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Instability analysis of deepwater riser with fairings

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ABSTRACT

The paper investigates the mechanism of instability of deepwater risers fitted with fairings and presents an analytical model to predict the instability onset conditions. The simplified case of a two-dimensional (2D) problem was considered. The governing equations were derived, and the hydrodynamic forces were calculated and the effect of motion in these forces was taken into consideration. The final equations were linearised and an eigenvalue analysis was employed to systematically examine the stability with the emphasis on identifying the critical current speed for a given system. This model was validated against the available test results and showed a good agreement. A parametric study was also carried out. It showed the significant role of the hydrodynamic coefficients as well as mass distribution in the stability of the system.

1. Introduction

Suppression of the vortex-induced-vibration (VIV) of deepwater risers in ocean currents is an important issue. Various methods have been proposed to control this phenomenon. Among them, outfitting the riser with a VIV suppression device is one of the most prevalent techniques. These devices reduce the VIV in different ways and each has its own advantages and drawbacks. Helical strakes, perhaps the most implemented device, suffer from an increase in the drag force. Riser fairings are capable to mitigate VIV while simultaneously reducing drag by streamlining the fluid current round the riser and consequently weakening the vortices shed aft of the body. They are typically of teardrop geometry, varying in terms of the chord length c, thickness t, span length and tip and tail details.

Tank tests have revealed that fairings are exposed to severe vibrations when the current velocity exceeds a certain limit. Some designs demonstrated typical VIV response meaning that these sections, though streamlined to some extent, were still experiencing vortex shedding while some other designs underwent vibrations with different features from VIV. They exhibited self-induced oscillation or dynamic instability characterised by the increase of responses upon excitation (Ericsson and Reding, 1980; Ikeda et al., 2003; Lee and Allen, 2005; Meyer et al., 1995; Slocum et al., 2004).

Dynamic instability, defined in a classical sense, is the fact that response of a system increases with time which is caused by negative damping in the system (Lee and Allen, 2005). Lee and Allen expound that in the context of VIV, dynamic stability can be described otherwise. As the flow speed increases the VIV motion of a cylinder rises to a certain level, and then the motion interferences with the vortex shedding process and begins to break up the symmetric pattern of alternate vortices. The motion magnitude does not increase even if the flow speed continues to rise, thus the process is self-limiting. When the cylinder is fitted with fairings, they can rotate and form an asymmetric section with respect to flow which entails lift force and may amplify the vibration beyond that of a bare riser. This type of vibration is not self-limiting anymore and the amplitude increases along with the velocity. The frequency of this vibration was reported to be less than the frequency of corresponding vortex shedding (Braaton et al., 2008). In general, as the current speed increases the first peak in the vibrations (Fig. 1) is caused by vortex shedding (Blevins, 2001) while the second peak at a higher reduced velocity U_r is associated with the instability of a riser fitted with fairings.

Some researchers tried to explain the source of the problem through early separation of boundary layer and stall (Calkins, 1984; Ericsson and Reding, 1980). Accordingly, it was recommended to reduce the angle of fairing contour in the leeside to match the fairing profile to the flow regime (Ericsson and Reding, 1980; Grimminger, 1945). Meyer et al. argued that observed instability was due to the fact that the centre of rotation of the fairing was located behind the aerodynamic centre (Meyer et al., 1995). Several methods have been proposed to rectify the problem, e.g. trailing-edge fins or adding vortex generators (Calkins, 1984; Gardner and Cole, 1982; Grant and Patterson, 1977; Meyer et al., 1995). On the other hand, large hydrodynamic damping that some fairings generate (Lee et al., 2004) can be a key reason for their dynamically stable response as well as dominant suppression mechanism (Lee and Allen, 2005).

The instability of fairing has made the design engineers carry out extensive model testing on the stability of each suggested fairing profile, e.g. short fairing or dual fin splitter (Spencer et al., 2007). Therefore, it is vital and beneficial to predict the instability onset condition for a given system theoretically in the design

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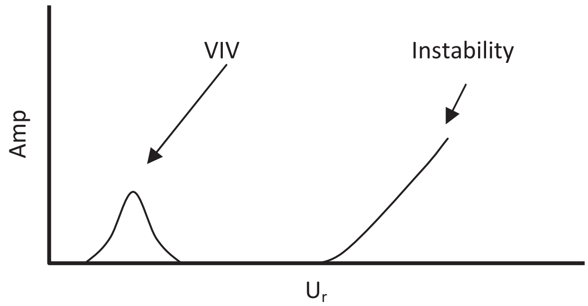

Fig. 1. Typical response of a system vs. reduced velocity.

phase. An analytical model was proposed to explain the mechanism of instability. This model was based on a simple two-dimensional model of airfoil flutter and did not include the effect of hydrodynamic damping (Slocum et al., 2004). The riser and the fairing were modelled as a single body in this model.

