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A FIXED-MESH METHOD FOR GENERAL MOVING OBJECTS IN FLUID FLOW

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In this work, a fixed-mesh method for general moving objects in fluid flow was developed and implemented into the commercial CFD software FLOW-3D†. A general moving object is a rigid body with any type of six-degrees-of-freedom, fixed-point and fixed-axis motion which can be either user-prescribed or dynamically coupled with fluid flow. The method allows multiple general moving objects, and each of them can possess any different type of motion. Area and volume fractions to represent the objects in the fixed-grid are calculated at every time step to describe time-variation of object locations and orientations. Continuity and momentum equations for fluid are modified to account for the effects of object motion on fluid flow. A good agreement is achieved between computational and experimental results in an application to a valve problem.

Keywords: computational fluid dynamics; fixed-mesh method; moving objects.

1. Introduction

There are many engineering practices in which objects move in fluid. Conventional CFD methods for moving objects are mainly based on moving and deforming mesh techniques. They have the limitations that either distance between moving objects cannot be too close or they fail when mesh distortion is severe. Although remeshing may help overcome the limitations, it requires automatic mesh generation repeatedly in a computation, thus it can be prohibitively expensive. FLOW-3D, a commercial CFD software developed by Flow Science Inc, utilizes the Fractional Area-Volume Obstacle Representation (FAVOR†) technique to describe object geometry in fixed rectangular meshes by means of area fractions (AF) and volume fractions (VF). In each mesh cell, VF is defined as the ratio of the volume open to fluid to the total cell volume, and AFs are defined at each of the six faces as ratios of the respective open area to the total area. In this work, a fixed-mesh method for general moving objects[2] based on the FAVOR technique is developed and implemented into FLOW-3D. At each time step, AF and VF in fixed-rectangular meshes are calculated to describe object motion. It allows multiple moving objects, and each of them can possess any different type of six-degrees-of-

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†FLOW-3D and FAVOR are registered in the US Patent and Trademark Office.

freedom (DOF), fixed-point and fixed-axis motion, which is either user-prescribed or dynamically coupled with fluid flow. This new method possesses advantages over the moving and deforming mesh methods because it treats complex moving object geometries very efficiently and conveniently and there is no restriction on closeness between objects. Treatment of collisions between objects is also possible. Successful applications of the method have been made by FLOW-3D users in automobile, hydraulic, aerospace, casting and electronic industries.

2. Mathematical Model

General motion of a rigid body can be divided into a translation along with a reference point and a rotation. For six-DOF motion, it is convenient to select the object mass center as the reference point. Equations of motion governing the two separate motions are[3]

$$\vec{F} = m\frac{d\vec{V}_G}{dt} \tag{1}$$

$$\vec{T}_G = [J]\cdot\frac{d\vec{\omega}}{dt} + \vec{\omega}\times\left([J]\cdot\vec{\omega}\right), \tag{2}$$

where $\vec{F}$ is total force, m is mass, $\vec{T}_G$ is total torque about mass center in body-fixed reference system ("body system"), $\vec{V}_G$ is mass center velocity, $\vec{\omega}$ is angular velocity in the body system, and [J] is moment of inertia tensor about the mass center. The body-fixed coordinate system has its origin at the mass center and its coordinate axes initially parallel to those of the space system. Coordinate transformation between the space and body systems is conducted using a coordinate transformation tensor [R] satisfying

$$\frac{d[R]}{dt} = [\Omega]\cdot[R] \tag{3}$$

where [Ω] is the cross-product matrix of the object angular velocity. The continuity equation based on the FAVOR method is

$$\frac{V_f}{\rho}\frac{\partial\rho}{\partial t} + \frac{1}{\rho}\nabla\cdot(\rho\vec{u}A) = -\frac{\partial V_f}{\partial t} \tag{4}$$

where ρ is fluid density, $\vec{u}$ is fluid velocity, V_f is volume fraction, A is area fraction. A key treatment of Eq. (4) is that in its discretized form the right side is replaced by $\vec{V}_{obj}\cdot\vec{n}\,S_{obj}\big/V_{cell}$ for a better mass conservation property of fluid, where S_{obj}, $\vec{n}$ and $\vec{V}_{obj}$ are surface area, surface normal direction and velocity of moving object boundary in a mesh cell, respectively. Derivation shows there exist no terms due to time-change of V_F in the momentum equations written in a non-conservative form. The only modification of the momentum equations is the addition of tangential velocity of the moving object boundaries in the wall shear stress terms.

3. Implementation and application

At each time step, the equations of rigid body motion are solved if the object moves in a coupled fashion. Effects of hydraulic force (pressure and shear), gravitational force, non-inertial force and control force on coupled motion are considered. Locations and orientations of all moving objects are tracked, and area and volume fractions are updated.

