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A new ALE finite element techniques for wind-structure interactions

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Abstract. A new finite element technique to solve the problem of wind and structure interactions is presented. Conventionally, wind analysis is performed on the Eulerian description in which the finite element mesh would not move in accordance with the wind flow. However, it is not the case in wind-structure interaction problems because nodes attached to the surface of structure should move with the displacement of structure. The arbitrary Lagrangian-Eulerian (ALE) method treats the mesh and flow independently, and allow the mesh to move. In this study, the analysis domain is divided into regions of the structure, air around the structure and the interface of two regions. To satisfy the compatibility and equilibrium conditions between separated regions and to carry out the efficient analysis, the rigid link is used. Also the equation of wind and that of structure are arranged in a single matrix equation.

Key words:

1. Introduction

Aerodynamic characteristics of flow around structures become more important in civil engineering as structures become larger and taller. To date, the aerodynamic stability of structures under planning and/or construction have been mostly estimated from the wind tunnel test rather than numerical simulation. The main reasons are ; 1) the computing time for numerical simulation of nonlinear transient equation is too large, 2) the spatial descritization of structures and its circumference is not easy, and 3) the algorithm that promise the robust solution is yet to be found in spite of a lot of research efforts in the past. However, the amazing development of computer hardware and its increased availability will reduce the computing time and expenses to make the numerical computation technology more practically applicable in the wind engineering.

Wind induced vibration of structures is one of the interesting subject to many researchers. Conventionally, the computational fluid analysis is performed on the Eulerian description in which the analysis mesh would not move in accordance with the flow. However, it is not true in the wind-structure interaction problem because nodes attached to the surface of structure actually move with the displacement of structure. On the contrary, the Lagrangian description which is frequently used in the contained fluid cannot be used in the case of convection dominated flow such as the wind because the serious mesh distortion can not be avoided. In the arbitrary Lagrangian-Eulerian formulation (ALE), the mesh and flow are treated independently and the mesh is admitted to move.

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Thus, the ALE formulation can be regarded as a suitable algorithm for the wind-structure interaction problem. Donea (1982) showed kinematics and conservation laws of fluid in the ALE description. Liu (1988) established a general ALE formulation of finite element method (FEM) and applied to the problems of wave propagation, penetration, impact, and so on. ALE formulation for incompressible viscous flows is developed and applied to modeling the fluid subdomain of fluid-structure interaction and free-surface problems (Hughes 1981).

In the wind induced vibration problems of civil structures, e.g., for a bridge section, the deflection of structure is more important factor than the deformation of section itself to many engineers. To date, only limited literatures are available in this area of study. The structure can be idealized as a rigid body supported by a series of springs in this case (Nomura and Hughes 1992). Sarrate *et al.* (1998) proposed the nonlinear algorithm of rotational case and solved the vibration of bluff body around fluid. Mendes and Branco (1999) used a flutter model for bridge section in place of rigid body equation proposed by Nomura (1992).

In this paper, the combined matrix procedure is proposed to reduce the computation time. The matrix equations of wind and structure are combined to form one matrix equation so that the compatibility and equilibrium conditions can be satisfied automatically. The penalty function method which can reduce the number of independent variables is adopted for the purpose of computational efficiency and the selected reduced integration is carried out for the convection and pressure terms to maintain the stability of solution. When the Galerkin formulation is applied to the convection term, numerical solutions are unstable and wiggle phenomena will appear. To prevent the wiggle problem, the quadrature upwind technique is used (Hughes 1979) and the predictor multi-corrector scheme is used to solve nonlinear equation.

2. Formulation of wind

In the Fig. 1, the wind flows into the domain Ω_F and the prescribed velocity and traction are given on the boundaries Γ_G and Γ_H, respectively. The interaction boundary Γ_I between the structure and fluid moves in accordance with the motion of the structure denoted as Ω_S. The governing equation of wind based on ALE description can be derived as

Incompressibility condition : $u_{i,i} = 0$

Navier-Stokes equation : $\rho \dot{u}_{i,i} + \rho(u_j - \hat{u}_j)u_{i,j} + u_{,j} - \mu(u_{i,j} + u_{j,i}) = 0$ (1)

where u is the velocity of wind, $\hat{u}$ is the moving velocity of mesh, P is the pressure, ρ is the

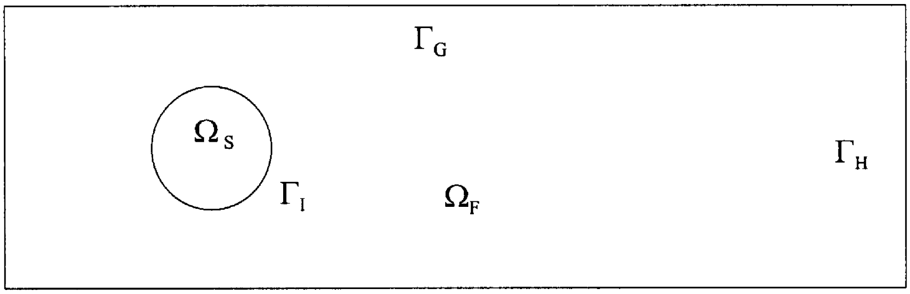


Fig. 1 Problem statement of the wind structure interaction

density of air and μ is the viscosity of air. The element matrix equation is obtained from the governing Eq. (1) by conventional Galerkin formulation.

