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REVIEW ARTICLE

COMPARISON BETWEEN DIRECT AND INDIRECT COUPLING FOR SEISMIC ANALYSIS OF FLUID-STRUCTURE COUPLED SYSTEM

***Kalyan Kumar Mandal and Damodar Maity**

Department of Civil Engineering, Indian Institute of Technology Kharagpur, India

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ABSTRACT

The present paper deals with the analysis of the fluid–structure systems considering the coupled effect of elastic structure and fluid adjacent to it. Both fluid and structure are discretized and modeled by finite elements. In the governing equations, pressure for the fluid domain and displacement for the structure are considered as independent nodal variables. Two different methods namely, direct coupled and indirect iterative approach for the analysis of fluid-structure system has been carried out in this study. In direct coupled approach, the solution of the fluid-structure system are accomplished by considering these as a single system while in indirect iterative method, the responses are obtained by solving the two systems separately with enforcing the interaction effects at the interface. The results obtained from these two methods are compared in terms of CPU times to evaluate the effectiveness of these methods for varieties of fluid-structure interaction problems. The outcomes of the results show that the effectiveness of these methods mainly depends on the degree of flexibility of structure and the length of the reservoir adjacent to it.

INTRODUCTION

The interaction between an elastic structure and compressible fluid adjacent to it due to dynamic loading has become the subject of intensive investigation in recent years. The interaction between the fluid and the structure has to be accounted foran accurate dynamic analysis of these types of structures. Chopra (Chopra, 1967) presented an analytical solution of the wave equation to obtain the hydrodynamic pressure on the vertical face of the structures during earthquake. Another analytical expression for calculating hydrodynamic pressure on structure with inclined upstream face was evaluated by Chwang (1978). However, such analytical methods are suitable for rigid structures. However, the structures are practically elastic in nature. Formulations based on displacement variables are usually chosen for the structure while the fluid is described by different variables such as displacement, pressure, velocity, velocity potential etc.

The governing equations of fluid interms of displacements are carried out by many researchers (Olson and Bathe, 1983; Chen and Taylor, 1990; Bermudez *et al*., 1995; Maity and Bhattacharyya, 1997). In such formulation, the fluid elements can easily be coupled to the structural elements using standard finite element assembly procedures. But the degrees of freedom for fluid domain increase significantly especially for three dimensional problems. Moreover, the fluid displacements must satisfy their rotationalitycondition, otherwise zero-frequency spurious modes may occur (Bermudez *et al*., 1995). Fenves and Vargas (Fenves *et al*., 1978) considered velocity and pressure as nodal variables to represent the governing equations for fluid. However, as number of unknown parameters increase in the fluid domain, the requirement of computational time becomes higher. Zienkiewicz *et al*. (1983) represented the equations of fluid domain in terms of a displacement potential. The coupled equations of motion in this case become unsymmetrical, but irrotationality condition on fluid motion is automatically satisfied. Many researchers (Zienkiewicz *et al*., 1978; Muller, 1981; Maity and Bhattacharyya, 2003) considered hydrodynamic pressure as unknown variable in finite element discretization of the fluid domain. Many simplified Eulerian approachesare available to deal fluid-structure interaction problem. Some of which, fluid-structure interaction is studied in a decoupled manner. In this type of analysis, the response of fluid is first calculated assuming the structure as rigid and calculated pressure is imposed on the structure to obtain the response of structure.

****Corresponding author: Kalyan Kumar Mandal,***
Department of Civil Engineering, Indian Institute of Technology Kharagpur, India.

But such type of analysis does not always lead to a conservative design of structure particularly for the case of resonance between fluid and structures. Sami and Lotfi (Sami and Lotfi, 2007) studied dam-reservoir system by modal coupled approach and reported that the coupled modal approach yields good approximation even with a relatively low number of combinations of modes. But, main disadvantage of this method is the calculation of eigenvectors through solving unsymmetrical mass and stiffness matrix of dam-reservoir system. The authors also studied the dam-reservoir system in decoupled modal approach. The accuracy of decoupled modal approach increases much lower rate as the number of combined modes grows.

Many researchers (Maity and Bhattacharyya, 2003; Akkose *et al*., 2008; Onate *et al*., 2006; Singh *et al*., 1991; Lotfi *et al*., 2004; Antoniadis and Kanarachos, 1988; Gogoi *et al*., 2005) used indirect iterative method to deal the fluid-structure interaction problems. In this method, the hydrodynamic pressure in fluid domain is first determined considering structure as rigid. The resulting pressure exerts forces on the adjacent structure. Due to this additional forces structure undergoes new displacement. The fluid domain is solved again with the calculated displacement to get the response of the elastic structures. The process is continued till a desired level of convergence in both pressures and displacements are achieved. The major advantage of this method is that the coupled field problems can betackled in a sequential manner. The analysis is carried out for each field separately and interaction effect is accommodated by updating the variables of the fields in the respective coupling terms.

Another group of researchers used direct coupled approach (Zienkiewicz and Bettes, 1978; Sharan and Gladwell, 1985; Hall and Chopra, 1982). In this method, fluid and structure is coupled and solved as a single system. A number of researchers used hydrodynamic pressure as the unknown variable in finite element discretization of the fluid domain to overcome the development of spurious modes. But the resulting equations in this case lead to unsymmetrical matrices and require a special purpose computer program for the solution of coupled systems is required (Sandberg and Goransson, 1988; Sandberg, 1995). From the past literature, it is observed that the coupled interaction between fluid and structure are incorporated either by coupling of two systems directly (known as strong coupling) or coupled interaction effects are ensured indirectly at the interface by an iterative method (known as weak coupling).