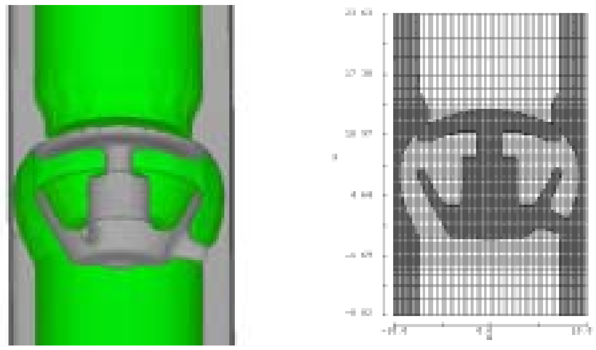
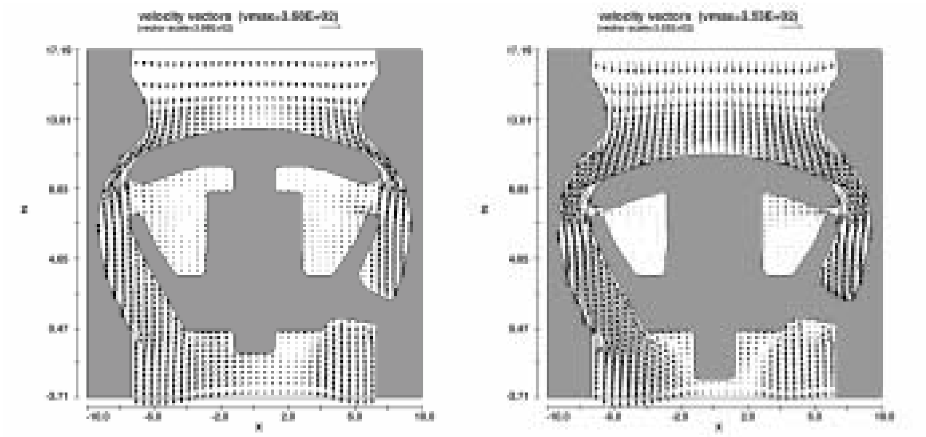


Fig. 1. Geometry and mesh about the valve piston. (a) Geometry at t=0, (b) mesh in x-z plane (x and z in cm).



(a) (b)

Fig. 2. Valve piston locations with pressure and velocity distributions at (a) t=0.6 sec and (b) t=1.5 sec.

An example application of the method is prediction of the opening of a valve in a pipe at different fluid flow rates. Figure 1 shows the initial location of the valve piston and the non-uniform mesh around. Water flow goes toward –z direction. A spring under the piston is compressed when the valve opens to prevent fast valve opening. A three-dimensional computational domain is set from z = -52 cm to 62 cm, which is longer than what is shown in Figure 1. The total number of mesh cells is approximately 178,000. In the experiment, the water flow rate increases from 0 to 50, 125, 180, 250, 325, 400, 450, 500 and 550 gal/min step by step. In the computation, the flow rate increases linearly from one flow rate value to the next within one second, remains constant for another second, and then increases linearly to the next value, until it reaches 550 gal/min. An RNG turbulence model was used in the calculation. Figure 2 shows two predicted positions of the valve piston and the corresponding velocity distributions. Figure 3 shows a comparison between the predicted and measured piston positions at different flow rates. The prediction matches the experimental result very well at flow rates less than 300 gal/min. The piston is opened completely at about 350 gal/min in the prediction, but in the experiment it stopped moving at 340 to 460 gal/min and completely opened at 500 gal/min. One possible reason for this mismatch is that bubbles were observed in the experiment at high flow rates, which might have reduced the pressure drop around the valve, causing a smaller drag force on the piston than that predicted by the model.

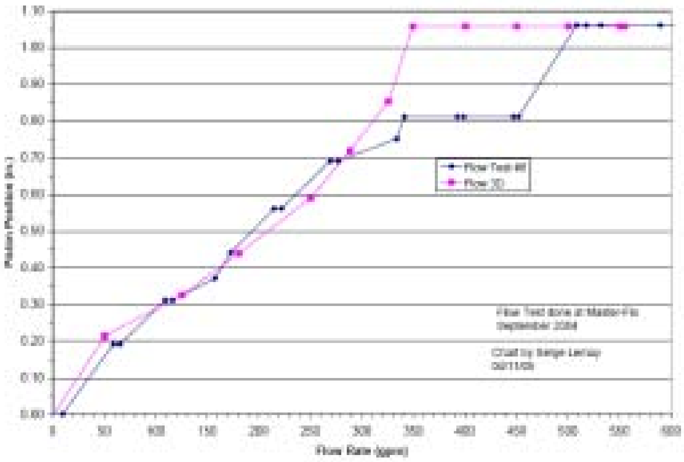


Fig. 3. Variation of piston position with flow rate (Courtesy of Stream-flo Industries Ltd)

4. Conclusions

A fixed-mesh method for general moving objects in fluid flow was developed and implemented into the commercial CFD package FLOW-3D. It allows multiple moving objects with different types of motion that is either prescribed or dynamically coupled with fluid flow. Application of the method to valve opening in a pipe demonstrated a good agreement between computational and experimental results.

References

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