(\underset{\sim}{t}_B^T) \qquad \text{(A1-4)}$$

The left hand side of (A1-4) represents a modified structural operator in which the boundaries of the actual structure are supported by nonlinear hysteretic connections to a base which moves with velocity $\underset{\sim}{v}_B^T$. The right hand side represents the interface loading from the trial calculation.

In physical terms this means that the traction $\underset{\sim}{t}_B^T$ can be used to load the actual structure. However, to account for the fact that $\underset{\sim}{t}_B^T$ corresponds to a slightly different structure, the boundary supports of the actual structure are modified by the use of non-linear supports. These supports are attached to a base with the approximate motion $\underset{\sim}{v}_B^T$ to the structure at each of its nodes or velocity points. The support behavior $\underset{\approx}{F}$ is chosen so as to represent the appropriate loading/unloading/reloading behavior of the medium surrounding the structure.

As a first choice, take

$$\underset{\approx}{F} = \rho \underset{\approx}{c} \qquad \text{(A1-5)}$$

so that (A2-1) becomes

$$\underset{\sim}{t}_B^T - \underset{\sim}{t}_B = \rho \underset{\approx}{c} \cdot (\underset{\sim}{v}_B^T - \underset{\sim}{v}_B) \qquad \text{(A1-6)}$$

in which $\underset{\approx}{c}$ is a tensor formed from the wave speeds in the medium. This is equivalent to the plane wave approximation used for linear media and involves only linear dashpot supports on the structure. Similarly, $\underset{\approx}{F}$ can be chosen to give an interactive scheme analogous to the doubly asymptotic approximation.

APPENDIX 2

Computational Procedure for Interactive Approximation

Consider the i^{th} node of a finite element structural program such as SAP IV at the n^{th} time step. Let A_i be the wetted area associated with this node and ν_i the normal (into the structure) to A_i. Let the free field pressure and normal velocity at (i, n) be p_{Fi}^n and u_{Fi}^n, respectively. Then the nonlinear interaction approximation leads to the following explicit procedure for computing the load $F_{\nu i}^n$ on the structure at (i, n) due to the fluid:

$$\psi_i^o = 0 \tag{A2-1}$$

$$F_{\nu i}^n = \begin{cases} A_i \max[0,\ p_{Fi}^{n-1} + \rho_o c(u_{Fi}^{n-1} - v_i^{n-1})] & \text{if } \psi_i^{n-1} = 0 \\ 0 \quad \text{if } \psi_i^{n-1} > 0 & \end{cases} \tag{A2-2}$$

Compute n^{th} normal structural velocity v_i^n. Then

$$\psi_i^n = \begin{cases} \max[0,\ \psi_i^{n-1} + (v_i^n - u_{Fi}^n)\Delta t] & \text{if } F_{\nu i}^n = 0 \\ 0 \quad \text{if } F_{\nu i}^n > 0 & \end{cases} \tag{A2-3}$$

where ψ_i^n represents the amount of separation, if any, due to cavitation.

The linear approximation is merely

$$F_{\nu i}^n = A_i [p_{Fi}^{n-1} + \rho_o c(u_{Fi}^{n-1} - v_i^{n-1})] \tag{A2-4}$$