It is observed that both the methods have certain advantages and disadvantages. However, no paper is available which compares these two methods and recommends the suitability of the method to solve a particular type of fluid-structure interaction problem. To investigate the efficacy of the above mentioned methods, *i.e.,* direct coupling and indirect coupling, a comparative study has been performed for different cases. Computer codes have been developed both for direct coupled approach and indirect iterative approach in MATLAB environment. Both the structure and fluid domain are discretized in finite elements and displacement and pressure are considered as unknown variables to describe the structure and fluid respectively. By comparing different responses of the fluid-structure system and their execution time from direct and indirect coupling, the efficiency and relative advantages and disadvantages of these methods are investigated.

Theoretical formulation

Theoretical Formulation for Structure

The equation of motion of a structure subjected to external forces can be written in standard finite element form as

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{F_d\} \tag{1}$$

Where, $[M]$, $[C]$ and $[K]$ are mass, damping and stiffness matrix of structure respectively, $\{\ddot{u}\}$, $\{\dot{u}\}$ and $\{u\}$ are nodal accelerations, velocities and displacements, $\{F_d\}$ is the nodal forces. In present investigation the structure has been discretised by two dimensional eight node rectangular elements. The dam body is assumed to be in a state of plane strain. The structural Rayleigh damping can be expressed as

$$[C]=a'[M]+b'[K] \tag{2}$$

where a' and b' are called the proportional damping constants. The relationship between a', b' and the fraction of critical damping at a frequency ω is given by the following equation.

$$\xi'=\frac{1}{2}\left(a'\omega+\frac{b'}{\omega}\right) \tag{3}$$

Damping constants a' and b' are determined by choosing the fraction of critical damping ξ_1 and ξ_2 at two different frequencies ω_1 & ω_2 and solving simultaneously equations a' and b'. Thus,

$$a' = \frac{2(\xi_2'\omega_2 - \xi_1'\omega_1)}{(\omega_2^2 - \omega_1^2)}$$
$$b' = \frac{2\omega_1\omega_2(\xi_2'\omega_1 - \xi_1'\omega_2)}{(\omega_2^2 - \omega_1^2)} \quad (4)$$

Usually, ω_1 is taken as the lowest natural frequency of the structure, and ω_2 is the highest frequency of interest in the loading or response. In the present study, the fraction of critical damping for both the frequencies are chosen as the same i.e. $\xi_1' = \xi_2' = \xi'$. Thus, above equation may be expressed as

$$a' = \frac{2\xi'}{(\omega_2 + \omega_1)}$$
$$b' = \frac{2\xi'\omega_1\omega_2}{(\omega_2 + \omega_1)} \quad (5)$$

Theoretical Formulation for Fluid

Assuming fluid to be linearly compressible, inviscid and with small amplitude irrotational motion, the hydrodynamic pressure distribution due external excitation is given as

$$\nabla^2 p(x, y, t) = \frac{1}{C^2}\ddot{p}(x, y, t) \quad (6)$$

Where C is the acoustic wave velocity in the water and ∇^2 is the Laplacian operator in two dimensions. The pressure distribution in the fluid domain is obtained by solving eq. (6) with the following boundary conditions. The geometry of fluid - structure system is shown in Fig. 1.

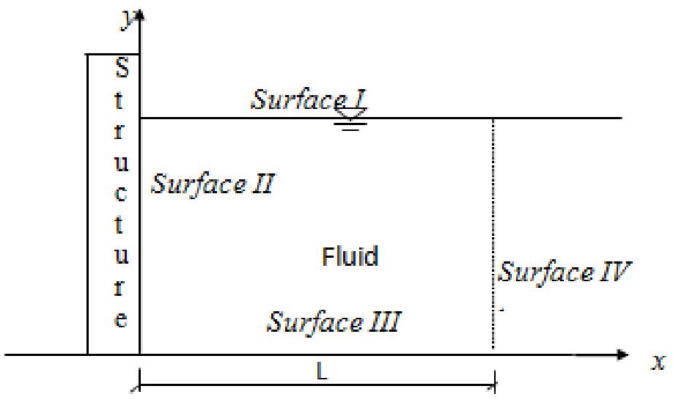

Fig.1. Geometry of fluid-structure system

i) *At surfaceI*

Considering the effect of surface wave of the fluid, the boundary condition of the free surface is taken as

$$\frac{1}{g}\ddot{p} + \frac{\partial p}{\partial y} = 0 \quad (7)$$

ii) *At surface II*

At fluid-structure interface, the pressure should satisfy

$$\frac{\partial p}{\partial n}(0, y, t) = \rho_f a e^{i\omega t} \quad (8)$$

Where $ae^{i\omega t}$ is the horizontal component of the ground acceleration in which, ω is the circular frequency of vibration and $i = \sqrt{-1}$,n is the outwardly directed normal to the element surface along the interface. ρ_f is the mass density of the fluid.

iii) *At surface III*

This surface is considered as rigid surface and the pressure should satisfy the following condition

$$\frac{\partial p}{\partial n}(x,0,t)=0.0 \tag{9}$$

iv) *At surface IV*

In case of finite fluid domain, this surface is considered to be rigid and thus the boundary condition in this case will become as follows:

$$\frac{\partial p}{\partial n}(L,y,t)=0.0 \tag{10}$$

Where, L is the distance between structural surface and surface IV. In case of infinite fluid domain, the domain needs to be truncated as a suitable distance for the finite element analysis. The truncation boundary as proposed by Maity and Bhattacharyya (1999) has been implemented for the finite element analysis of infinite reservoir.

