

Experimental Study on Vortex-Induced Vibrations of Submarine Pipeline near Seabed Boundary in Ocean Currents^{*}

YANG Bing (杨兵), GAO Fu-ping (高福平)¹, WU Ying-xiang (吴应湘)
and LI Dong-hui (李东晖)

Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080, China

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ABSTRACT

Unlike most previous studies on vortex-induced vibrations of a cylinder far from a boundary, this paper focuses on the influences of close proximity of a submarine pipeline to a rigid seabed boundary upon the dynamic responses of the pipeline in ocean currents. The effects of gap-to-diameter ratio and those of the stability parameter on the amplitude and frequency responses of a pipeline are investigated experimentally with a novel hydro-elastic facility. A comparison is made between the present experimental results of the amplitude and frequency responses for the pipes with seabed boundary effects and those for wall-free cylinders given by Govardhan and Williamson (2000) and Anand (1985). The comparison shows that the close proximity of a pipeline to seabed has much influence on the vortex-induced vibrations of the pipeline. Both the width of the lock-in ranges in terms of V_r and the dimensionless amplitude ratio A_{\max}/D become larger with the decrease of the gap-to-diameter ratio e/D . Moreover, the vibration of the pipeline becomes easier to occur and its amplitude response becomes more intensive with the decrease of the stability parameter, while the pipeline frequency responses are affected slightly by the stability parameter.

Key words: submarine pipeline; vortex-induced vibrations; ocean current; seabed

1. Introduction

The submarine pipeline is a common facility widely used for offshore oil and gas transport. When a pipeline is installed on a seabed and not buried, unsupported spans may exist in some locations, especially in the uneven zones of the seabed. The span length may vary from approximately 10 to 100 times of the pipeline diameter, with a clearance between the pipeline and seabed in the range of practically nil to 2 or even 3 times the pipeline diameter (Origill *et al.*, 1992). When exposed to currents or other hydrodynamic loads, such a suspended pipeline may experience vortex-induced vibrations (VIVs), which have been widely recognized as one of the main causes for the fatigue damage to the pipeline (Shen and Zhao, 1996; Lou *et al.*, 2005). Therefore, it is necessary to analyze the dynamic responses of a pipeline in the vicinity of seabed in the ocean environments for a proper design of a submarine pipeline.

For a submarine pipeline, particularly in deep waters, currents will be the dominant ocean environmental load upon it. A cylinder in a steady current may experience vortex shedding when the

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¹ Corresponding author. E-mail: fpgao@imech.ac.cn

Reynolds number is larger than 40 approximately (Sarpkaya and Isaacson, 1981). The vortex-shedding would result in a periodic variation of the hydrodynamic forces on the cylinder. The lift force oscillates at the vortex-shedding frequency, while the drag force oscillates at twice the vortex-shedding frequency. The prediction of this type of VIVs has received wide interests from experimental researchers. Most researchers have studied either fixed cylinders or cylinders with a single degree of freedom. Numerous experimental results have shown that, when the vortex-shedding frequency brackets the natural frequency of an elastic or elastically mounted rigid cylinder, the cylinder takes control of the shedding frequency in an apparent violation of the Strouhal law. Then the vortex-shedding and pipeline oscillation collapses into a single frequency, which is well known as lock-in phenomenon (Sarpkaya and Isaacson, 1981). The widths of the lock-in range are often in terms of the reduced velocity, which is defined as:

$$V_r = \frac{U}{Df_n} \quad (1)$$

where U is the flow velocity, D is the pipeline diameter and f_n is the natural frequency of the pipeline in still fluid. Most existing experimental work is restricted to cylinders with a single degree of freedom in the cross stream direction, such as the work by Khalak *et al.* (1999), who have studied transverse oscillations of an elastically mounted rigid cylinder at very low mass and damping. A few experimental results for cylinders with two degrees of freedom indicate that, the ratio between the streamwise and cross-stream vibration frequencies is around two (Moe *et al.*, 1994; Shen *et al.*, 2000); however, the amplitudes of in-line vibration are one order less than those of cross-stream vibration (Bryndum *et al.*, 1989). For the above reasons, many researchers paid attention mainly on the cross-stream vibrations of cylinders. Nevertheless, in the aforementioned investigations, only the responses of a cylinder far from the boundary, i. e. under wall-free conditions, were taken into account.