$$[\boldsymbol{M}]\left\{\begin{array}{c}\dot{\boldsymbol{u}}\\ \dot{\boldsymbol{v}}\\ \dot{\boldsymbol{p}}\end{array}\right\}+[\boldsymbol{N}(u,v)]\left\{\begin{array}{c}\boldsymbol{u}\\ \boldsymbol{v}\\ \boldsymbol{p}\end{array}\right\}+[\boldsymbol{K}]\left\{\begin{array}{c}\boldsymbol{u}\\ \boldsymbol{v}\\ \boldsymbol{p}\end{array}\right\}=\left\{\begin{array}{c}\boldsymbol{F}_u\\ \boldsymbol{F}_v\\ \boldsymbol{0}\end{array}\right\} \tag{2}$$

To reduce the number of total degrees of freedom and avoid any additional iterative calculation for pressure, the penalty formulation is introduced. The pressure can be replaced by the penalty parameter l and the incompressibility condition. (Huebner 1995)

$$P = -\lambda\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right) \tag{3}$$

The value of penalty parameter λ depends on the computer capacity, the physical parameters of wind, equation solver used, and so on. By the penalty formulation, Eq. (2) is rearranged without pressure P as

$$\begin{bmatrix}\boldsymbol{M} & \boldsymbol{0}\\ \boldsymbol{0} & \boldsymbol{M}\end{bmatrix}\left\{\begin{array}{c}\dot{\boldsymbol{u}}\\ \dot{\boldsymbol{v}}\end{array}\right\}+\begin{bmatrix}\boldsymbol{N} & \boldsymbol{0}\\ \boldsymbol{0} & \boldsymbol{N}\end{bmatrix}\left\{\begin{array}{c}\boldsymbol{u}\\ \boldsymbol{v}\end{array}\right\}+\begin{bmatrix}2\boldsymbol{K}_{11}+\boldsymbol{K}_{22} & \boldsymbol{K}_{12}\\ \boldsymbol{K}_{21} & \boldsymbol{K}_{11}+2\boldsymbol{K}_{22}\end{bmatrix}\left\{\begin{array}{c}\boldsymbol{u}\\ \boldsymbol{v}\end{array}\right\}+\lambda\begin{bmatrix}\boldsymbol{L}_{11} & \boldsymbol{L}_{12}\\ \boldsymbol{L}_{12}^{T} & \boldsymbol{L}_{22}\end{bmatrix}\left\{\begin{array}{c}\boldsymbol{u}\\ \boldsymbol{v}\end{array}\right\}=\left\{\begin{array}{c}\boldsymbol{f}_u\\ \boldsymbol{f}_v\end{array}\right\}$$

$$\boldsymbol{M} = \int_{\Omega}\rho\{N\}[N]d\Omega \qquad \boldsymbol{N} = \int_{\Omega}\left((u-\hat{u})\{N\}\left\langle\frac{\partial N}{\partial x}\right\rangle+(v-\hat{v})\{N\}\left\langle\frac{\partial N}{\partial y}\right\rangle\right)d\Omega$$

$$\boldsymbol{K}_{ab} = \int_{\Omega}\boldsymbol{\mu}\left\{\frac{\partial N}{\partial x_b}\right\}\left[\frac{\partial N}{\partial x_a}\right]d\Omega \qquad \boldsymbol{L}_{ab} = \int_{\Omega}\left\{\frac{\partial N}{\partial x_a}\right\}\left[\frac{\partial N}{\partial x_b}\right]d\Omega \tag{4}$$

The matrices $\boldsymbol{M}$, $\boldsymbol{N}$, $\boldsymbol{K}$, $\boldsymbol{L}$ are the element mass, convection, viscosity, and pressure matrix, respectively. To prevent wiggle phenomena and obtain a stable solution, the optimal upwind technique needs to be applied to the computation of convection matrix. Details of element matrices can be found in references (Choi and Yu, 1998, 1999a)

3. Modeling of structure

The concept of mass-spring system, which is frequently used in the wind tunnel test for wind induced vibration of bridge section, can also be applied to the numerical modeling. Nomura and Hughes (1992) proposed the simple mass-spring system in which the structure is assumed as a rigid body as shown in Fig. 2(a). Some transformation matrix is needed to establish the relationship between the nodal kinematic variables on the interface and degrees of freedom of rigid body structure, and to match the force equilibrium condition.

In the previous work, a new modeling for the structure is proposed using beam elements as shown in Fig. 2(b) (Choi and Yu 1999b). As nodes on the surface of structure are connected to the support inside the structure with beam elements of large stiffness, the compatibility and equilibrium conditions are satisfied automatically since they are in one system. However, the numerical instability may occur when beams used do not have masses. Thus, a new formulation to obtain stable solution is developed.