Finite Element Formulation for Fluid domain

By using Galerkinapproach and assuming pressure to be the nodal unknown variable, the discretised form of eq. (6) may be written as

$$\int_{\Omega} N_{rj}\left[\nabla^2\sum N_{ri}p_i-\frac{1}{c^2}\sum N_{ri}\ddot{p}_i\right]d\Omega=0 \tag{11}$$

Where, N_{rj} is the interpolation function for the reservoir and Ω is the region under consideration. Using Green's theorem eq. (11) may be transformed to

$$-\int_{\Omega}\left[\frac{\partial N_{rj}}{\partial x}\sum\frac{\partial N_{ri}}{\partial x}p_i+\frac{\partial N_{rj}}{\partial y}\sum\frac{\partial N_{ri}}{\partial y}p_i\right]d\Omega-\frac{1}{c^2}\int_{\Omega}N_{rj}\sum N_{ri}\,d\Omega\;\ddot{p}_i+\int_{\Gamma}N_{rj}\sum\frac{\partial N_{rj}}{\partial n}d\Gamma\;p_i=0 \tag{12}$$

in which i varies from 1 to total number of nodes and Γ represents the boundaries of the fluid domain. The last term of the above equation may be written as

$$\{B\}=\int_{\Gamma}N_{rj}\frac{\partial p}{\partial n}d\Gamma \tag{13}$$

The whole system of equation (12) may be written in a matrix form as

$$\left[\bar{E}\right]\left\{\ddot{P}\right\}+\left[\bar{G}\right]\left\{P\right\}=\left\{F\;\right\} \tag{14}$$

Where,

$$\left[\bar{E}\right]=\frac{1}{C^2}\sum\int_{\Omega}\left[N_r\right]^T\left[N_r\right]d\Omega \tag{15}$$

$$\left[\bar{G}\right]=\sum\int_{\Omega}\left[\frac{\partial}{\partial x}\left[N_r\right]^T\frac{\partial}{\partial x}\left[N_r\right]+\frac{\partial}{\partial y}\left[N_r\right]^T\frac{\partial}{\partial y}\left[N_r\right]\right]d\Omega \tag{16}$$

$$\left[F\right]=\sum\int_{\Gamma}\left[N_r\right]^T\frac{\partial p}{\partial n}d\Gamma=\left\{F_f\right\}+\left\{F_{fs}\right\}+\left\{F_{fb}\right\}+\left\{F_t\right\} \tag{17}$$

Here the subscript *f*, *fs*, *fb* and *t* stand for the free surface, fluid-structure interface, fluid-bed interface and truncation surface respectively. For surface wave, the eq. (7) may be written in finite element form as

$$\{F_f\} = -\frac{1}{g}[R_f]\{\ddot{p}\} \tag{18}$$

In which,

$$[R_f] = \sum \int_{\Gamma_f} [N_r]^T [N_r] d\Gamma \tag{19}$$

At the fluid-structure interface if $\{a\}$ is the vector of nodal accelerations of generalized coordinates, $\{F_{fs}\}$ may be expressed as

$$\{F_{fs}\} = -\rho[R_{fs}]\{a\} \tag{20}$$

In which,

$$[R_{fs}] = \sum \int_{\Gamma_{fs}} [N_r]^T [T][N_d] d\Gamma \tag{21}$$

Where,(T) is the transformation matrix at fluid structure interface and N_d is the shape function of dam. At fluid-bed interface

$$\{F_{fd}\} = 0 \tag{22}$$

And at the truncation boundary:

For finite fluid domain,

$$\{F_t\} = 0 \tag{23}$$

For infinite fluid domain,

$$\{F_t\} = \varsigma[R_t]\{p\} - \frac{1}{C}[R_t]\{\dot{p}\} \tag{24}$$

$$[R_t] = \sum \int_{\Gamma_t} [N_r]^T [N_r] d\Gamma \tag{25}$$

Where,

ς is a coefficient as expressed by Maity and Bhattacharyya (23).After substitution all terms the eq. (14) becomes

$$[E]\{\ddot{P}\} + [A]\{\dot{P}\} + [G]\{P\} = \{F_r\} \tag{26}$$

Where,

$$[E] = [\bar{E}] + \frac{1}{g}[R_f] \tag{27}$$

$$\{F_r\} = -\rho[R_{fs}]\{a\} \tag{28}$$

For finite fluid domain,

$$[A] = 0.0 \tag{29}$$

$$[G] = [\bar{G}] \tag{30}$$

And for infinite fluid domain,

$$[A]=\frac{1}{C}[R_t] \tag{31}$$

$$[G]=[\bar{G}]+\varsigma[R_t] \tag{32}$$

For any given acceleration at the fluid-structure interface, the eq. (26) is solved to obtain the hydrodynamic pressure within the fluid.

Direct Coupling for Fluid-Structure System

In the fluid-structure interaction problems, the structure and the fluid do not vibrate as separate systems under external excitations, rather they act together in a coupled way. Therefore, this fluid-structure interaction problem has to be dealt in a coupled way.
In present study, a direct coupling approach is developed to get the coupled fluid-structure response under external excitation. The coupling of structure and fluid may be formulated in following way.

