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Vortex-Induced Vibration of Composite Risers at Moderate Reynolds Numbers Using Computational Fluid Dynamics

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Prepared by:

Charles Dalton, Tuhin Rakshit, and Sampath Atlutri

Composites Engineering and Applications Center (CEAC), and
Department of Mechanical Engineering
University of Houston
4800 Calhoun Road
Houston, TX 77204-0931

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RPSEA Project Manager
Robert W. Siegfried
Vice-President, Unconventional Gas Technology

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This study has been a computational effort to determine the vortex-induced vibration (VIV) of a long slender riser, made from composite materials, subject to an ocean current. A riser made from composite materials differs structurally from a conventional riser made of steel. A composite-material riser has a smaller value of density and a different structural damping behavior. A riser made of steel has a structural damping that is essentially constant because of the homogeneous composition of the material. A composite riser however has a structural damping that changes as the natural frequency of the composite structure changes. The fluid forcing on a composite riser is the same as on a homogeneous riser when the risers are stationary. The geometry of the riser dictates the fluid-forcing response. Therefore, the circular cross-section of a riser, be it made of steel or a composite material, renders the same fluid forcing behavior when there is no vibration. However, when the risers vibrate, the fluid forcing function is influenced by the riser motion. So, it is quite likely in a VIV oscillation that the forcing function for risers of two different materials will be different because the amplitudes of oscillation could be different.

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1. Summary

This study has been a computational effort to determine the vortex-induced vibration (VIV) of a long slender riser, made from composite materials, subject to an ocean current. A riser made from composite materials differs structurally from a conventional riser made of steel. A composite-material riser has a smaller value of density and a different structural damping behavior. A riser made of steel has a structural damping that is essentially constant because of the homogeneous composition of the material. A composite riser however has a structural damping that changes as the natural frequency of the composite structure changes. Recent tests by Yu (2004) show that structural damping of a composite-material riser decreases with increases in the natural frequency. This damping issue will be discussed in more detail in the analysis of the composite riser subjected to VIV.

The fluid forcing on a composite riser is the same as on a homogeneous riser when the risers are stationary. The geometry of the riser dictates the fluid-forcing response. Therefore, the circular cross-section of a riser, be it made of steel or a composite material, renders the same fluid forcing behavior when there is no vibration. However, when the risers vibrate, the fluid forcing function is influenced by the riser motion. So, it is quite likely in a VIV oscillation that the forcing function for risers of two different materials will be different because the amplitudes of oscillation could be different. We will discuss this issue more later in the report.

Our approach to describing VIV on a composite riser is the same as for a steel riser. We treat the riser vibration as a coupled fluid-structure interaction problem. This approach is the same as that in the study of Al-Jamal and Dalton (2004) in which a rigid riser was considered. However, there is one difference between composite and steel risers that provides an interesting contrast between the two types of materials. The material damping of a composite material riser typically is not constant. It has been found to vary with the natural frequency of the riser; in fact, it decreases with increasing frequency. Yu (2004) conducted some cantilever-beam damping tests for a composite beam as a part of this RPSEA study. This data has been incorporated into these VIV calculations so that the appropriate material damping is properly represented. Yu's data will be presented later in this report. The frequency-dependent damping will be addressed again in the discussion of the governing vibration equations. The results for the damping tests will be discussed in the section in which the cases to be considered are summarized. There is also a second notable difference between a composite riser and a steel riser; the mass of the composite riser is significantly less, at least by a factor of at approximately four.

In the approach of Al-Jamal and Dalton (2004), the governing equations describing the fluid motion and the structural vibratory response are solved using a time-advancing computational method. At each time step, the governing equations are solved. First, the governing flow equations are solved to determine the instantaneous pressure and shear stress distributions around the circumference of the riser. These distributions are then integrated around the circumference to determine the instantaneous forcing function on the cylinder, which is then used as the instantaneous force excitation for the riser vibration. The riser displacement and velocity are then determined from the structural vibration equation and are used to modify the boundary conditions on the surface of the cylinder. These modified boundary conditions are then used in solving the flow equations at the next time step as time advances in the solution process. Again, we are treating the riser vibration as a coupled fluid-structure interaction problem. The boundary conditions for the flow equations are updated at each time step referenced on the riser response to the instantaneous fluid-forcing description.