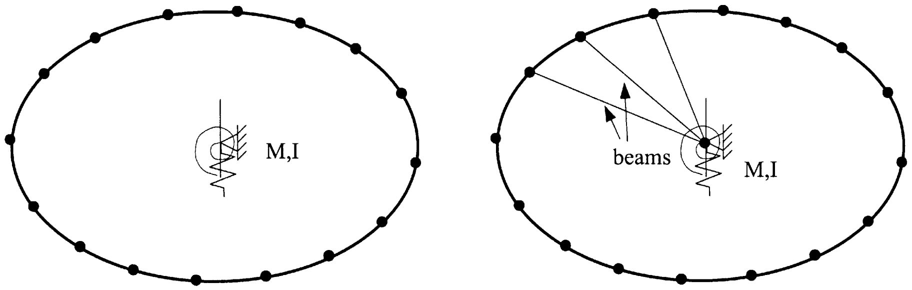


Fig. 2 Modeling of structure using connection beams

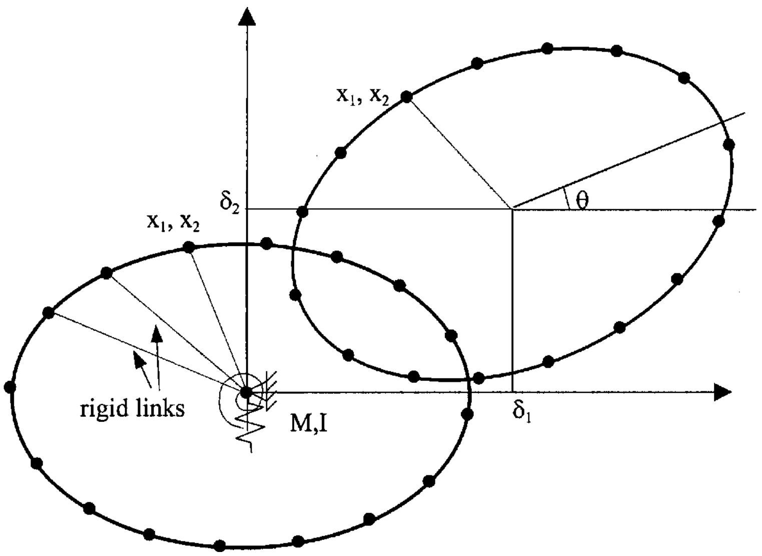


Fig. 3 Modeling of structure using ligid links

When the structure is uncoupled with wind, the matrix equation for the structure is given as

$$\boldsymbol{M}^S\boldsymbol{a}_s + \boldsymbol{C}^S\boldsymbol{u}_s + \boldsymbol{K}^S\boldsymbol{d}_s = \boldsymbol{f}_s \tag{6}$$

where superscript *s* and subscripts *s* denotes structure. ***M***, ***C***, and ***K*** are global mass, damping, and stiffness matrices of structure modeled as a rigid body, respectively, and ***a***, ***u***, and ***d*** are acceleration, velocity, and displacement vectors of the structure, respectively. Kinematic variables are defined as

$$\boldsymbol{d}_s = \begin{Bmatrix} \delta_1 \\ \delta_2 \\ \theta \end{Bmatrix}, \quad \boldsymbol{u}_s = \begin{Bmatrix} \dot{\delta}_1 \\ \dot{\delta}_2 \\ \dot{\theta} \end{Bmatrix}, \quad \boldsymbol{a}_s = \begin{Bmatrix} \ddot{\delta}_1 \\ \ddot{\delta}_2 \\ \ddot{\theta} \end{Bmatrix} \tag{7}$$

Nomura (1992) showed the compatibility relationship of kinematic variables to relate variables of center with those on the surface. Then, displacements, velocity and acceleration on the surface are written as

$$\boldsymbol{d}_I = \begin{Bmatrix} d_1 \\ d_2 \end{Bmatrix} = \begin{Bmatrix} \delta_1 \\ \delta_2 \end{Bmatrix} + \begin{bmatrix} \cos\theta - 1 & -\sin\theta \\ \sin\theta & \cos\theta - 1 \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} \tag{8a}$$

$$u_I = \begin{bmatrix} 1 & 0 & -L_2 \\ 0 & 1 & L_1 \end{bmatrix} \begin{Bmatrix} \dot{\delta}_1 \\ \dot{\delta}_2 \\ \dot{\theta} \end{Bmatrix} = \boldsymbol{T}^t \boldsymbol{u}_s \tag{8b}$$

$$\boldsymbol{a}_I = \begin{bmatrix} 1 & 0 & -L_2 \\ 0 & 1 & L_1 \end{bmatrix} \begin{Bmatrix} \ddot{\delta}_1 \\ \ddot{\delta}_2 \\ \ddot{\theta} \end{Bmatrix} - \begin{bmatrix} L_1 \\ L_2 \end{bmatrix} \dot{\theta}^2 = \boldsymbol{T}^t \boldsymbol{a}_s + \boldsymbol{A} \dot{\theta}^2 \tag{8c}$$

4. Interaction problem

The governing equation for wind (Eq. (4)) can be rearranged in a single equation as

$$[\boldsymbol{M}^W]\{\boldsymbol{a}\} + [\boldsymbol{C}^W]\{\boldsymbol{u}\} = \{\boldsymbol{f}\} \tag{9}$$