The discrete structural equation with damping may be written as:

$$M\ddot{u}+C\dot{u}+Ku-Qp-F_d=0 \tag{33}$$

The coupling term (Q) in eq. (33) arises due to the acceleration and pressure specified on the fluid-structure interface boundary (Zienkiewicz and Newton (Yang *et al*., 1996) and can be expressed as:

$$\int_{\Gamma_s} N_s^T np\,d\Gamma=\left(\int_{\Gamma_s} N_s^T nN_r\,d\Gamma\right)p=Qp \tag{34}$$

Where, n is the direction vector of the normal to the fluid-structure interface. N_s and N_r are the shape functions of structure and fluid respectively. Similarly, discretized fluid equation may be written as:

$$E\ddot{p}+A\dot{p}+Gp+Q^T\ddot{u}-F_r=0 \tag{35}$$

Now, the system of eq. (33) and (35) are coupled in a second-order ordinary differential equations, which defines the coupled fluid -structure system completely. These sets of coupled equations are solved on two different meshes of fluid and structure. The eq. (33) and (35)may be written as a set:

$$\begin{bmatrix} M & 0 \\ Q^T & E \end{bmatrix}\begin{Bmatrix} \ddot{u} \\ \ddot{p} \end{Bmatrix}+\begin{bmatrix} C & 0 \\ 0 & A \end{bmatrix}\begin{Bmatrix} \dot{u} \\ \dot{p} \end{Bmatrix}+\begin{bmatrix} K & -Q \\ 0 & G \end{bmatrix}\begin{Bmatrix} u \\ p \end{Bmatrix}=\begin{Bmatrix} F_d \\ F_r \end{Bmatrix} \tag{36}$$

For free vibrations analysis, the above equation can be simplified to the following expression after omitting all the damping terms:

$$\begin{bmatrix} M & 0 \\ Q^T & E \end{bmatrix}\begin{Bmatrix} \ddot{u} \\ \ddot{p} \end{Bmatrix}+\begin{bmatrix} K & -Q \\ 0 & G \end{bmatrix}\begin{Bmatrix} u \\ p \end{Bmatrix}=0 \tag{37}$$

Natural frequency of fluid-structure system can be obtained by eigenvalue solution of eq. (37). However, the matrices in eq. (37) are unsymmetrical and standard eigenvalue solutions cannot be used directly. So the above matrices are to be transformed into symmetric matrices. This can be accomplished by change of variables as follows. Introducing two variables $\tilde{u}=ue^{i\omega t}$ and $\tilde{p}=pe^{i\omega t}$, eq.(37) can be expressed as

$$K\tilde{u}-Q\tilde{p}-\omega^2M\tilde{u}=0 \tag{38}$$

$$E\tilde{p}-\omega^2Q^T\tilde{u}-\omega^2G\tilde{p}=0 \tag{39}$$

Further, introducing another variable q such that

$$\tilde{p} = \omega^2 q \tag{40}$$

After manipulation and substitution of above three equations in eq. (37), the final form of this equation becomes

$$\left[\begin{bmatrix} K & 0 & 0 \\ 0 & A & 0 \\ 0 & 0 & 0 \end{bmatrix} - \omega^2 \begin{bmatrix} M & 0 & Q \\ 0 & 0 & E \\ Q^T & E^T & G \end{bmatrix}\right] \begin{Bmatrix} \tilde{u} \\ \tilde{p} \\ \tilde{q} \end{Bmatrix} = 0 \tag{41}$$

The above matrices in fluid-structure system are symmetric and are in standard form. Further, the variable can be eliminated by static condensation and the final fluid-structure system becomes symmetric and still contains only the basic variables.

Indirect Iterative Approach for Fluid-Structure System

The coupled effect of fluid-structure system can also be achieved by an iterative scheme. At any time instant *t*, hydrodynamic pressure in fluid domain is evaluated by solving eq. (26) with appropriate boundary conditions and considering the structure to be rigid. But, the result is inaccurate because in practical, the structure is elastic in nature. To determine accurate hydrodynamic pressure, forces developed due to hydrodynamic pressures at rigid structure-fluid interface are considered as additional forces on the adjacent structure. Hence, at the same time instant, the structure is analyzed with these additional forces $\{F_{rr}\}$, using eq. (42).

$$M\ddot{u} + C\dot{u} + Ku = -F_d - F_{rr} \tag{42}$$

Here, the external force F_d can be expressed as follows.

$$F_d = M\ddot{u}_g \tag{43}$$

The ground acceleration is considered as $\ddot{u}_g$ .Due to these additional forces, the structure undergoes a displacement $\{d\}_t$, as a result boundary condition at the fluid- structure interface changes. Therefore, the fluid domain is solved again with the changed displacement at fluid-structure interface. Thus at time *t*, both the hydrodynamic pressure $\{p\}_t$ and the structural displacement $\{d\}_t$ are iterated simultaneously till a desired level of convergence is achieved. Thus,

$$\left|\frac{\{p_{i+1}\}_t - \{p_i\}_t}{\{p_i\}_t}\right| \le \varepsilon', \text{ and } \left|\frac{\{d_{i+1}\}_t - \{d_i\}_t}{\{d_i\}_t}\right| \le \varepsilon'' \tag{44}$$

Where,*i* is the no. of iteration.ε′ and ε″ are small pre-assigned tolerance values. For an efficient and accurate analysis of fluid-structure coupled system, the steps to be followed are given in the form of flow chart in Fig. 2.