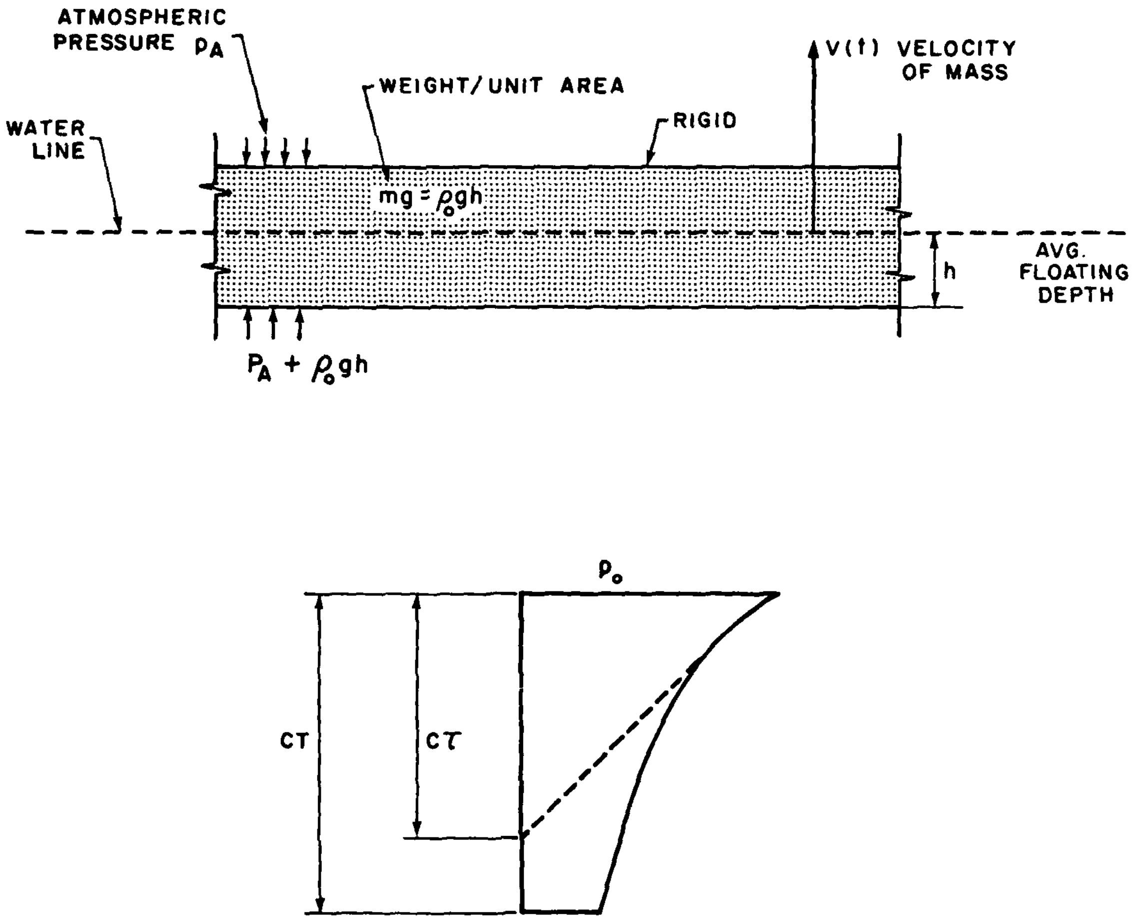


FIG. 1 - 1D MODEL

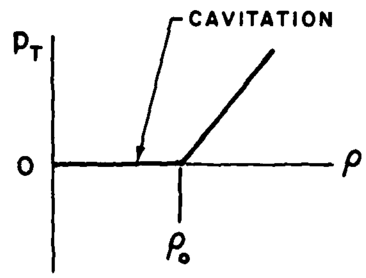
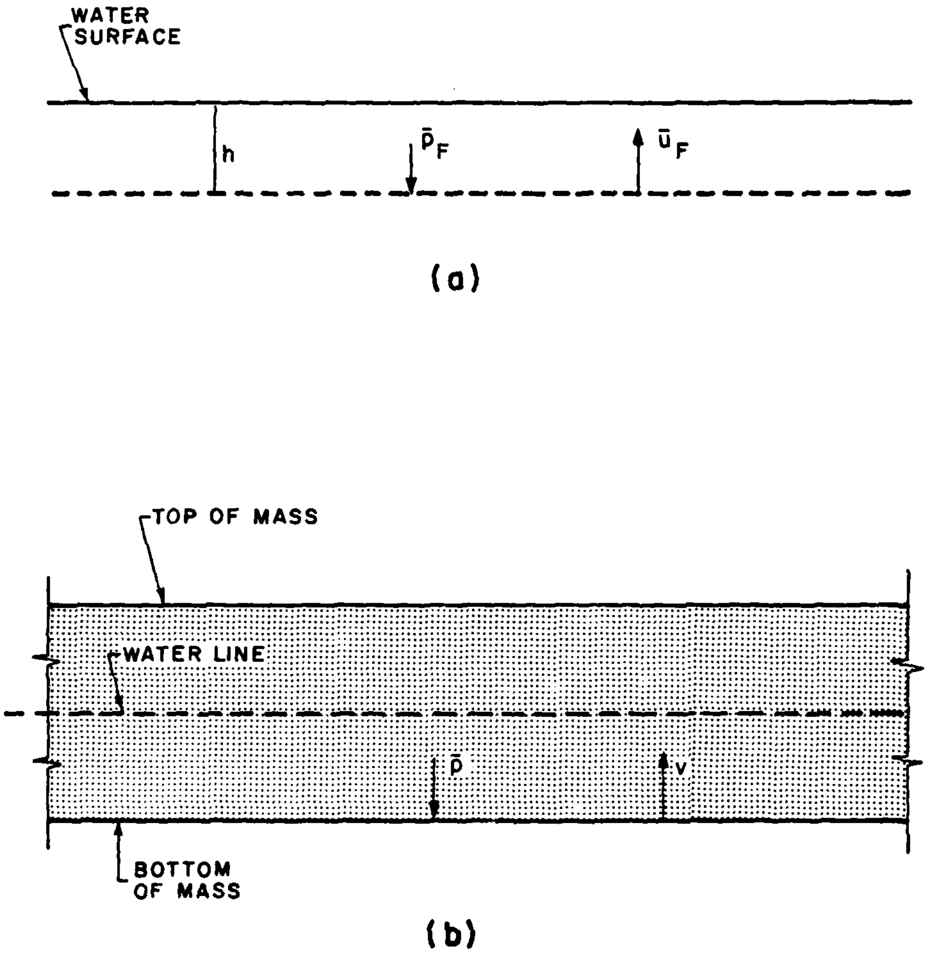