Then, Eqs. (6) and (9) are arranged to form one equation as uncoupled form between wind and structure.

$$\begin{bmatrix} \boldsymbol{M}^W_{w1} & \boldsymbol{M}^W_{wI} & \boldsymbol{0} \\ \boldsymbol{M}^W_{Iw} & \boldsymbol{M}^W_{II} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{M}^S \end{bmatrix} \begin{Bmatrix} \boldsymbol{a}_w \\ \boldsymbol{a}_I \\ \boldsymbol{a}_s \end{Bmatrix} + \begin{bmatrix} \boldsymbol{C}^W_{w1} & \boldsymbol{C}^W_{wI} & \boldsymbol{0} \\ \boldsymbol{C}^W_{Iw} & \boldsymbol{C}^W_{II} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{C}^S \end{bmatrix} \begin{Bmatrix} \boldsymbol{u}_w \\ \boldsymbol{u}_I \\ \boldsymbol{u}_s \end{Bmatrix} + \begin{bmatrix} \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{K}^S \end{bmatrix} \begin{Bmatrix} \boldsymbol{d}_w \\ \boldsymbol{d}_I \\ \boldsymbol{d}_s \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{f}_w \\ \boldsymbol{f}_I \\ \boldsymbol{f}_s \end{Bmatrix} \tag{10}$$

where subscripts *w*, *I* and *s* describe the regions of wind only, interface, and structure only, respectively, and superscripts *w* and *s* denote the wind and structure, respectively.

As a general expression, Eq. (10) can be rewritten as

$$[\boldsymbol{M}]\{\boldsymbol{a}\} + [\boldsymbol{C}]\{\boldsymbol{u}\} + [\boldsymbol{K}]\{\boldsymbol{d}\} = \{\boldsymbol{f}\} \tag{11}$$

Eq. (11) should be solved by the nonlinear transient solution algorithm since the matrix C has the nonlinear effect arising from convection term. The predictor multi-corrector algorithm with velocity-form method is used for the time history analysis (see Hughes *et al.* 1979 for detail). In the predictor multi-corrector algorithm, predictors at the time $t = n+1$ are given as

$$\tilde{\boldsymbol{d}}_{n+1} = \boldsymbol{d}_n + \Delta t \boldsymbol{u}_n + \frac{\Delta t^2}{2}(1 - 2\beta)\boldsymbol{a}_n \tag{12a}$$

$$\tilde{\boldsymbol{u}}_{n+1} = \boldsymbol{u}_n + (1 - \gamma)\Delta t \boldsymbol{a}_n \tag{12b}$$

$$\tilde{\boldsymbol{a}}_{n+1} = \boldsymbol{0}$$

The recursive relation determines $\boldsymbol{u}_{n+1}$ as

$$\left(\frac{\boldsymbol{M}}{\gamma\Delta t}+\boldsymbol{C}+\frac{\beta\Delta t\boldsymbol{K}}{\gamma}\right)\boldsymbol{u}_{n+1} = \boldsymbol{F}_{n+1}-\left(\frac{\boldsymbol{M}}{\gamma\Delta t}+\frac{\beta\Delta t\boldsymbol{K}}{\gamma}\right)\tilde{\boldsymbol{u}}_{n+1}-\boldsymbol{K}\tilde{\boldsymbol{d}}_{n+1} \tag{13}$$

For the nonlinear problems, Eq. (13) should be changed to an incremental form as given

$$\boldsymbol{C}^{*}\Delta\boldsymbol{u}_{n+1}^{(i+1)} = \boldsymbol{R}_{n+1}^{(i)} \tag{14}$$

where the effective coefficient matrix $\boldsymbol{C}^{*}$ and the residual $\boldsymbol{R}_{n+1}^{(i)}$ are given as

$$\boldsymbol{C}^{*} = \frac{\boldsymbol{M}}{\gamma\Delta t}+\boldsymbol{C}+\frac{\beta\Delta t}{\gamma}\boldsymbol{K} \tag{15a}$$

$$\boldsymbol{R}_{n+1}^{(i)} = \boldsymbol{f}_{n+1}-\boldsymbol{M}\boldsymbol{a}_{n+1}^{(i)}-\boldsymbol{C}\boldsymbol{u}_{n+1}^{(i)}-\boldsymbol{K}\boldsymbol{d}_{n+1}^{(i)} \tag{15b}$$

The fast solution of nonlinear problem can be obtained using Eq. (15), because the effective coefficient matrix (or tangent matrix) $\boldsymbol{C}^{*}$ is calculated every iteration steps. The convergence of iteration is checked comparing the residual $\boldsymbol{R}_{n+1}^{(i)}$ and cervergence criterion. Finally, correctors in the incremental form are given as

$$\begin{aligned}
\boldsymbol{u}_{n+1}^{(i+1)} &= \boldsymbol{u}_{n+1}^{(i)}+\Delta\boldsymbol{u}_{n+1}^{(i+1)}\\
\boldsymbol{a}_{n+1}^{(i+1)} &= (\boldsymbol{u}_{n+1}^{(i+1)}-\tilde{\boldsymbol{u}}_{n+1})/(\gamma\Delta t)\\
\boldsymbol{d}_{n+1}^{(i)} &= \tilde{\boldsymbol{d}}_{n+1}+\beta\Delta t^{2}\boldsymbol{a}_{n+1}
\end{aligned} \tag{16}$$