NUMERICAL RESULTS

Validation of Developed Direct Coupling Method

The accuracy of the proposed direct coupled approach is studied considering a bench marked problem. The results are compared with an existing literature (12) for the Pine flat dam. The material properties of dam and reservoir are considered as follows: modulus of elasticity=22.75GPa,Poisson's ratio=0.2, unit weight of concrete=2480 kg/m^3, pressure wave velocity = 1440 m/s, unit weight of water = 981kg/m^3,height of dam (H_d) = 121.91 m, width at top (t_d) = 9.75 m, width at base (L_d) = 95.71,depth of reservoir (H_f)= 116.19 m. Fig. 3 shows the geometric details and a typical finite element discretization for the dam-reservoir system. For the finite element analysis, the infinite reservoir is truncated at a distance (L_t) 200m from dam-reservoir interface and Somerfeld's boundary condition is implemented at truncation surface as considered by Sami and Lotfi (12). The first five natural frequencies of the dam-reservoir system are listed and compared with those values obtained by Samii and Lotfi (12) in Table 1. The tabulated results show the accuracy of the developed direct coupled approach.

Validation of the Developed Indirect Iterative Method

Validation of indirect iterative approach is carried out on a problem that is considered by Yang *et al.*(25) in their study. The geometry and material properties of fluid-structure system considered in the present case are same as considered by Yang *et al* (25) and are as follows. Structure: height (H_s) = 120m, width at top and base (t_s) = 90m, mass density (ρ_d) = 23.6 kN/m^3, Poisson's ratio (ν)=0.2, modulus of elasticity (E_d) = 2.76 × 10^7 kN/m^2, structural damping = 5%; Fluid: depth (H_f)= 120m, acoustic speed (*c*)

= 1439 m/sec, mass density (ρ_d) = 9.97 kN/m^3. The infinite reservoir domain is truncated at a distance (*L)* = 60m and the truncation boundary condition as proposed by Maity and Bhattacharyya (23) is implemented at the truncation surface.

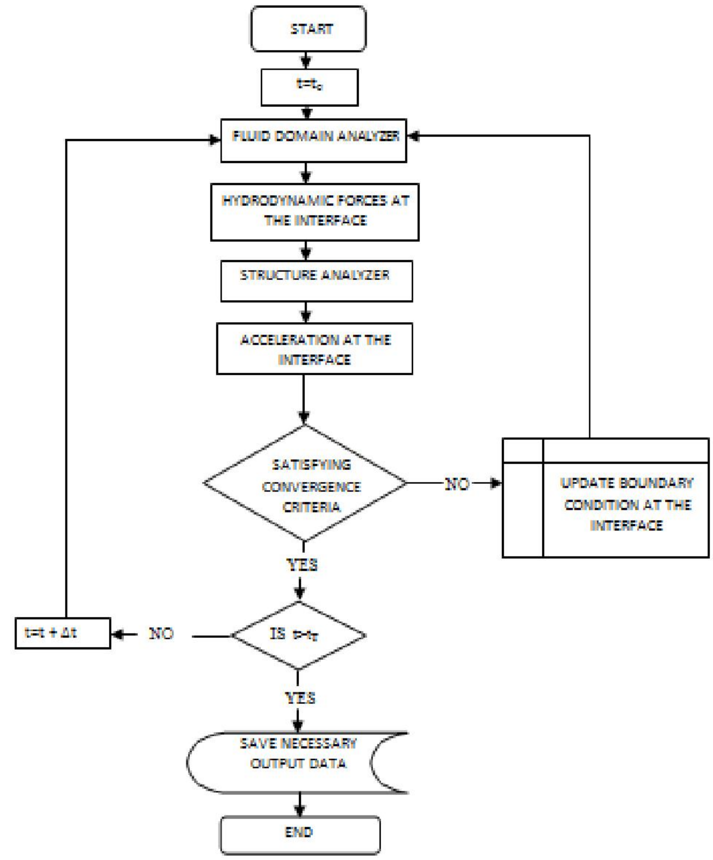

Fig. 2. Flow chart for fluid-structure analyzer of indirect approach

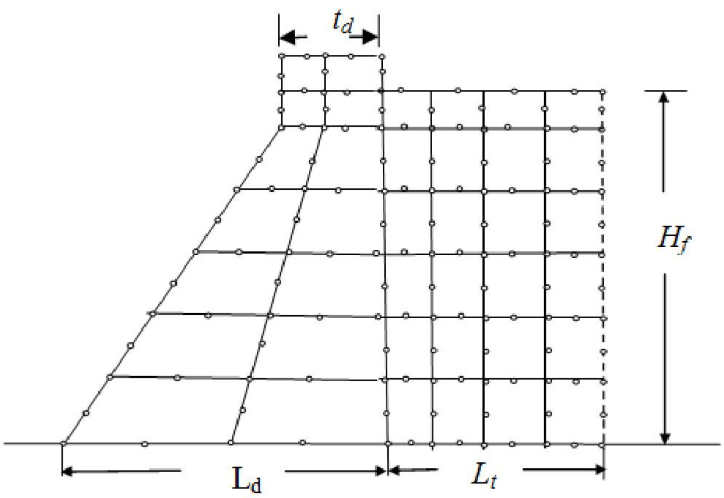

Fig. 3. Finite element mesh of dam-reservoir system

Table 1. First five natural frequencies of the Pine flat dam-reservoir system

Mode number	Natural Frequency (Hz)	
	Present Study	Samii and Lotfi (Sami and Lotfi, 2007)
1	2.5341	2.5267
2	3.2712	3.2681
3	4.5626	4.6651
4	6.2326	6.2126
5	7.9435	7.9181

