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Flow-Induced Acoustics in Corrugated Pipes

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Abstract. When gas flows through corrugated pipes, pressure waves interacting with vortex shedding can produce distinct tonal noise and structural vibration. Based on established observations, a model is proposed which couples an acoustic pipe and self-excited oscillations with vortex shedding over the corrugation cavities. In the model, the acoustic response of the corrugated pipe is simulated by connecting the lossless medium moving with a constant velocity with a source based on a discrete distribution of van der Pol oscillators arranged along the pipe. Our time accurate solutions exhibit dynamic behavior consistent with that experimentally observed, including the lock-in frequency of vortex shedding, standing waves and the onset fluid velocity capable of generating the lock-in.

AMS subject classifications: 76Q05

Key words: Computational fluid dynamics, aeroacoustics, sound generation, riser, corrugated pipes, wave propagation, low Mach number, gas flow, flow-induced vibrations.

1 Introduction

Flexible risers are specially designed pipes that facilitate fluid flow between sea installations and surface facilities located on drill platforms (see Fig. 1). The flexible risers often experience the phenomenon of ”singing”: large pressure fluctuations are generated within the riser and can be heard clearly as acoustic tones. The problem can be attributed to flow induced pulsations that are generated on the inner corrugated wall layer of the flexible riser. When the vortex shedding frequency excites the acoustic natural frequency of the pipeline, resonance between structural vibrations, standing acoustical waves and vortex shedding appear. This phenomenon is known as lock-in. The minimum fluid velocity for which a lock-in frequency appears is referred to as the onset velocity.

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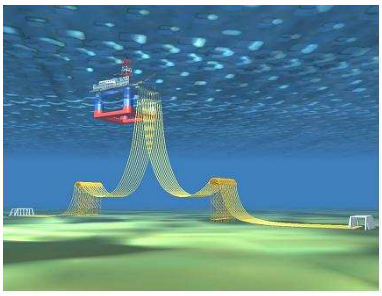
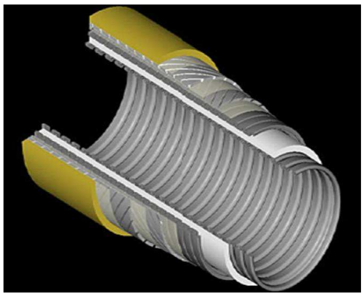


(a)



(b)

Figure 1: Flexible riser: (a) General view of offshore flexible riser system; (b) The structure of flexible riser.

Various studies have been conducted to better understand the vortex shedding and acoustics associated with flows in corrugated pipes. The shedding frequency of vortices can be characterized by the Strouhal number, defined as $S_t = f \cdot L/U$, where f is the frequency, L is characteristic length and U is characteristic velocity. Ziada et al. [33] established that the vibrations occur over a certain range of Strouhal numbers. Nakamura and Fukamachi [20] showed that the frequency of the loudest sound from a corrugated pipe is proportional to the flow velocity. In other words, the Strouhal number can be approximated as constant. Weaver and Ainsworth [32] showed that the Strouhal number is typically larger than 0.45 for the maximum vibration amplitude. This value is in agreement with the results of Gerlach [10], Bass and Holster [2] and Klaeui [17]. Furthermore, Nakamura and Fukamachi [20], and Kristiansen and Wiik [19] reported the connection between sound emitted in a tube and shear layer instability resulting from the flow over the corrugation. They suggested that the interaction between the fluid flow and the cavities is responsible for the resonance and noise. In a more generic context, Howe [14] demonstrated theoretically that shear layer-cavity interaction results in two types of resonance sources: monopole and dipole. Hémon et al. [12] presented an experimental and theoretical study of the pressure oscillations generated by the flow over a deep cavity. A review of recent advances in understanding, modeling and controlling oscillations of flow past a cavity has been given by Rowley and Williams [28].

Rockwell and Schachenmann [25] provided the first measurements of the physical behavior of an unsteady shear layer along the mouth of a circular cavity at the end of a long pipe, including both the locked-in and the non-locked-in state. They showed that during lock-in, the magnitude of the fluctuating velocity due to acoustic resonance is within the same order as that associated with the hydrodynamic fluctuations.

There is also work done specifically in modeling of the fluid flow over cavities. Debut et al. [6,7] presented a phenomenological model of the flow around a corrugation. They proposed a way to describe the feedback mechanism of the acoustics-cavity interactions. Unfortunately, this model describes the flow from the middle of the pipe like a collection of discrete sources. Tam and Block [29] derived a mathematical model of an acoustic cavity, and explored coupling of cavity tones, shear layer instability and acoustic feedback