FIG. 2 - BILINEAR PRESSURE - DENSITY RELATION



$$\bar{p} - \bar{p}_F = F \{\bar{u}_F - v\}$$

FIG. 3-INTERACTIVE APROXIMATION

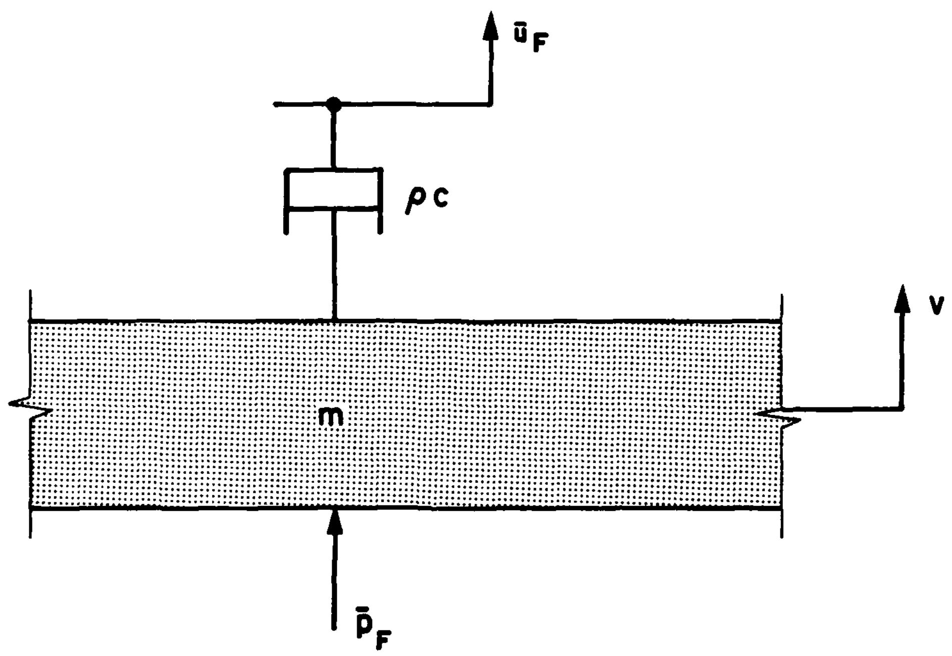


FIG. 4-LINEAR INTERACTION APROXIMATION

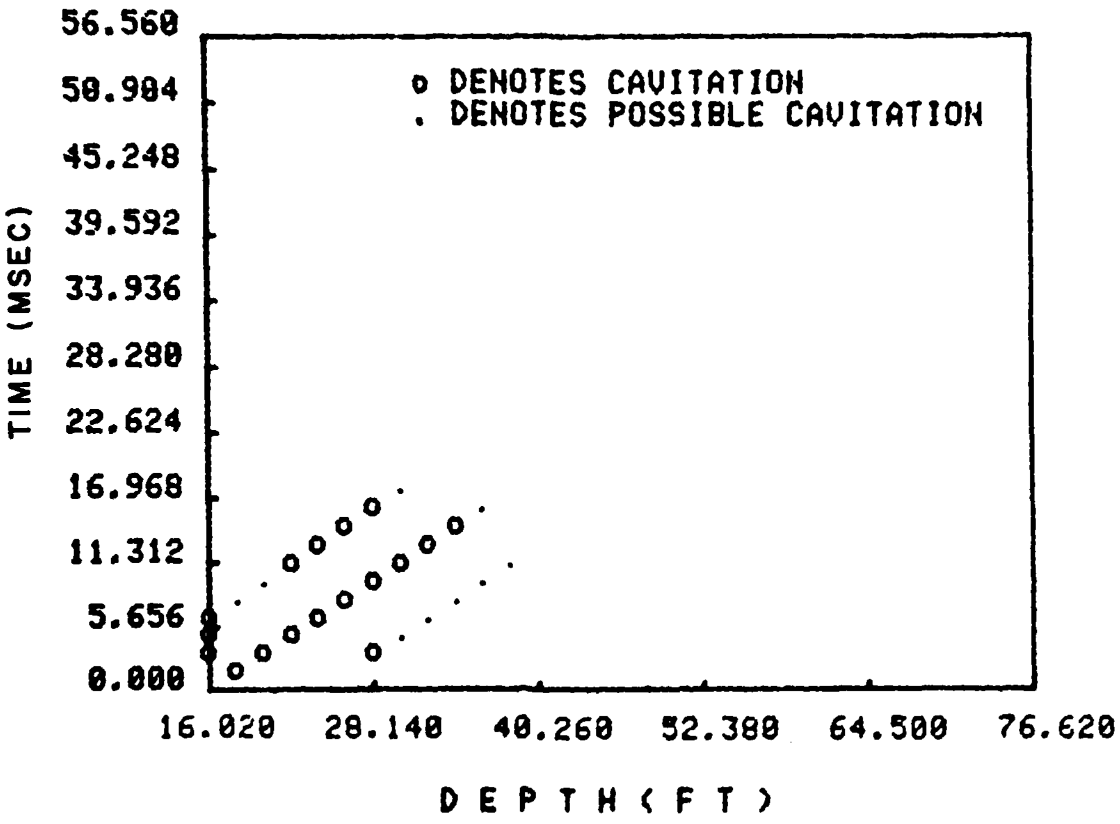


FIG. 5 EXTENT OF CAVITATION