Both the fluid and structure are modeled with eight node rectangular elements. A typical finite element discretization for the fluid-structure system is shown in Fig.4.The horizontal displacement due to ramp acceleration at the top of the structure is plotted in Fig.5. The results obtained from present indirect iteration approach are superimposed with the results obtained by Yang *et al*. (25). The comparison of the results shows the accuracy of the indirect iterative approach.

Comparison between Direct and Indirect Approach

In order to investigate the efficiency of direct coupled and indirect iterative approach, few numerical examples related to fluid-structure interaction problems are studied. For indirect iterative approach, the tolerance for both pressure in fluid domain and displacement in structure is considered as 10^{-5}. The comparison between these two methods is made by comparing the maximum hydrodynamic pressure developed in the fluid-structure interface, maximum tip displacement of the structure and CPU time. All computer codes have been run in a PC of following configuration: Processor:- Intel(R) Core(TM) 2 Duo CPU T5870 @ 2.00 GHz, Installed memory (RAM):- 3.00 GHz, System type:- 32 bit operating system.

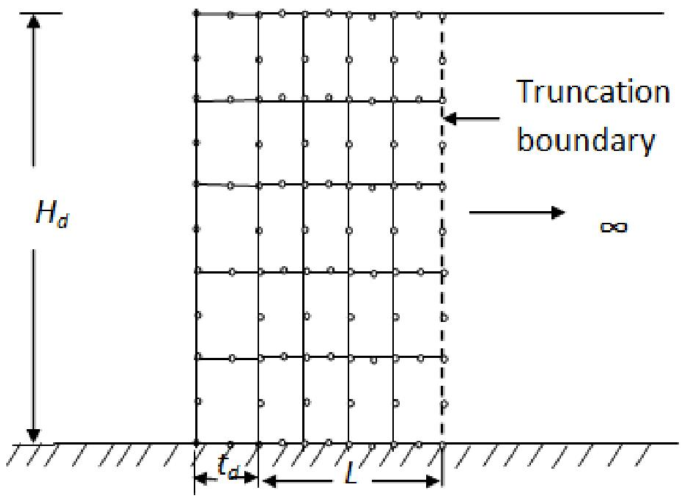

Fig. 4. Finite element mesh of fluid-structure system

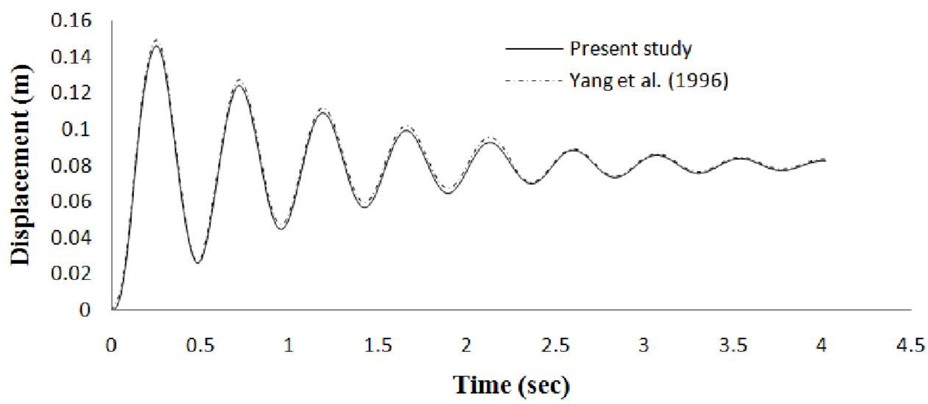

Fig. 5. Horizontal displacement at top of the structure due to ramp acceleration

Example 1

To study the efficiency of direct coupled and indirect iterative approach a problem considering a cantilever log gate structure is studied. The geometric details and material properties are consider as follows: Gate structure: height (H_d) = 5 m, mass density (ρ_d) = 7800 kg/m^3, Poisson's ratio (ν) = 0.3, modulus of elasticity (E_d) = 200 GPa and structural damping = 5%; Water: depth (H_f) = 5 m, acoustic speed (c) = 1440 m/sec, mass density (ρ_f) = 1000 kg/m^3.The infinite reservoir is truncated at a distance 2.5 m from the fluid-structure interface and boundary condition developed by Maity and Bhattacharyya (23) is implemented at the truncation surface. For the finite element analysis, the gate structure is discretized by 4 × 12 (i.e., no. of element in horizontal direction, N_h = 4 and no. of element in vertical direction, N_v = 12) and reservoir water is discretized by 12 ×12 (i.e., N_h = 12 and N_v = 12).

