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Vortex-induced vibration on a two-dimensional circular cylinder with low Reynolds number and low mass-damping parameter

Juan B.V. Wanderley*, Luiz Felipe N. Soares

COPPE/UFRJ, Rio de Janeiro, RJ, Brazil

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ABSTRACT

The vortex induced vibration (VIV) on a circular cylinder with low mass-damping parameter and low Reynolds number is investigated numerically as basis for applications on dynamics of risers used in the offshore oil and gas industry and as a first step before tackling the harder high Reynolds number problem. The cylinder is supported by a spring and a damper and free to vibrate in the transverse direction. The numerical solution of the Unsteady Reynolds-Averaged Navier–Stokes equations written in curvilinear coordinates is obtained using an upwind and Total Variation Diminishing conservative scheme and the k–ε turbulence model. Results were obtained for the phase angle, response amplitude, response frequency, and lift coefficient for reduced velocities from 2 to 12, for six different fixed Reynolds numbers, and for three different proportional variations of Reynolds number with reduced velocity, 2000–6000, 2000–12,000, and 2000–24,000. The results indicate the strong effect of the Reynolds number on the response amplitude, lift coefficient, and response frequency for a low mass-damping parameter. The upper branch of the response amplitude curve is only obtained when the Reynolds number varies proportionally to reduced velocity. For a fixed Reynolds number, only the initial and lower branches are captured.

1. Introduction

Vortex-induced vibration (VIV) is found in many engineering applications, for example, risers in the offshore petroleum exploration, bridge piers, antennas, etc. Risers in the offshore industry are subjected to VIV due to marine currents and the resulting hydrodynamic periodic loads can excite highly dangerous response amplitudes causing the failure of the structure. Many researchers have been spending time and effort trying to understand, predict and possibly suppress the occurrence of vortex-induced vibration.

Khalak and Williamson (1996) measured the response amplitude and frequency of the vortex-induced vibration around a circular cylinder after imposing a progressive increment of the flow speed with Reynolds number varying from 2000 up to 12,000. They observed that at very low mass-damping ratio the response amplitude has two branches of resonance. There are actually two distinct levels of resonance, rather than a single one as previously assumed. Another observation is that the variation of the mass ratio affects the response even when the combined mass-damping ratio is kept constant.

Williamson and Roshko (1979) reported two modes of vortex shedding in the lock-in region; say the 2S and 2P modes. In the 2S mode, one vortex is shed in each half cycle of oscillation, and in the 2P mode, two vortices are shed in each half cycle. The 2S mode is observed at the initial branch of the displacement amplitude curve, and the 2P mode is observed at the upper and lower branches, but at the upper branch, the second vortex shed in each half cycle is weaker than the first one.

In previous works, different turbulence models were utilized to study Vortex-Induced Vibration on a circular cylinder. Wanderley and Levi (2005) used the Baldwin and Lomax (1978) turbulence model, Wanderley and Levi (2003) used Large Eddy Simulation and the Smagorinsky (1963) subgrid-scale model, and Wanderley et al. (2007) used the SST turbulence model of Menter (1992) and the k–ε turbulence model of Chien (1982). Only the k–ε turbulence model of Chien (1982) was able to duplicate the experimental data from Khalak and Williamson (1996).

Wanderley et al. (2008a) studied the vortex-induced vibration of a circular cylinder by the numerical solution of the unsteady Reynolds-Averaged Navier–Stokes equations. The Governing equations were solved using an upwind and total variation diminishing conservative scheme and the k–ε turbulence model. The numerical results showed that the transition between 2S and 2P modes of vortex shedding takes place exactly when the curve of power

* Corresponding author. Tel.: +55 3938 7750.
E-mail address: juanw@oceanica.ufrj.br (J.B.V. Wanderley).

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Nomenclature

D	cylinder diameter
I	turbulence intensity
L	length of the cylinder
M	Mach number
Re	Reynolds number
St	Strouhal number
U_r	reduced velocity
f_{na}	body natural frequency in air
f_{nw}	body natural frequency in water
k	turbulent kinetic energy
l	turbulence length scale
p	pressure
t	time
u	x-velocity component
v	y-velocity component
w	z-velocity component
y	displacement of the cylinder
$\dot{y}$	vertical velocity of the cylinder
ε	dissipation rate of turbulent kinetic energy
η	distance from a point in the flow field to the body surface
μ	dynamic viscosity
ρ	density
τ	isothermal compressibility
τ_w	frictional stress on the wall
υ	kinematics viscosity
∞	free-stream conditions

absorbed by the system changes declivity. For the rising of power absorption, the 2S mode is observed, and for the falling of power absorption, the 2P mode governs the vortex shedding.