REGION - FREE FIELD

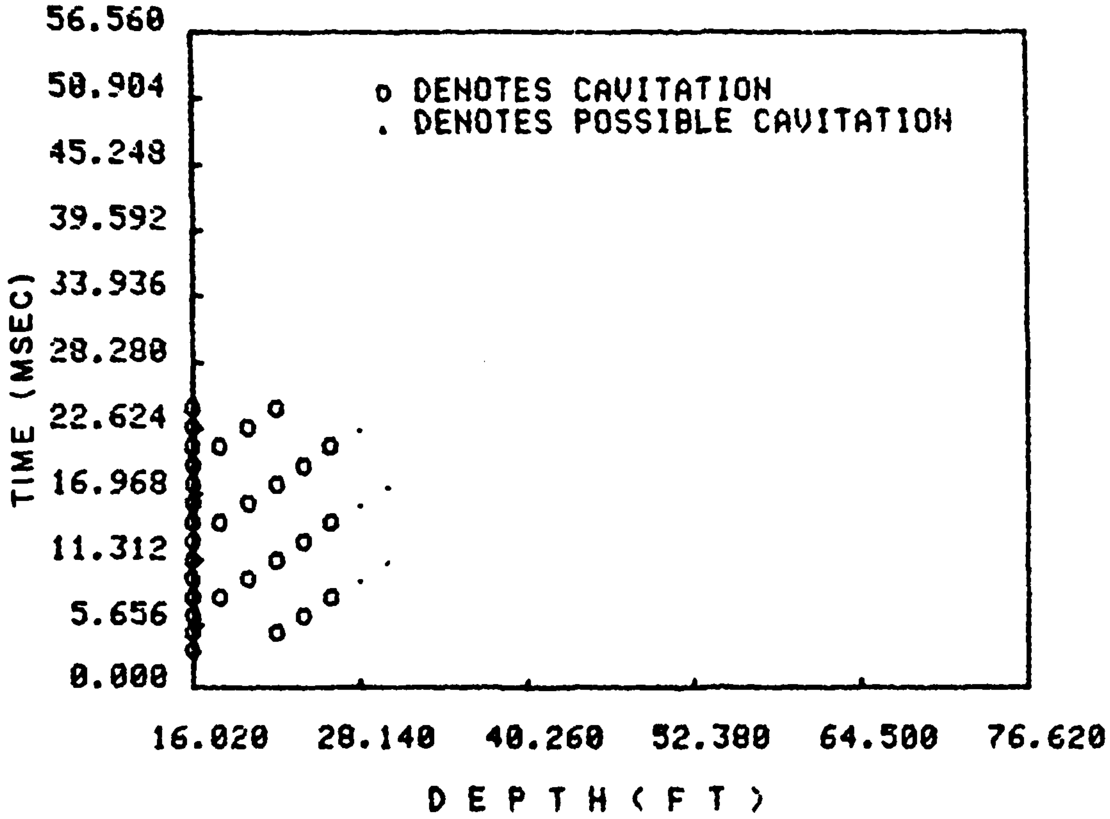


FIG. 6 EXTENT OF CAVITATION REGION- MASS PRESENT

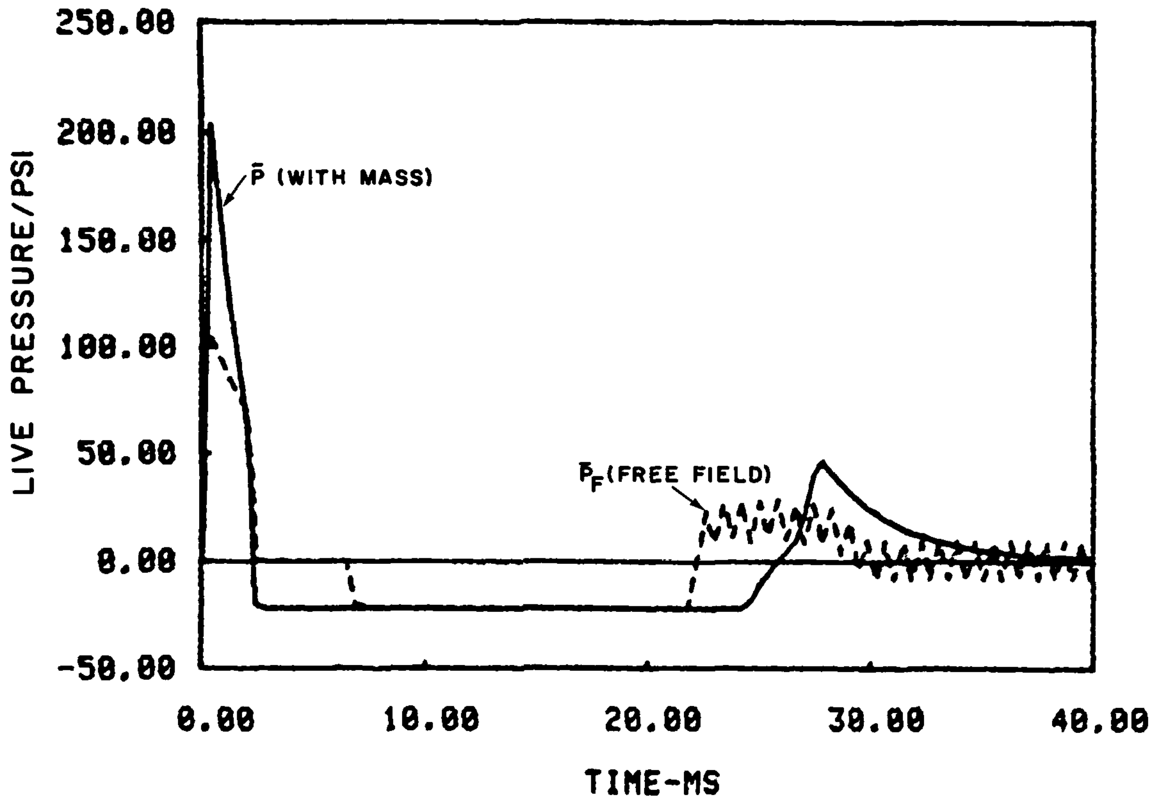