At this point, the compatibility conditions between variables of nodes on the surface and those of center of rigid body should be considered in Eq. (14). Eq. (14) is described as

$$\begin{bmatrix} \boldsymbol{C}_{ww}^{*} & \boldsymbol{C}_{wI}^{*} & 0\\ \boldsymbol{C}_{Iw}^{*} & \boldsymbol{C}_{II}^{*} & 0\\ 0 & 0 & \boldsymbol{C}_{ss}^{*}\end{bmatrix}\begin{Bmatrix}\Delta\boldsymbol{u}_{w}\\ \Delta\boldsymbol{u}_{I}\\ \Delta\boldsymbol{u}_{s}\end{Bmatrix}_{n+1}^{(i+1)} = \begin{Bmatrix}\boldsymbol{R}_{w}\\ \boldsymbol{R}_{I}\\ \boldsymbol{R}_{s}\end{Bmatrix}_{n+1}^{(i)} \tag{17}$$

where residual vector is given as

$$\begin{aligned}
\begin{Bmatrix}\boldsymbol{R}_{w}\\ \boldsymbol{R}_{I}\\ \boldsymbol{R}_{s}\end{Bmatrix}_{n+1}^{(i)} = \begin{Bmatrix}\boldsymbol{f}_{w}\\ \boldsymbol{f}_{I}\\ \boldsymbol{f}_{s}\end{Bmatrix}_{n+1} &- \begin{bmatrix} \boldsymbol{M}_{ww} & \boldsymbol{M}_{wI} & 0\\ \boldsymbol{M}_{Iw} & \boldsymbol{M}_{II} & 0\\ 0 & 0 & \boldsymbol{M}_{ss}^{*}\end{bmatrix}\begin{Bmatrix}a_{w}\\ a_{I}\\ a_{s}\end{Bmatrix}_{n+1}^{(i)} - \begin{bmatrix} \boldsymbol{C}_{ww} & \boldsymbol{C}_{wI} & 0\\ \boldsymbol{C}_{Iw} & \boldsymbol{C}_{II} & 0\\ 0 & 0 & \boldsymbol{C}_{ss}\end{bmatrix}\begin{Bmatrix}u_{w}\\ u_{I}\\ u_{s}\end{Bmatrix}_{n+1}^{(i)}\\
&- \begin{bmatrix} 0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & \boldsymbol{K}_{ss}\end{bmatrix}\begin{Bmatrix}d_{w}\\ d_{I}\\ d_{s}\end{Bmatrix}_{n+1}^{(i)}
\end{aligned} \tag{18}$$

Substituting Eq. (8) into (17) and multiplying the transformation matrix $\boldsymbol{T}$ to rows of interface, the condensed matrix equation can be obtained.

$$\begin{bmatrix} \boldsymbol{C}^*_{ww} & \boldsymbol{C}^*_{wI}\boldsymbol{T}^t \\ \boldsymbol{T}\boldsymbol{C}^*_{Iw} & \boldsymbol{T}\boldsymbol{C}_{II}\boldsymbol{T}^t + \boldsymbol{C}_{ss} \end{bmatrix} \begin{Bmatrix} \Delta\boldsymbol{u}_w \\ \Delta\boldsymbol{u}_s \end{Bmatrix}^{(i+1)}_{n+1} = \begin{Bmatrix} \boldsymbol{R}_w \\ \boldsymbol{T}\boldsymbol{R}_I + \boldsymbol{R}_s \end{Bmatrix}^{(i)}_{n+1} \tag{19}$$

In this procedure, displacements, velocities, and accelerations of nodes on the surface are treated as dependent variables of those of the center by Eq. (8).

As the computation of incremental wind-structure interaction proceeds, a new mesh should be defined at every time step in accordance with the movement of the structure. New coordinates of nodes do not depend on the solution algorithm or velocity of flow. That is, the shape of new mesh can be arbitrary if the boundary conditions are satisfied and proper shapes of elements are maintained.

The new fluid mesh distribution around structure is needed at each time step for next analysis after the structure is moved. The mesh distribution is arbitrary in ALE analysis. Thus many individual researchers proposed different schemes for ALE mesh generation. Donea (1982) used a grid mean velocity of neighboring nodes at the previous time step. Benson (1989) recommended finite difference mesh relaxation stencils to get a smoothed mesh distribution. If the distortion of element shape generated by the scheme can be minimized, the time consuming scheme for mesh distribution will not be recommended.

A simple and efficient scheme for mesh distribution is proposed in which the solution domain is separated into three zones; i.e., Attached, Interim, and Fixed zone as sketched in Fig. 4. In the Attached zone, nodes move in the fashion of rigid body motion as the structure moves. On the other hands, nodes do not change coordinates through the entire solution time in the Fixed zone. In the Interim zone, the new coordinates of nodes vary in the proportion to the distance between Fixed circle and Attached circle. This scheme makes the re-distribution very simple and smooth, and the distortion of elements is minimized.