Wanderley et al. (2011) studied the hysteresis effect on vortex-induced vibration on a circular cylinder by the numerical solutions of the unsteady Reynolds-Averaged Navier–Stokes equations. The Governing equations were solved using an upwind and total variation diminishing conservative scheme and the k–ε turbulence model. Results were obtained for the power absorbed by the system, phase angle, response amplitude, response frequency and lift coefficient. The numerical simulation indicated that the hysteresis effect is observed only when the frequency of vortex shedding crosses the natural frequency of the structure in air.

Dai et al. (2014) investigated the vortex-induced vibration of a long flexible pipe conveying fluctuating flow by a two-mode discretization of the governing differential equations. The internal fluid velocity is assumed to have a harmonic varying component superposed on a steady mean velocity. Direct perturbation method of multiple scales was adopted to transform the governing non-linear partial differential equation into ordinary differential equations. The results indicated that in the case of a pipe containing fluctuating flow, the peak of vibration amplitudes is larger than of a pipe conveying steady flows.

Cui et al. (2014) studied the vortex-induced vibration of two elastically coupled circular cylinders in side-by-side arrangement with mass ratio 2 and for a fixed Reynolds number of 5000. The Unsteady Reynolds-Averaged Navier–Stokes equations were solved using the finite element method. Simulations were carried out for one symmetric configuration and one asymmetric configuration. Five response regimes were found in both cases and they are the first-mode lock-in regime, the second-mode lock-in regime, the sum-frequency lock-in regime, and two transition regime.

Rahmania et al. (2014) investigated numerically the vortex-induced vibration of two side-by-side circular cylinders of different diameters and free to vibrate in the transverse direction in steady incompressible flow. The two-dimensional Reynolds-Averaged Navier–Stokes equations with the SST turbulence model were solved using the Petrov–Galerkin finite element method. The Reynolds number based on the larger cylinder diameter and free stream velocity was fixed at 5000. The numerical results indicated that collision between the two cylinders is dependent on the difference of the reduced velocities of the cylinders. The presence of the small cylinder in the proximity of the large one appears to have significant effects on the vortex shedding regime and vibration amplitude of the large cylinder.

Lee et al. (2014) simulated numerically the flow past a fixed rigid cylinder and a self-oscillating cylinder at Reynolds number 5000 using the CFD OpenFoam package based on the finite volume method. Span wise-pressure correlations and spectral calculations were conducted using longer cylinder span lengths of 4D, 8D, and 16D. The numerical results indicated that as the cylinder span size increases, better span wise correlations are obtained. The numerical results obtained for the fixed rigid cylinder and for the self-oscillating cylinder compare favorably with the experimental data.

The present work investigates the Reynolds number effect on the vortex-induced vibration (VIV) of a circular cylinder restricted to move in the in-line direction and free to vibrate in the transverse direction. The slightly compressible Unsteady Reynolds-Averaged Navier–Stokes equations (URANS) are solved numerically for the two-dimensional (2D) flow around a circular cylinder. The upwind and TVD scheme of Roe (1984) and Sweby (1984) is used to solve the governing equations written in the conservative form and in general curvilinear coordinates. The Reynolds stresses in the URANS equations are evaluated through the hypothesis of Boussinesq (1877) and the k–ε turbulence model of Chien (1982). In previous work, the numerical code was validated for VIV investigations with low mass ratio, Wanderley et al. (2008b). Results were obtained by duplicating the flow conditions used in the experimental investigation carried out by Khalak and Williamson (1996).

The vortex induced vibration on a circular cylinder with low mass-damping parameter and low Reynolds number was investigated numerically as basis for applications on dynamics of risers used in the offshore oil and gas industry and as a first step before tackling the harder high Reynolds number problem. Results were obtained for the phase angle, response amplitude, response frequency, and lift coefficient for reduced velocities from 2 to 12, for six different fixed Reynolds numbers, and for three different proportional variations of Reynolds number with reduced velocity, 2000–6000, 2000–12,000, and 2000–24,000. The numerical results indicate the strong influence of Reynolds number on the response amplitude, lift coefficient, and response frequency.

2. Mathematical formulation

The Unsteady Reynolds-Averaged Navier Stokes equations are obtained by time averaging the Navier–Stokes equations (continuity and momentum). The URANS equations and the k - ε turbulence model equations in 2-D general curvilinear coordinates are given below in the conservative form. Details about the k–ε turbulence model can be found in Chien (1982).

$$Q_t + (E_e - E_v)_\xi + (F_e - F_v)_\eta = H \tag{1}$$