The excitation on the structure is considered to be sinusoidal acceleration with amplitude equal to 1m/sec^2 and frequency of 5rad/sec. The no. of time step per cycle of the excitation is taken as 32 and the analysis is carried out up to three complete cycles. The analysis is conducted for different thickness of structure, starting from 125mm to 340 mm. The different cases are summarized in a tabular form along with the results such as tip displacement of structure, maximum hydrodynamic pressure at the bottom of the fluid-structure interface and CPU time. The pressures at point A and tip displacement of the structure presented in Table 2 are corresponding to time 2.25T. From Table 2, it is observed that the displacements obtained from both the methods are almost similar and it decreases with the increase of thickness of the structure as is expected. Also, the hydrodynamic pressure increases with the increase of thickness of the structure for both the methods.

However, the hydrodynamic pressure obtained from indirect coupling is slightly greater than the value obtained from direct coupling for all the cases. The CPU time for direct coupling with different thickness of structure are same as the number of degrees of freedom of the coupled system is taken same. However, a wide variation of CPU time for different thickness of structure in indirect iterative approach is noticed. The CPU time in indirect iterative approach for lower thickness has higher value and the computational time decreases with the increase of structural thickness. This observation implies that in indirect iterative approach, more no of iterations are required to converge the result for relatively flexible structure. From the tabular results, it may be concluded that the indirect coupling is efficient in terms of computational time when the structure is relatively rigid. However, for flexible structure, this method takes relatively much more computation time as compare to direct coupling approach.

Table 2. Comparison of results between two different approaches

Thickness of structure (mm)	Horizontal displacement at tip of the structure (mm)		Maximum hydrodynamic pressure (N/m^2)		CPU time (sec)	
	Direct coupling	Indirect coupling	Direct coupling	Indirect coupling	Direct coupling	Indirect coupling
125	7.6	7.7	3417	3433	44.6	156.6
150	4.3	4.3	3429	3439	44.6	115.4
200	2.1	2.1	3470	3476	44.6	58.9
250	1.2	1.2	3498	3504.	44.6	46.7
275	0.9	0.9	3556	3562	44.6	42.7
300	0.7	0.7	3585	3591	44.6	41.1
325	0.6	0.6	3681	3689	44.6	40.7
350	0.4	0.4	3696	3711	44.6	40.3
375	0.3	0.3	3727	3735	44.6	40.2

Example 2

Here, the behavior of a flexible separator wall in a water storage tank is considered as a fluid structure interaction problem. Fig. 6. shows the geometry of water tank and the separator wall within it. The walls of the water tank and at the bottom of the tank are assumed to be rigid. The detailed data for this problem are as follows: size of tank = 6 m × 6 m × 2.5 m, height of separator wall (H_s) = 2 m, modulus of elasticity = 200 GPa, Poison's ratio = 0.3, depth of fluid (H_f) = 1.6 m, mass density of fluid = 1000 kg/m^3, mass density of separator wall = 7800 kg/m^3.

The study is carried out for three different position of separator wall (L) (Fig. 6): 3.2 m, 1.6 m and 0.8 m. The thickness of the separator wall also is varied from 25 mm to 100 mm for each case. Here the flexible separator wall and fluid are discretized by 2 × 10 (i.e., N_h = 2 and N_v = 10) and 10 ×8 (i.e., N_h = 10 and N_v = 8) respectively. Some rfeld boundary condition is adopted at the rigid wall boundary. A sinusoidal acceleration of frequency 20 rad/sec and 10 m/sec^2 amplitude is applied on the structure.

Tip displacement of separator wall, hydrodynamic pressure at point A and the CPU time for different cases are listed in Table 3.Displacements at the tip of the separator wall from both the methods are almost same for different values of thickness and decreases with the increase of thickness of separator wall like previous example. Comparison of hydrodynamic pressure and CPU time shows a similar trained as obtained in Example 1.

From Table 3, it is also observed that CPU time for indirect iterative approach depends on truncation length and thickness of the separator wall. The computation time becomes higher in case of indirect iterative approach compare to that in direct coupled approach. Thus, the efficiency of the indirect approach depends on the thickness of separator wall as well as its position inside the tank.

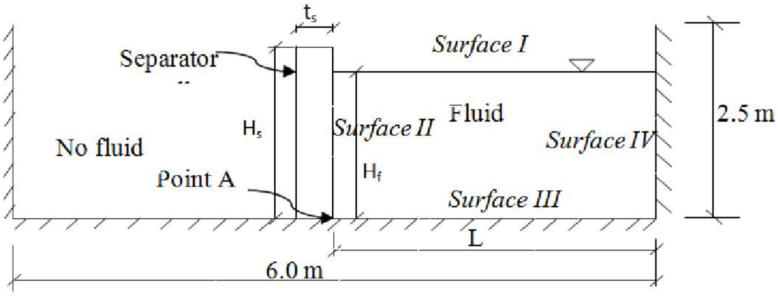

Fig. 6. Geometry of water tank and separator wall

Table 3. Comparison of results between two different approaches for flexible separator wall

L/H_f	Thickness of structure (mm)	Horizontal displacementat tip of the structure (mm)		Hydrodynamic pressure at point - A (N/m^2)		Time (sec)	
		Direct coupling	Indirect coupling	Direct coupling	Indirect coupling	Direct coupling	Indirect coupling
2	25	15.0	15.0	1154	1166	22	36
	50	9.8	9.8	1188	1200	22	30
	75	3.6	3.6	1194	1224	22	24
	100	1.9	1.9	1216	1222	22	21
1	25	15.0	15.0	1132	1173	22	40
	50	9.0	9.0	1176	1198	22	34
	75	3.6	3.6	1189	1203	22	28
	100	1.9	1.9	1201	1218	22	24
0.5	25	17.0	17.4	1824	1843	22	48
	50	11.0	11.5	1885	1914	22	41
	75	3.8	3.8	1933	1950	22	37
	100	2.1	2.1	1998	2106	22	33

