A DISCRETE VORTEX STRIP METHOD FOR VORTEX INDUCED VIBRATION ANALYSIS

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Summary Vortex Induced Vibration (VIV) causes the most severe fatigue damage to deepwater risers. Two intrinsic mechanisms are involved: lock-in and hysteresis, which are not correctly captured in the prevailing commercial software. Accurate prediction of VIV response of a deepwater riser is thus both necessary and urgent. In this paper, we propose a Discrete Vortex Strip Method to solve VIV of a long slender structure in current. The riser, modelled as a nonlinear cable, is cut into many sections (strips). In each section three-dimensional effect of flow is neglected, and fluid force is found using two-dimensional discrete vortex method. Through Fluid-Structure Interaction coupling, the oscillatory fluid forces are added to the structure as loading while structural deformations affect locations of vortex shedding. A one DOF example is employed for validation of the method. Finally, examples are given to demonstrate the method. The method is encouraging for it captures lock-in and hysteresis.

MOTIVATIONS

Deepwater drilling system is a very complicated one consisting of three main subsystems: platform, riser and sea-bottom production unit. Among the three subsystems, riser dynamics is remains poorly understood. Failure of the riser subsystem may lead to millions of dollars loss and marine pollution. Among all possible failure modes of deepwater risers, fatigue resulting from Vortex Induced Vibration (VIV) dominates. VIV prediction is thus very important for deepwater riser design.

VIV is a nonlinear Fluid-Structure Interaction (FSI) phenomenon, characterized by two well-known mechanisms: lock-in and hysteresis. A close examination of prevailing professional and general-purpose commercial software, however, shows that none of them can capture the two mechanisms correctly. For example, lock-in mechanism is replaced in prevailing professional software by an oversimplified nonlinear wake or van der Pol oscillators without properly considering FSI effect. The values of the parameters appearing in the oscillator need to be determined from experimental tests. General-purpose CFD software is, however, short of providing turbulence models good enough for high Reynolds number ($>10^5$) flows. Personal experience showed that a well-known commercial CFD software failed to capture the wake field behind a cylinder once Reynolds numbers was higher than 10^4, totally smearing vortices behind.

In this paper, we propose a Discrete Vortex Strip (DVS) Method. The riser, modelled as a nonlinear cable, is cut into many sections (strips). In each section three-dimensional effect of flow is neglected, and fluid force is found using two-dimensional discrete vortex method. Through Fluid-Structure Interaction coupling, the oscillatory fluid forces are added to the structure as loading while structural deformations affect locations of vortex shedding. The method is encouraging for it is capable of properly capturing VIV phenomenon starting from the very basic governing equations of fluid and structural dynamics.

DISCRETE VORTEX METHOD FOR HIGH REYNOLDS NUMBER FLOWS

Numerical accuracies of an Eulerian method for simulating high Reynolds flows are determined by mesh resolution. It is believed that the mesh resolution of an Eulerian method is proportional to squared Reynolds number. Discrete Vortex Method[1], a Lagrangian method, is proportional to Reynolds number, however. Therefore, Discrete Vortex Method is very attractive to simulate high Reynolds flows.

Discrete vortex method approximates the continuous vortex field by a group of point vortices in the two-dimensional flows. The flow field evolves through tracking the motion of each point vortex. Through adjusting the strength and locations of the point vortices to satisfy body boundary conditions, the velocity field can then be numerically determined. The fluid force is then estimated from the velocity field. In the approximation process, no mesh is employed, and thus discrete vortex method is meshless. The solution is split into two steps: the first is to simulate point vortex motions through Biot-Savart formula free of viscosity; the second is to handle viscous motions through random walk simulations. Combining the two steps yield the total solution to the viscous flows governed by N-S equation and continuity equation.

Consider a fixed cylinder of unit radius subjected to incoming currents of variable speed. The wake flow obtained from the method is given in Fig. 1 for Reynolds number=10^5. Vortex shedding patterns can be seen behind the cylinder. Our personal experience showed that some CFD commercial software, employed to numerically simulate the same problem, produced a smeared wake flow field without patterned vortices. This is thus a very attractive advantage of the method. In Table 1 are given the drag coefficient C_D and Strouhal number S_t .