FIG. 7 PRESSURE AT DEPTH h

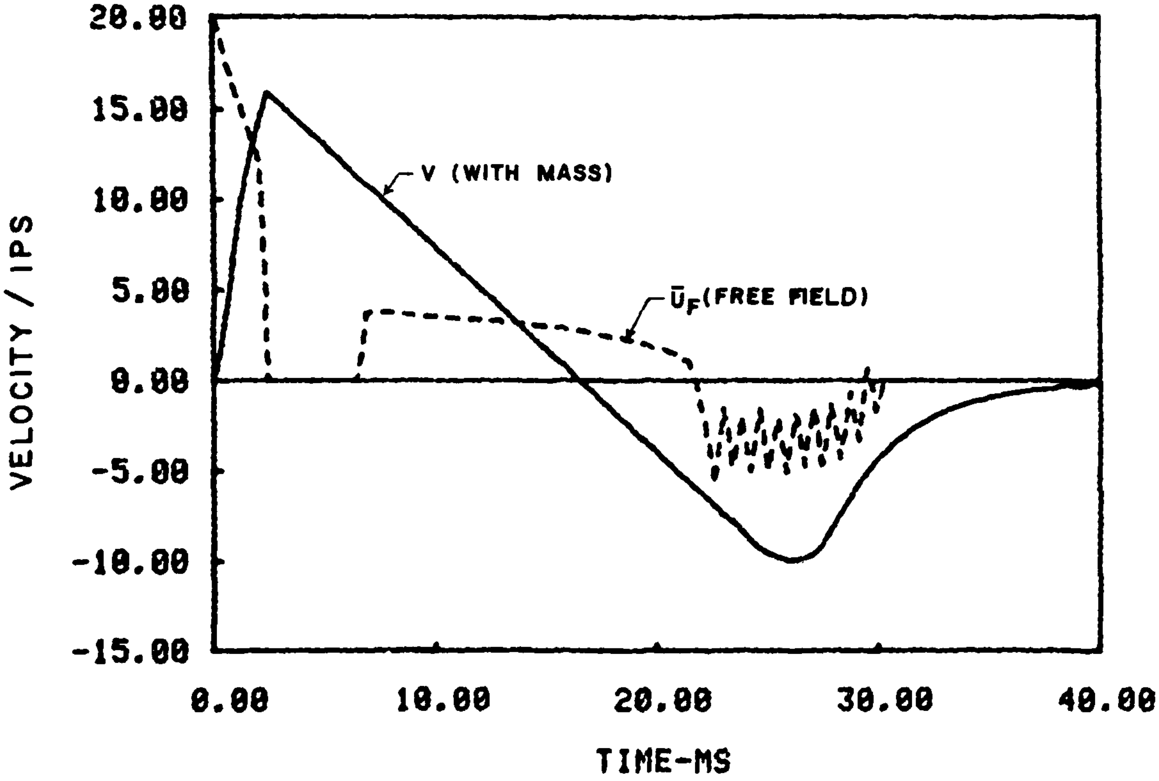


FIG. 8 VELOCITY AT DEPTH h

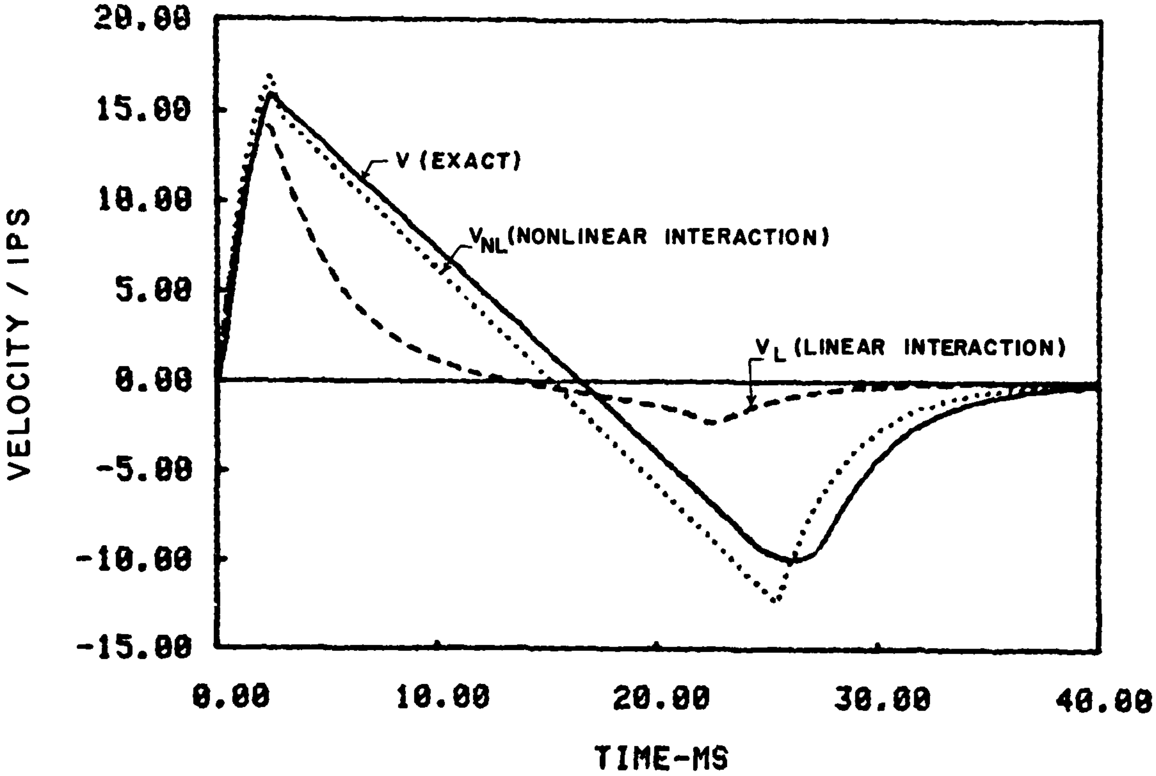