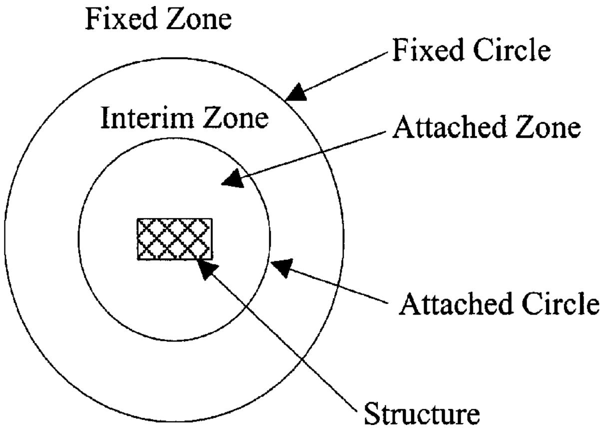


Fig. 4 Separation of solution domain for new location of nodes

5. Numerical examples

The free vibration analysis of a single cylinder in a circular domain filled with viscous fluid as shown in Fig. 5 has been performed to verify the ability of the proposed procedure to solve the fluid-structure interaction problem. The mass and the spring coefficient of the interior cylinder are 3.408 g and 34611.3 g/s^2, respectively. The inner diameter and the outer diameter are 1.27 cm and 6.35 cm, respectively. The inner cylinder is forced to deflect by 0.0127 from the initial zero velocity state. The natural angular frequency of the cylinder is 100 rad/sec or the natural period is 0.0623 second. The time step for analysis is 0.001 second.

Displacement, velocity and acceleration histories for the four cases were depicted in the Fig. 6. Since the density and the viscosity of air is very small compared with those of cylinder, the amplitude of displacement history curve and the frequency of vibrating cylinder are nearly the same as those of inner cylinder. On the other hand, densities of other three fluids are fairly large to generate the added mass effect. The ratios of densities of fluids to that of inner cylinder are approximately 1 to 3. The amplitude of displacement is reduced most rapidly in the case of silicon oil which has the largest viscosity value. Properties of the four different fluids filled and damped natural frequencies are given in Table 1 with some results of Nomura (1992). The velocity distribution of the air at time $t = 0.02$ second is drawn in Fig. 7.

In the second example, the rotational motion of a rectangular cylinder submerged in a viscous fluid is shown in Fig. 8. The mesh consists of 324 elements and 344 nodes. At the initial state, the cylinder is rotated with 0.02 angular velocity at zero displacement. The rotational stiffness and inertia are given as 707.56 and 10000, respectively. To observe the effects of the viscosity, three different values of dynamic viscosity are selected, these are 0.01, 0.001, 0.0001.

Fig. 9 shows the rotational displacements for three different viscosity values of fluids. It can be found that the larger the viscosity, the faster the amplitude decreases. This tendency can also be found in the reference (Sarrate *et al.* 1998). The natural frequency of this cylinder does not change in three cases of different viscosity because the ratios of densities of fluids to cylinder are larger than 100. Fig. 10 shows the streamlines and mesh (displacements are scaled by 10) for dynamic

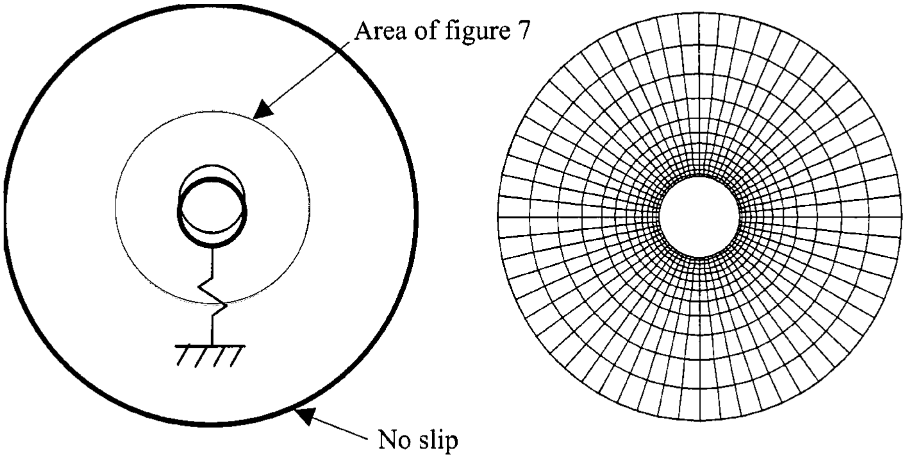
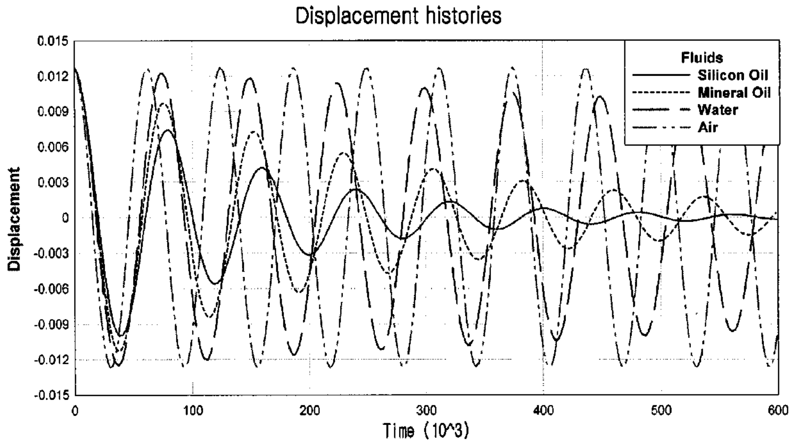
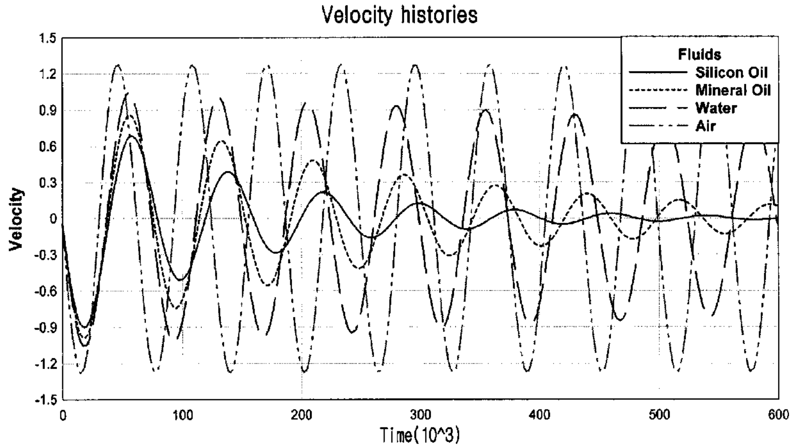


