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Investigating of Simulation Methods for Synthetic Jet

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Abstract

Periodic velocity inlet and dynamic mesh boundary conditions are always used to simulate oscillatory piston of synthetic jet. Periodic velocity inlet condition is an easy way to simulate oscillation of membrane of synthetic jet, and dynamic mesh boundary condition is a realistic method using moving grid to simulate the motion of piston, but it needs more computing time because of updating the new grid topology at every time step. In this paper, the two methods' influence for synthetic jet simulation is investigated, and two cases with different boundary conditions are conducted respectively in low Reynolds number laminar flow. The results show that the velocity profiles near the orifice are different distinctly on 0° and 180° phase, the max speed difference at center of orifice is about 0.017 m/s at the end of third period, which increased by 150% of the simulating results with dynamic mesh boundary method. On the other hand, the vortex dye-structure is a little different near the oscillating membrane located at the cavity bottom though it is same commonly outside of synthetic jet when using the two simulation methods. The simulation method with dynamic mesh is more reasonable because it is realistic motion of piston in fact, and the time cost is not more heavily than velocity inlet boundary condition.

Keywords: Synthetic jet; laminar flow; dynamic mesh; numerical simulation.

Nomenclature

A	amplitude (m)
d	width of the orifice (m)
f	frequency (hz)
L_0	stroke length (m)
Re	Reynolds number

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St	Strouhal number
t	time (s)
T	cycle (s, 1/f)
$\vec{u}_0(t)$	centerline velocity (m/s)
ν	kinematical viscosity (m^2/s)
φ	angle of phase ($^\circ$)

1. Introduction

Flow control is an essential technology in studying and designing the aerodynamic characteristics of aircraft. Recently, synthetic jet has proved to be useful active flow control (AFC) device. Synthetic jet has such advantages as lower-weight, more single compact device and non-requirement of internal fluid supply lines, and it has been a new field of AFC with the fast development of Micro-Electro-Mechanical Systems (MEMS) [1-6].

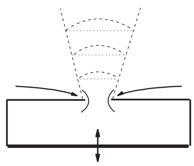

Fig.1. Schematic of a synthetic jet

Synthetic jet is a zero net mass flux jet. Figure 1 show a typical structure of a synthetic jet, which consists of an oscillating membrane located at the bottom of a cavity having small orifice in the face opposite the membrane. Fluid is expelled through the orifice when the membrane moves upwards, and a shear layer is formed at the orifice edge. The shear layer rolls up to form a vortex ring that moves away from the orifice under its own momentum. When the membrane moves downwards, fluid enters into the cavity. This entrainment process is not affected by the vortex ring, which is supposed to be sufficiently far from the cavity. Over one period of oscillation of the membrane the net mass flux is zero. The jet is created by the advection and interaction of discrete vertical structures, which has the potential of manipulating flow fields in order to achieve transition delay (or advancement), separation prevention (or provocation), and turbulence suppression (or enhancement). The modifications of these flow properties can lead to large benefits in aeronautical applications, such as increased aerodynamic efficiency, reduced structural weight, reduced operating costs and reduced emissions. More and more researches about synthetic jet are carrying out through experiment or CFD (Computational Fluid Dynamics).

Periodic velocity inlet [7-9] and dynamic mesh boundary conditions [10-16] are always used to simulate oscillatory piston of synthetic jet in CFD, but they are different obviously. Periodic velocity boundary condition is an easy way to simulate oscillation of membrane of synthetic jet, but it couldn’t express the true boundary condition when it is working. However, dynamic mesh simulation method simulating the motion of piston realistically is obviously better than periodic velocity inlet, but it need more computing time because of updating the new grid. Some papers gave the simulation results of synthetic jet with their methods such as periodic velocity inlet boundary condition, but not claimed the difference of the two boundary conditions.

In this work, two cases using the different simulation methods are conducted to investigate the influence for synthetic jet simulation in low Reynolds number flow, after comparing and discussing the computing results, some solution is present in the final.