2. Problem Statement

The physical problem is the vortex-induced vibration (VIV) of a long slender flexible riser made with composite materials. Current computational techniques and present-day computers do not have the capability to treat this problem in its full 3-D form. Sufficient computer resources, such as computational speed and memory, are simply not available to represent this problem in its full complexity. The difficulty stems from both the fluid and structural sides of the problem. The flow past a stationary cylinder has a 3-D turbulent wake for Reynolds numbers ($\mathrm{Re}=Ud/v$) above about 300. Computationally, it is very difficult to capture the full features of this 3-D flow, especially for larher values of Reynolds number. Using the technique of Direct Numerical Simulation (DNS), Dong and Karniadakis (2004) have done a 3-D calculation of the steady approach flow past a stationary circular cylinder very accurately at Re=10,000. Lu et al. (1997), using a turbulence modeling procedure known as Large Eddy Simulation (LES), were able to obtain accurate 3-D solutions to Re=44,200. In the above discussion, the term Re is the Reynolds number in which U is the approach velocity of the fluid, d is the diameter of the cylinder, and v is the kinematic viscosity of the fluid.

These 3-D nonvibrating cylinder calculations, in their own right, are very expensive and require significant computer storage. Furthermore, they are restricted to fairly short lengths of cylinder, typically no more than four to six diameters. Riser pipes, in a typical deep-water offshore situation, can have a length-to-diameter ratio of several thousand. Thus, it is impractical to expect that a full fluid flow solution can be obtained, even for a stationary cylinder at values of Re and riser lengths which occur in offshore applications. If the cylinder were vibrating over its entire length, then the solution complexity would be increased by several orders of magnitude. Thus, it is quite clear that some sort of simplification is necessary to calculate the fluid-forcing description for a vibrating riser. The approach that we will take is to use the strip-theory method. In this method, the cylinder (or riser) length is divided into a number of segments, as shown in Figure 1. The riser vibration equation is developed from the idea of a tension-dominated cable where the loading is assumed to be uniform. The strip theory method is easily applied to this vibration equation as shown in the next section. However, in this application, the tension in the vertical riser is dependent on axial position.

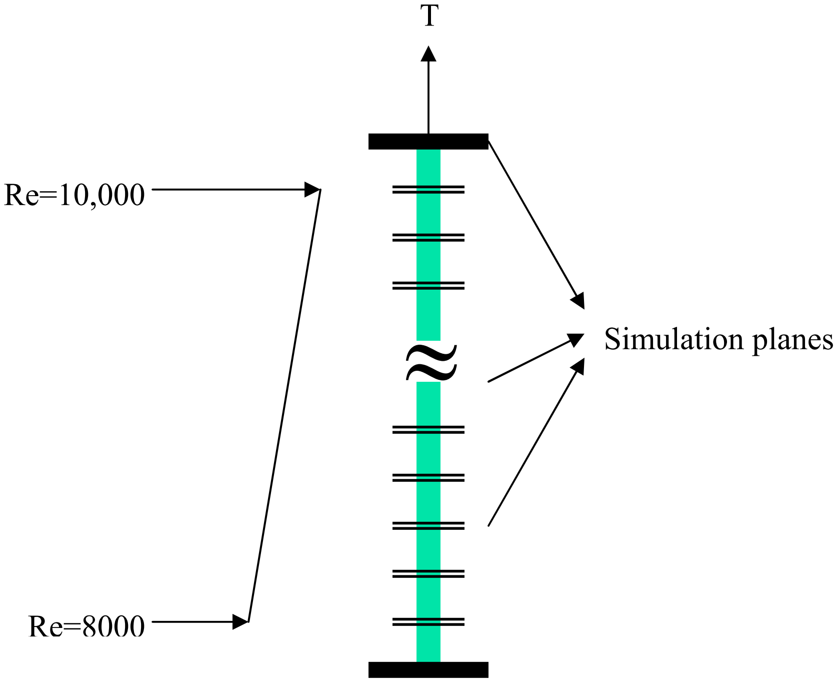

Figure 1 Representation of the riser in strip theory formulation