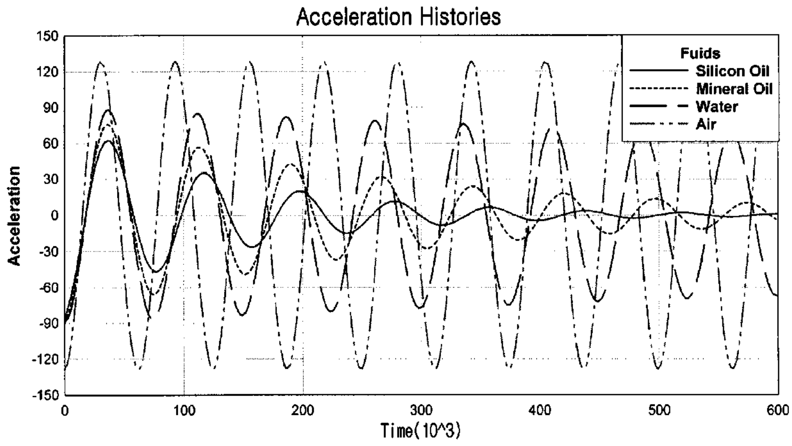
Fig. 5 Vibration of a circular cylinder



(a) Displacement history



(b) Velocity history



(c) Acceleration history

Fig. 6 Displacement, velocities, and acceleration histories

Table 1 Fluid properties and damped natural angular velocity

Fluid	Silicon oil	Mineral oil	Water	Air
Density(g/cm^2)	0.956	0.935	1.000	0.00118
Viscosity(g/cm s)	1.450	0.410	0.0133	0.000182
f_d (1/s) (Nomura 1992)	12.37	12.87	13.26	15.96
f_d (1/s) (present)	12.37	12.86	13.26	15.95