Unlike the wall-free cylinder, the submarine pipeline in the vicinity of seabed may undergo different responses. When a pipeline comes closer to seabed in currents, it will not shed regular vortices but still vibrate, as observed by Jacobson *et al.* (1984). Despite quite a few papers dedicated to the problem of a cylinder vibrating transverse or both transverse and in-line to a fluid flow, there are very few researches on the effects of close proximity of a boundary (e. g. seabed) on the responses of a cylinder.

In this paper, a dimensional analysis is made on the vortex-induced vibrations of a pipeline in the vicinity of seabed in currents. Based on the similarity analysis, a new experimental apparatus is designed and constructed to simulate dynamic responses of a pipeline in currents. The influences of close proximity of seabed and those of stability parameters upon the responses of a pipeline are further investigated.

2. Experimental Design

2.1 Similarity Analysis

When a spanned submarine pipeline is close to a horizontal rigid seabed and exposed to a steady flow, its dynamic responses including the vibration frequency (f) and vibration amplitude (A) may be

mainly influenced by the following variables, i. e.

$$\begin{pmatrix} f \\ A \end{pmatrix} = \Phi(D, m, f_n, \xi, U, \rho, \nu, e, k_s, \dots) \quad (2)$$

where m is the mass of a pipeline per meter, ξ is the structural damping factor, ρ is the mass density of fluid, ν is the kinematic viscosity of fluid, e is the initial gap between the pipeline and seabed, and k_s is the roughness of the pipeline surface.

Based on the π -theorem, Eq. (2) can be expressed with the non-dimensional parameters as:

$$\begin{pmatrix} f/f_n \\ A/D \end{pmatrix} = \Phi(M, V_r, K, Re, e/D, k_s/D \dots) \quad (3)$$

in which, f/f_n and A/D are the frequency and amplitude ratios, respectively; M is the mass ratio and

$$M = \frac{m}{\pi D^2/4} \quad (4)$$

K is the stability parameter, i. e. the combined mass-damping parameter, which is defined as:

$$K = \left(\frac{m + m_a}{\pi D^2/4} \right) \xi \quad (5)$$

where m_a is the added mass and $m_a = C_A m_d$, m_d being the displaced fluid mass per meter and C_A being the potential added-mass coefficient. $C_A = 1.0$ and $m_d = \pi D^2/4$ for a cylinder (e. g. a pipeline) (Govardhan and Williamson, 2000); Re is the Reynolds number, which is defined as:

$$Re = \frac{UD}{\nu} \quad (6)$$

e/D is the ratio of the gap between the pipe and boundary to the pipeline diameter; k_s/D is the relative roughness of the pipeline.

2.2 Experimental Setup

A hydro-elastic facility was constructed for the present experimental investigation, which is in conjunction with a water flow channel, as depicted in Fig. 1.

The water flow channel is 0.5 m wide, 19 m long and 0.6 m high, capable of generating steady currents with velocity up to approximately 0.4 m/s. The test pipe is attached to the supporting frame by two connecting poles, two sliding poles and some sets of springs. The sliding poles may move along the four runners, which are connected to the two localizers by four bearings. The structural damping factor can be varied by means of adjusting the contact conditions between the localizers and the sliding poles. A laser displacement transducer is employed for the non-contact measurement of the vertical displacements of the pipeline (see Fig. 1). The vortex shedding from the test pipe is visualized by flow field visualization technique with hydrogen bubbles. In this study, the smooth pipes ($k_s/D \approx 0$) are considered. The test pipe is 0.04 m in diameter and 0.47 m in length, and the water depth is 0.4 m. Since one of the principal interests of this study is to examine the effects of the proximity of a pipeline to seabed upon the dynamic responses of the pipeline, the gap between the test pipe and the bottom of flow channel is designed to be varied easily by adjusting the height of the supporting frame with two

