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Influence of seabed proximity on the vibration responses of a pipeline accounting for fluid-structure interaction

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Cylindrical bodies subjected to external flow can vibrate due to the fluctuations of the forces induced by vortex shedding. The way these coherent fluid flow structures are formed and how they excite the structure depends on parameters, such as the Reynolds number, the reduced velocity, and the geometry e.g., the proximity of the structure to other bodies. These vibrations change the drag and lift forces by means of a nonlinear interaction. In addition, vibrations can cause crack nucleation and propagation in the structure. This is especially important when oil or natural gas is being transported in pipe-like structures, subjected to waves and sea currents. The present paper aims to characterize the influence of the proximity of the seabed on the fluid–structure interaction, considering horizontal pipes anchored by dunes. The simulations were undertaken for a nominally horizontal, elastic pipeline, 42 m in length and 0.273 m in diameter, with a mid–span static sag of 1.06 m due to self-weight. Seven different distances between the pipeline and the seabed were tested. The structural and fluid-dynamic models were coupled numerically, which allows the simulation and analysis of the flow using a single computational tool. The equations modeling the flow were solved in an Eulerian domain, while the surface of the immersed body was represented by a set of Lagrangian points. The immersed boundary method was used to impose a Dirichlet boundary condition on the Eulerian domain at the boundary between the structure and the fluid. It was also used to determine the fluid dynamic forces acting on the structure. An in-house three-dimensional computational framework was developed to simulate the turbulent incompressible flow subjected to fluid–structure interaction in conjunction with a beam modeled according to Timoshenko's theory. The obtained results are consistent, as expected for this problem.
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1. Introduction

The interaction between flows and structures is a complex and recurring problem in engineering applications. This phenomenon can be found in aircraft [1,2], pipelines [3–5], wind turbines [6–8], bridges [9,10], offshore platforms [11–13], compressor valves [14,15], and others [16]. Computational fluid dynamics, together with techniques for the numerical solution of the equations that model the movement of structures, have been frequently used to solve fluid–structure interaction prob-

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lems. It is a typical multidisciplinary problem, since it involves disciplines such as fluid mechanics, structure mechanics, pure and applied mathematics, software engineering, and computer science.

Flows over cylindrical structures can be a source of vibrations induced by instabilities. These vibrations can induce increase in fluid dynamic forces (i.e., drag and lift), leading to increased stress on the structures [17]. In addition, vibrations can cause nucleation and crack propagation in the structure leading to fatigue failure. In some cases, the RMS value of the lift coefficient can vary from 0.3 to 1.75, depending on the operating regime [17]. This justifies the concern with fluid–structure interaction in cylinders. This is especially important when the cylinders are pipelines, excited by waves and/or currents, used to transport oil or natural gas. The maintenance of this type of structure is generally expensive, since they can be immersed at a depth of thousands of meters, and failure has the potential to cause environmental disasters and great financial losses.

Therefore, it is important to understand how the fluid–structure interaction process acts on the pipe dynamics to prevent failures. The main objective of this study is to acquire and expand the understanding of the influence of the seabed on the fluid–structure interaction process in horizontal pipelines anchored by dunes. This study was done through the numerical solution, in a distributed processing environment, of the equations that model the phenomenon. These simulations were done in a pipe of length $L = 42$ m and diameter $\phi = 0.273$ m in flows dynamically characterized by $Re_\phi = 8.64 \times 10^4$. The seabed was modeled as a plane wall. Different mid–span gap distances have been tested, namely: 0.1ϕ, 0.2ϕ, 0.3ϕ, 0.5ϕ, 1ϕ, 2ϕ, and 5ϕ.

The results presented herein were obtained from the in-house numerical framework Fluids3D, which has been being developed in the MFLab for more than nine years. MFLab is the laboratory of fluid mechanics specialized in computational fluid dynamics located at the Federal University of Uberlândia in Brazil. In this program it is possible to perform simulations of incompressible flows taking into account the movement of structures by using a single computational tool [18]. The Immersed Boundary Method, used in the present research, is particularly suitable for problems involving fluid–structure interaction, as it allows to treat the fluid and structure domains independently [19]. The equations that model the flows are solved in a fixed Cartesian Eulerian domain, while the surface of the immersed body is represented by a set of Lagrangian points [20]. Through this method, the forces at the interface between the structure and the fluid are evaluated and used both to impose the non-slip boundary condition and to calculate the displacements and velocities of the structure.

2. Methodology

The seabed geometry in deep water can be irregular. Pipes used to transport oil and natural gas laying on this uneven ground may have unsupported sections, known as free spans. These may be subjected to sea currents which, when interacting with the pipes, induce fluctuations of the fluid dynamical forces that excite the structure.

The purpose of this section is to present the physical, mathematical, and numerical models used to simulate the problem of interest.

2.1. Physical model

In the physical model, the problem of interest is evaluated and physical assumptions are adopted to make the solution feasible. The assumptions for each subsystem will be presented separately.

2.1.1. Fluid subsystem

In this subsection, the physical assumptions for the fluid subsystem are presented. They are separated into three subgroups: domain, flow, and physical properties. The domain of the physical problem is the ocean, in which the structure is immersed. It is important to note that the domain is delimited by the seabed, which although static, influences the flow and, as a consequence, the vibration of the structure. Since the simulation of the ocean in all its extension is impractical, it is necessary to choose a reduced domain for the analysis of the problem. A domain with length 42 m (154ϕ), 6 m wide (22ϕ), and 4 m high (14.6ϕ) was chosen, where, ϕ is the diameter of the pipe.

An illustration of the fluid domain with the structure deformed by its self weight is presented in Fig. 1 for the case in which the mid–span gap is 5ϕ. For the values of the material properties used in the computations, the mid–span pipe static sag is 1.076 m or 3.941ϕ for all mid–span gap values.

A supplementary view of Fig. 1 is presented in Fig. 2. A view looking downstream of the pipeline for a mid–span gap of 0.1ϕ showing mid–span deflection to scale. It is possible to see how little of the pipeline is actually in close proximity to the seabed.

The flow inside the structure is not considered here. The internal fluid is modeled as a rigid body and accounted on the inertia and self-weight calculation of the structure. The external flow and its influence on the structure is considered. A preliminary analysis of the external flow is required to make the appropriate assumptions for the case study. The flow may be characterized dynamically by the Reynolds number, $Re_\phi = u\phi/\nu$, where u is the mean fluid velocity at the inlet of the domain and ν is the kinematic viscosity of the fluid. For the determination of the Reynolds number, $u = 0.5$ m s^{-1}, $\nu = 1.58 \times 10^{-6}$ m$_2$ s^{-1} and $\phi = 2.73 \times 10^{-1}$ m were adopted, resulting in $Re_\phi = 8.64 \times 10^4$. It is well known that flows over cylinders become unstable over $Re_\phi = 47.5$ [21]. Therefore, it is safe to assume that the flow is turbulent downstream from the pipe. This Reynolds number is found on usual industrial cases. If the flow velocity increases, the boundary layer on the surface of the struc-

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