f_d: damped natural frequency

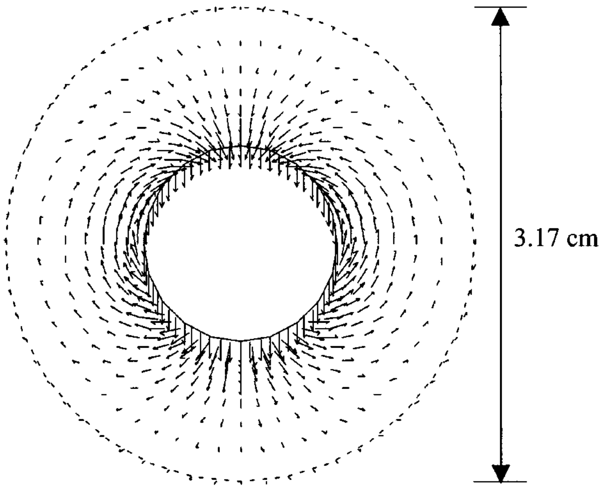


Fig. 7 Velocity vector of air at maximum velocity

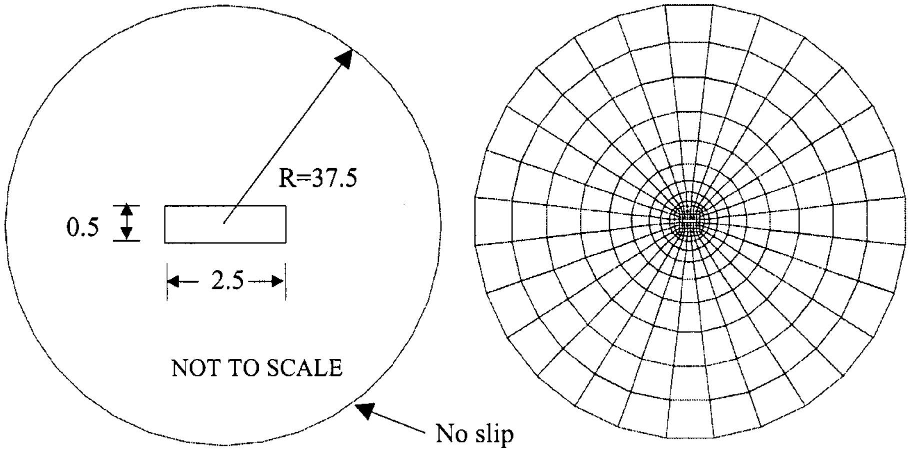


Fig. 8 Rotational vibration of rectangular cylinder

viscosity $\nu = 0.01$ during one period of vibration. As the radius of Fixed circle is the same as radius of outer cylinder, the Fixed zone does not appear.

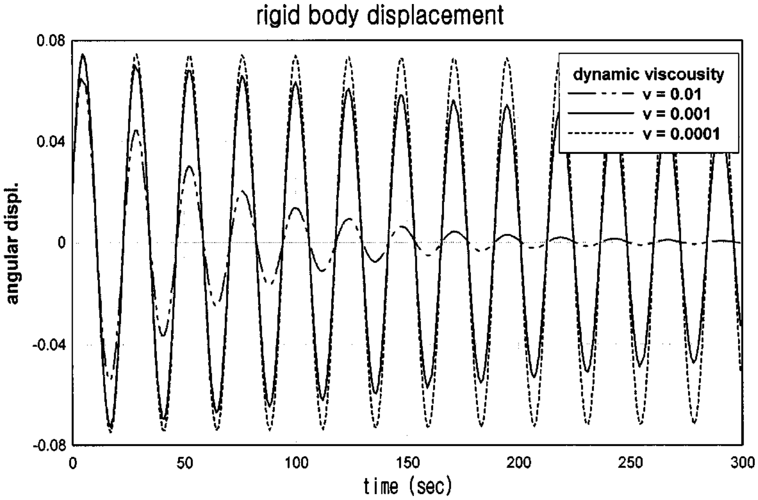


Fig. 9 Rotational displacement of cylinder

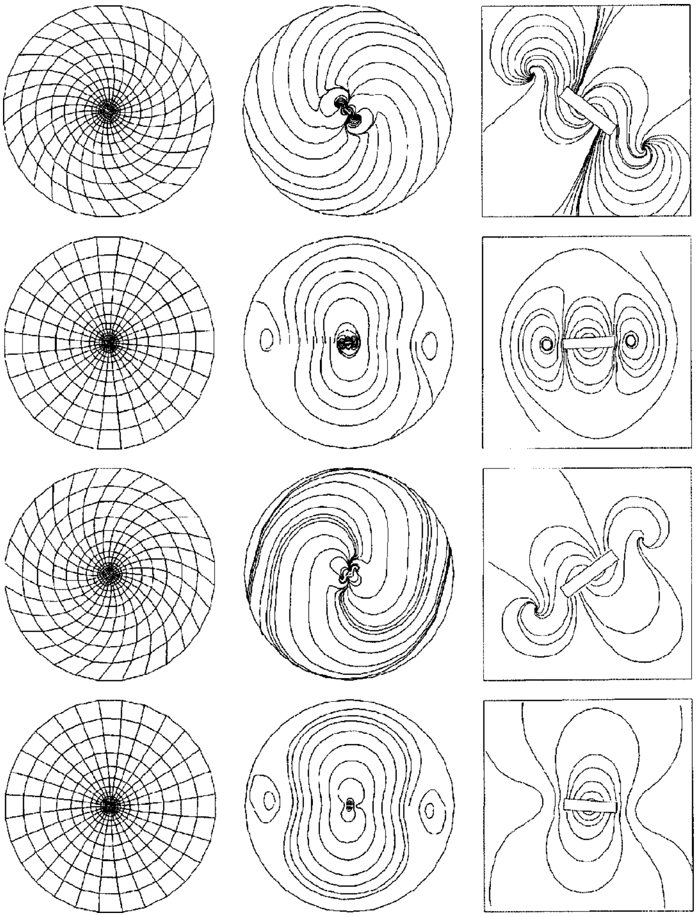


Fig. 10 Meshes, streamlines and Zoomed Streamlines during one period of vibration

6. Conclusions

A new scheme for wind-structure interaction analysis is proposed. As the structure is connected by rigid links and the governing equations of wind and structure are combined to form a single equation, the iteration process on the interface to satisfy the kinematic condition and force equilibrium is not needed. The ALE method is applied to the wind-structure interaction analysis to treat the fluid domain with moving mesh. The proposed scheme to determine new locations of nodes, in which the solution domain is separated into three zones, is simple and efficient. The numerical test results indicate that the potential of applicability of the proposed scheme to actual wind-structure interaction problems is high. The expansion of current study to include the 3-D effects and turbulence characteristics of wind will be of interest and should be continued to make the proposed scheme a useful tool for the practical wind-structure interaction analysis.

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