Example 3

A dam-reservoir system has been analyzed using both the method as discussed earlier for a comparison. For this study the following properties of dam-reservoir system are considered (Fig.2): dam: height (H_d) = 103 m, width at top (t_d) = 14.8 m, width at base (L_d) = 70, mass density (ρ_d) = 24000 kg/m^3, Poisson's ratio (ν) = 0.2, and structural damping = 5%; Reservoir: depth (H_f)= 103 m, acoustic speed (c) = 1440 m/sec, mass density (ρ_d) = 1000 kg/m^3. The infinite reservoir is truncated at a distance (L_t) 309 m from the face the structure and Maity and Bhattacharyya (23) boundary condition is implemented at the truncation surface. The Koyna Earth quake acceleration is considered as the external excitation. Here, the dam and fluid domain are discretized by 4 × 10 (N_h = 4 and N_v = 12) and 12 ×10 (N_h = 12 and N_v = 10) respectively. The responses of dam-reservoir system are evaluated for three different values of modulus of elasticity of concrete: 3.5×10^9 N/m^2, 3.5×10^{10} N/m^2 and 3.5×10^{11} N/m^2. Variations of hydrodynamic pressure at heel of the dam are obtained from these methods and are shown in Fig.7. From these graphical results it is clear that the hydrodynamic pressure obtained from direct coupling and indirect coupling are almost similar to each other. Similar trained are also observed for tip displacement of the dam (Fig. 8).The CPU time for analyzing the dam-reservoir system using direct and indirect coupling are listed in Table 4.The CPU time using indirect coupling is comparatively larger when the magnitude of modulus of elasticity is relatively less. However, for direct coupling, CPU times for different modulus of elasticity are equal and are less than that obtained from indirect coupling. Thus, it may be concluded that the CPU time required for analysis of dam-reservoir system under seismic excitation using direct coupling is comparatively less.

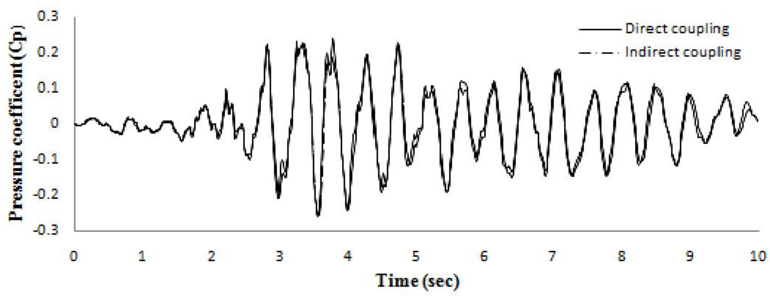

Fig. 7. Hydrodynamic pressure at the heel of the dam for E = 3.5×10^9 N/m^2

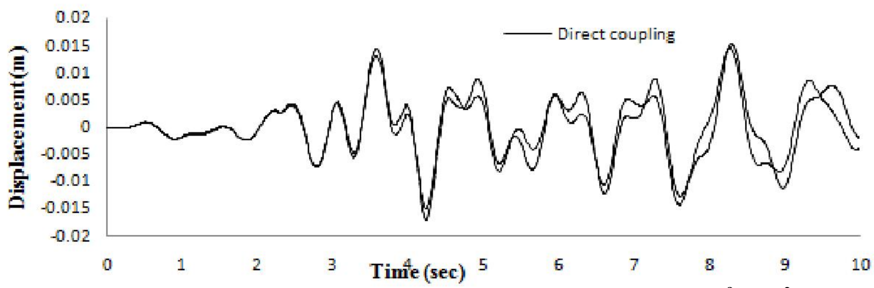

Fig. 10. Horizontal displacement of dam at top for E = 3.5×10^9 N/m^2

Table 4. CPU time for analysis of dam-reservoir system using two different methods

Modulus of elasticity (N/m^2)	CPU time (sec)	
	Direct coupling	Indirect coupling
3.5×10^9	104	513
3.5×10^{10}	104	326
3.5×10^{11}	104	253

Conclusion

This paper presents two methods of analysis for fluid-structure interaction problems and compares their efficiency in terms of computational time and accuracy. In direct coupled approach the fluid and structure are coupled together and solved as one system while in indirect iterative method, the fluid and structure are solved as two separate systems and their interaction effects are enforced at the interface by an iterative manner. The responses of fluid-structure system are almost same for both the approach. The results from various numerical exercise shows that both the methods have certain advantages as well as certain drawbacks. The CPU time required to analyze a fluid-structure coupled system by direct method will be same irrespective of the degree of structural flexibility if the matrix size remains unchanged. However, a wide variation of CPU time is noticedto solve the similar problem for different degree of structural flexibility having same matrix size. This is because of the number of iteration required to converge the results at a particular time instant. It is observed that the number of iteration increases if the structure becomes more flexible. In case of flexible separator wall in water tank, the efficiency of this method not only depends on the thickness of separator wall but also its position from the tank wall. From the numerical exercise, it is noticed that indirect iterative method takes less computational time when the structure is relatively less flexible and therefore this method will be suitable to use. If the structural flexibility is high, then the direct coupled approach will be effective for the analysis.

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