FIG. 9 VELOCITY OF MASS

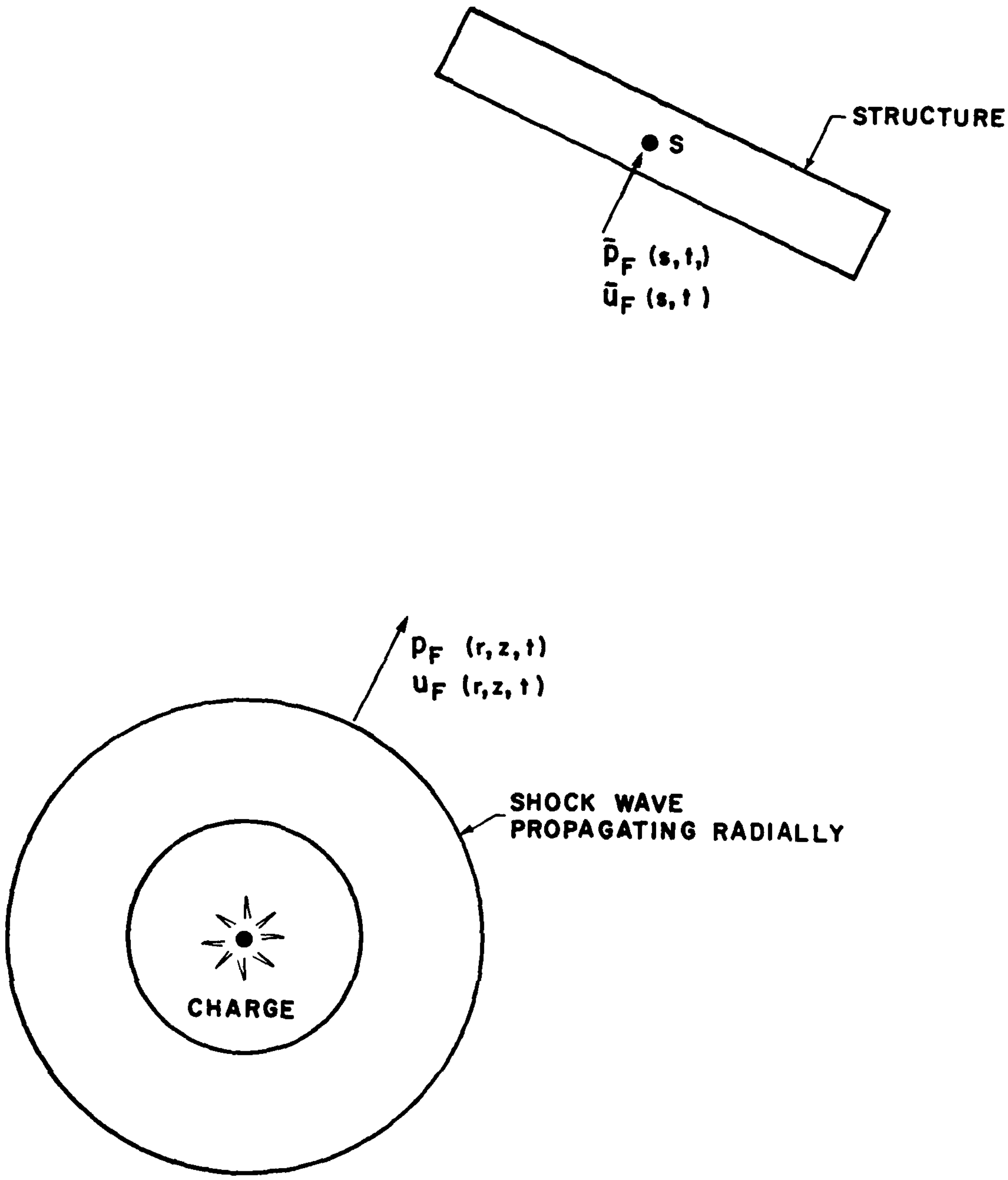


FIG. 10 – CYLINDRICAL SHOCK LOADING – PLAN VIEW