The present study endeavours to develop a more comprehensive analytical model and to take the effect of more parameters into consideration. The classical flutter theories cannot be applied directly because they are based on thin-airfoil theory with essential assumptions to ignore viscosity and thickness (Bertin and Smith, 1998). Moreover, an airplane wing is modelled as a cantilever beam with both flexural and torsional stiffness. On the contrary, riser fairings are designed to freely swing about the riser and therefore, no torsional stiffness exists to restore a distorted fairing to initial condition except the stiffness generated by hydrodynamic forces. Hydrodynamic forces depend on the orientation of fairing relative to flow and therefore in the equation of motion they will be coupled with the terms of the fairing motion. Navier–Stokes equations to define hydrodynamic forces require a numerical solution which masks the analytical feature of the model. Thus, it is necessary to make some simplifying approximations in both spatial and temporal domains.

To remove the effect of three-dimensionality on hydrodynamic forces, 'strip theory' approximation is deployed. Thereby, it is assumed that hydrodynamic characteristics of a 3D fairing are equal to that of a 2D section and spanwise variations of force are negligible. To eliminate the effect of flow history, the equations of motion will be derived under the assumption of quasi-steady dynamic derivatives. The last step is to assess stability of the system against an infinitesimal disturbance from equilibrium position. It should be noted that in a large proportion of all cases, an adequate definition of flutter properties of a system can be obtained by studying the stability of infinitesimal motions (Bisplinghoff et al., 1996).

The development of the analytical stability model discussed in the following is based on few assumptions outlined below:

- Fairing segments are installed on a vertical top tensioned riser.
- Individual fairing segments are rigid structures and do not experience any deformation.
- Fairing segments are free to rotate about the riser and there is no structural torsion-stiffness.
- Entrapped water within the fairing shell moves with the fairing as a rigid body.
- 'Strip theory' approximation is employed to reduce the three-dimensionality of hydrodynamic characteristics of fairing to a two-dimensional section.
- 'Quasi-steady' assumption is considered and the effect of flow history is eliminated.
- As observed in the tank tests, motion in-line with the current direction is of very limited amplitude in comparison with cross-flow translation, e.g. 0.6*D* against 4*D* where *D* is the riser diameter (Braaton et al., 2008). Thus, in-line motion has negligible effect on flutter-type instability.
- According to quasi-steady assumption, lift, drag and moment are functions of instantaneous angle of attack (AoA). However, the effects arise from cross-flow translation as well as influences due to time variation of AoA (torsional velocity) are to be considered.

These assumptions impose some limitations on the application of this model. This model will be helpful in determining the threshold velocity at which the instability can occur for a given system of riser and fairing. However, it is not capable of explaining the evolution of unstable motion and its development in subsequent stages. Whether the amplitude of this unstable motion continues to increase or is self-limiting is out of the scope of this model.

The other major limitation of this model is that the hydrodynamic coefficients are assumed to vary only with angle of attack, however, they may be affected by turbulence and vortex shedding too. On the other hand, the quasi-steady assumption requires that the vortex shedding frequency be well above the natural frequency of structure. Although vortex shedding from fairings is not very likely as they are devised to suppress VIV, this condition should be assessed if the fairing still experiences some vortices.

It should be mentioned that this model is based on linearization of hydrodynamic forces. Since real physical phenomenon are not linear, the question always arises how good the linearised theory is as an approximation to the real case, and to what extent of magnitude of the variables concerned the linearised theory is valid. At present, it can only be said that experimental observations show the linearised theory of flutter type instability represents fairly closely the real situation in the neighbourhood of the critical instability speed, provided that the amplitude of motion remains small (Fung, 2002).

2. Governing equations of motion

A cross-section of a riser fitted with fairings is shown in Fig. 2. The riser is a pipe, possibly covered by buoyancy module, filled with fluid and supported by a spring and damper in cross-flow (CF) direction which depict the contribution of the rest of the riser. As the test reports showed large amplitude vibration in CF direction, it is assumed that the negligible motion in line with the current is unimportant in comparison with CF oscillation (see Section 1). Thus, the riser has only the translational degree of freedom (DOF), $y(t)$.

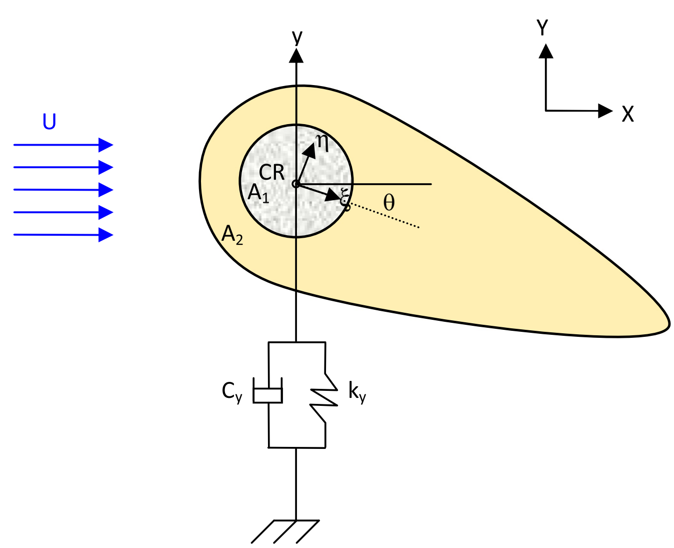

Fig. 2. Local and global coordinates, degrees of freedom.