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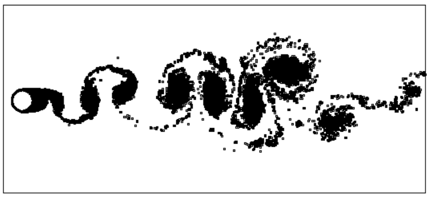

Fig. 1 Wake flow behind a cylinder, Re=10^5

Table 1 Comparison of numerical and test results

		Re=10^4	Re=10^5	Re=10^6
C_D	numerical	1.14	1.22	0.694
	test	1.12	1.2	0.75
S_t	numerical	0.195	0.195	0.234
	test	0.2	0.19	0.26

FLUID-STRUCTURE INTERACTION ANALYSIS AND VILIDATION

The vortices behind the cylinder are oscillatory as shown in Fig.1, producing an oscillatory transverse lifting force acting on the cylinder. This in turn drives the cylinder to move in the transverse direction, that is, the Vortex Induced Vibration (VIV). Therefore, VIV is a FSI problem. In the strip sense, in each section of the riser, the section of the riser is treated as a rigid body movable in the transverse direction. Then the location of a point vortex shedding from the rigid body is location-dependent, determined from the location of the rigid body at each time step.

A one degree of freedom oscillator in current, which experimental data are available in the open publications, is used as a benchmark problem. Some of the results, obtained from current method and experimental are given in Table 2 and Fig. 3. Table 2 shows that the results relevant to lock-in reduced velocity, lock-in velocity interval and Strouhal number. Two results for reduced mass ratio m^* are given, which show good correlation with experimental results. In Fig. 3 are shown the comparison of the present work, Khalak's experimental data. The Figure clearly shows that the present method reproduced lock-in phenomenon, a key mechanism in VIV.

Table 2 Lock-in values and Strouhal number comparison

m^*	Lock-in U_r		Lock-in ΔU_r		Strouhal *St*	
	Exp	Present	Exp	Present	Exp	Present
2.36	4.0	4.0	8.5	8.5	0.140	0.132
8.76	5.5	5.5	2.7	3.0	0.180	0.175

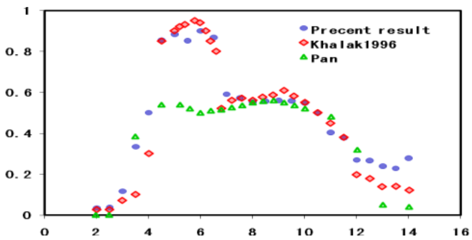

Fig.3 Lock-in in the validation

EXAMPLES

The method is applied to study some of practical problems, with some of the results given in Fig. 4. In Fig. 4(a) is shown the VIV in a uniform flow. The leftmost figure shows the vibration mode in the vertical direction, the middle figure shows the vortex shedding patterns behind the riser and the rightmost figure shows the oscillatory lift and drag. In Fig. 4(b) is shown the VIV in a shear flow.

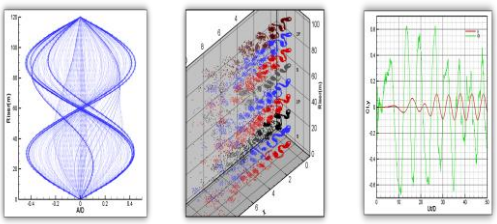

Fig. 4 (a) VIV in a uniform flow

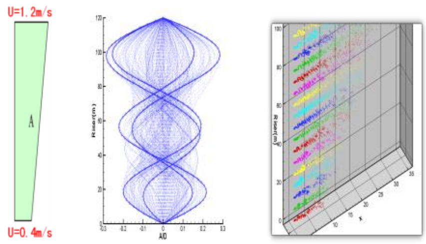

Fig. 4 (b) VIV in a shear flow

CONCLUSIONS

In this paper a discrete vortex strip theory is presented to solve VIV of deepwater risers. The method correctly reproduces lock-in and hysteresis phenomena, which are absent in the prevailing commercial software. The method has been validated through experimental data. Further efforts are needed to generalize the method to fully three-dimensional.

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