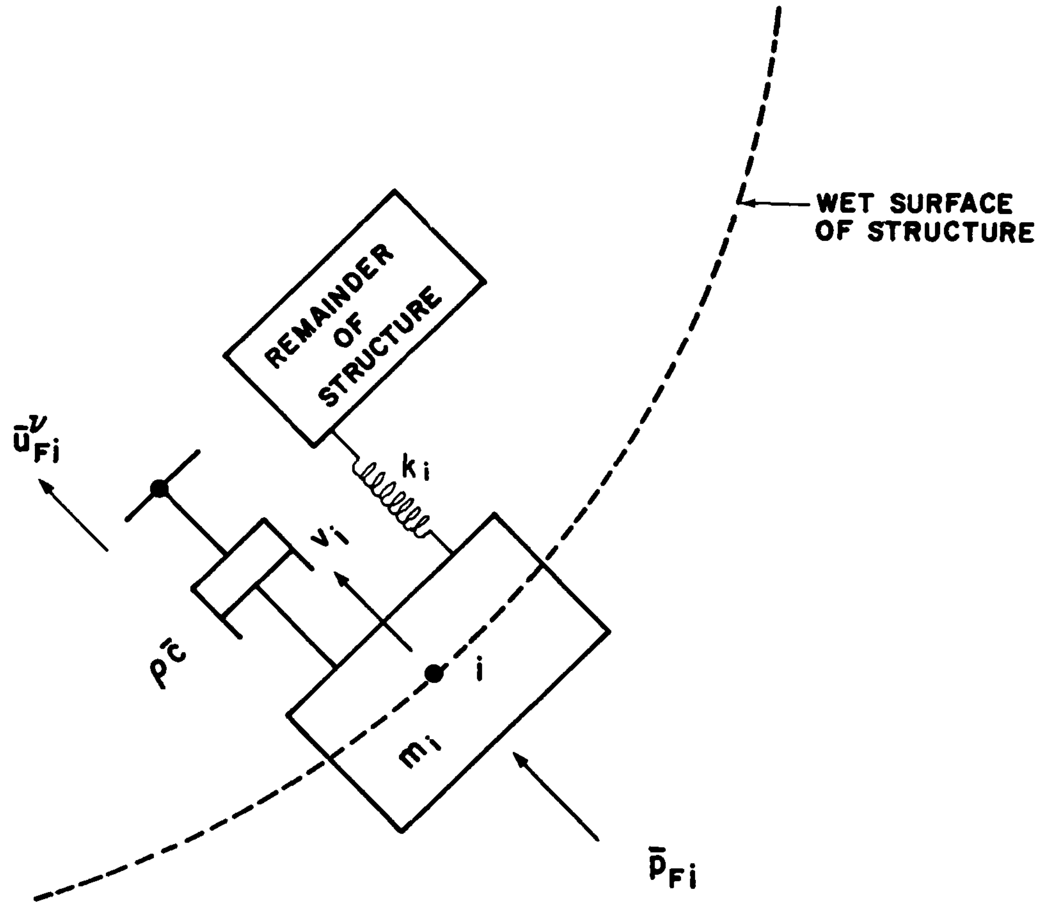


FIG. 11–SCHEMATIC OF EXTERNAL FINITE ELEMENT

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