2. Computing Model and Numerical Method

2.1. Computing Model

Computing model come from the reference [8], but the moving wall oscillates just like a piston. The cavity size of synthetic jet is 20mm*5mm, the orifice diameter is 1mm and its height is also 1mm. The model is a 2D axisymmetric system.

In the case, the amplitude A is 0.5 mm, the frequency f of diaphragm is 2 Hz and the kinematical viscosity ν is 3.75*10^{-5} m^2/s. The max velocity of oscillation is 3.14 mm/s, the Reynolds number Re is 10.7 and the Strouhal number St is 0.016. They are given by equations:

$$\mathrm{Re} = U_0 d / \nu \,,\; St = df / U_0$$

$$U_0 = L_0 / T \,,\; L_0 = \int_0^{T/2} \vec{u}_0(t) dt$$

where $\vec{u}_0(t)$ is mean velocity of jet through the orifice, T is the time of oscillation in one cycle.

2.2. Numerical Method

Time-average incompressible Navier-Stokes equation is used to simulate the flow. The time derivative term is used a first-order implicit scheme, viscidity term is used a first-order backward difference formula, and laminar model is chose. When boundary is moving (for dynamic mesh method), the integral form of the conservation equation on an arbitrary control volume, V ,can be written as

$$\frac{d}{dt}\iiint_V \rho\phi dV + \iint_{\partial V} \rho\phi\left(\vec{u} - \vec{u}_g\right)\cdot \vec{n}\, dF = \iint_{\partial V} \Gamma_\phi \nabla\phi \cdot \vec{n}\, dF + \iiint_V S_\phi dV$$

Where ϕ is a general scalar, ∂V is used to represent the boundary of the control volume V, dF is infinitesimal area of the control volume's surface, ρ is the fluid density, u is the flow velocity vector, u_g is the grid velocity of the moving mesh, Γ_ϕ is the diffusion coefficient and S_ϕ is the source term of ϕ.

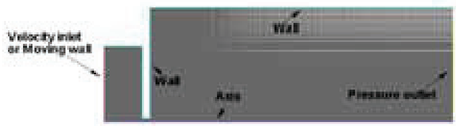

Fig.2 Computational geometry and boundary conditions

The structured grid was generated in the entire flow field, total nodes number are 170 000, and fine grids were specified near the diaphragm, walls and the orifice (Figure 2). All the boundary wall are non-slip and adiabatic, and outfield boundary is dealt with by extrapolation method (pressure outlet). When using dynamic mesh method, the piston motion equation is:

$$\vec{u}_{vel\_piston} = -\pi A f \sin(\omega t + \varphi)\vec{i}$$

It defines the velocity of piston every time step, then the moving piston drives fluid oscillating. And in this paper, dynamic layering method with structured meshes used to simulate the grids' movement near the moving piston. This method can add or remove layers of cells adjacent to a moving boundary based on the height of the layer adjacent to the moving wall. In the numerical programs, the mesh updated is:

If $h > (1 + a_s)h_0$, split the layer.or if $h < a_m h_0$, merge the layer.

where h is the layer cell height, h_0 is the criterion height, commonly, is the first cell height adjacent moving wall, a_s is the layer split factor and a_m is the layer merged factor.

A computing case once was conducted to validate the dynamic mesh solver, this dynamic motion equation could be use to simulate synthetic jet and get reasonable results. More details about the dynamic mesh solver can be found in reference [16].

For the down surface of synthetic jet, periodic velocity inlet boundary condition is:

$$\vec{u}_{vel\_inlet} = -\pi A f \sin(\omega t + \varphi)\vec{i}$$

where A is amplitude, f is the frequency of oscillation and ω is the angular velocity ($\omega = 2\pi f$), φ is the angle of phase, they all are set to define the velocity profile every time step of down wall in synthetic jet, and using common time-average incompressible unsteady Navier-Stokes equation to simulate the flow.

3. Results and Discussion

For showing vortex structure clearly, the fluid inner and outer cavities are set different color, the fluid is red inside of cave and the fluid is blue outside. The characters of fluid inside and outside are same, and the simulations are conducted under the boundary conditions of cave's bottom are different only. the initial position phase of piston is 0°, when the piston move downward finally, the phase is 180°, then the piston move upward to the initial position, the phase is 360°, the first moving period is finished, and the middle positions are 90°and 270°separately (Figure 3).

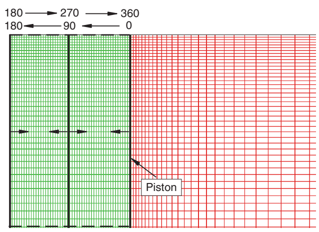

Fig.3 Dynamic layering grid simulating the moving piston

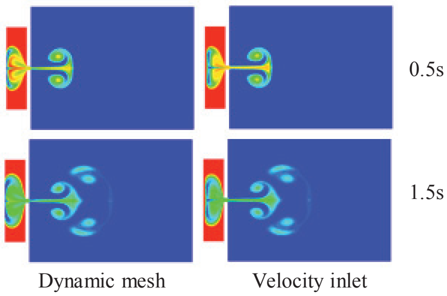

Fig.4 Vortex structure with different methods in the first period

Fig.4 gave the simulation results of vortex structure with different methods in the first period, and the vortex dye-structure is a little different near the oscillating membrane located at the cavity bottom though it is same commonly outside of synthetic jet when using the two simulation methods. The vortex dye-structure are changed on different time, but the fluid near the bottom of cave is red all along with velocity inlet method. The results with dynamic mesh method are more reasonable than velocity inlet method, because the blue fluid would strike the bottom of cave in the period of sucking.

The velocities of fluid on the orifice center are almost same, but they are inequable on 0° and 180° phase (Figure 5 & 6), which can view clearly through the velocity profiles near the orifice. The max speed difference at center of orifice is about 0.017 m/s at the end of third period, which increased by 150% of the simulating results with dynamic mesh boundary method. The reasons are unknown while computations have been conducted more times.

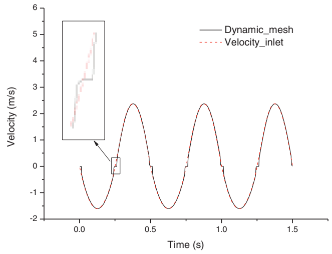

Fig.5 Velocity of fluid on the orifice center

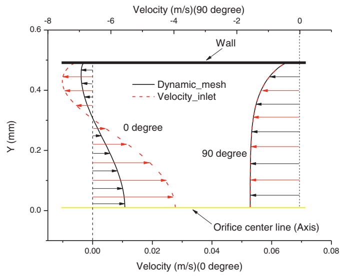

Fig.6 Velocity profiles near the orifice on 0° and 90° phase

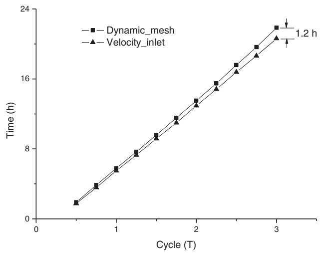

Fig.7 Time cost with different methods

Time cost of dynamic mesh method is not more heavily than velocity inlet boundary condition because only near grids of piston need update. For the case of this paper, the time cost of computing three piston movement cycles is more 1.2 hour than velocity inlet method (Figure 7). The grid update time will be increased when using more grid.

4. Conclusion

In this work, two cases with different simulation methods for synthetic are conducted respectively in low Reynolds number laminar flow to investigate the influence of them. The results show that the vortex dye-structure is almost same outside of cave, and the velocity profiles near the orifice are different distinctly on 0° and 180° phase while the reasons are unknown. Simulation using current grid in this paper, the time cost is not more heavily than velocity inlet method. The simulation method with dynamic mesh is more reasonable because it is realistic motion of piston.

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