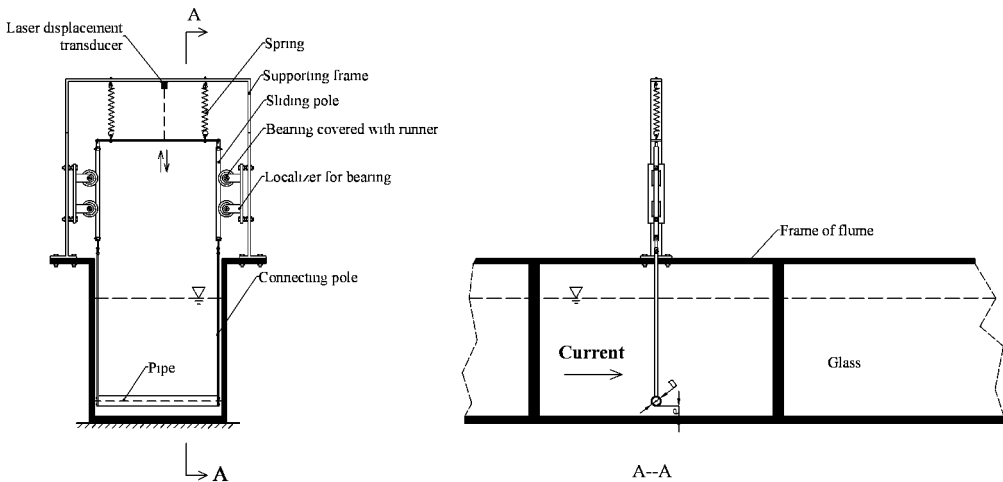


Fig. 1. Schematic diagram of experimental apparatus.

vertical slotted portions on it.

3. Experimental Results and Discussions

3.1 Effect of Close Proximity of A Rigid Seabed

As aforementioned, only rigid seabed is taken into account, i. e. the seabed scour is not involved in this study.

Typical time traces of the displacement of a pipe with large e/D (e. g. $e/D = 1.45$) are shown in Fig. 2. The pipeline displacements are almost symmetrical at various flow velocities. Flow field visualization shows that the vortices around the pipeline are influenced slightly by the boundary for the case of $e/D = 1.45$ (see Fig. 3 (a)).

Fig. 4(a) ~ (d) shows the time traces of the displacement of the pipeline in the vicinity of the rigid seabed ($e/D = 0.28$) at various velocities of steady current. Unlike the displacement responses of the pipe with large e/D , the displacements of the pipe close to seabed are asymmetrical, as shown in Fig. 4. The periodical collisions between the test pipe and the rigid boundary were observed for some flow velocities (see Fig. 4(a) ~ (c)). The flow field visualization with hydrogen bubbles indicates that the wake vortices are becoming much more irregular with the decrease of the gap between the pipe and boundary, as illustrated in Fig. 3. Even though regular vortex shedding does not take place when the pipe is laid closer to the boundary, the vibration of the pipe still occurs.

In these series of tests, the mass of the test pipeline is 1.363 kg. According to Equation (4), the mass ratio can be calculated, $M = 2.31$. The natural frequency of the pipeline in water $f_n (= 1.24 \text{ Hz})$ is obtained through analysis of the displacement response of the test pipe, which is given an initial displacement and then unclined. Meanwhile, the structural damping factor $\xi (= 0.067)$ is obtained through analysis of the displacement records. The effects of structural damping factor will be discussed in Section 3.2.

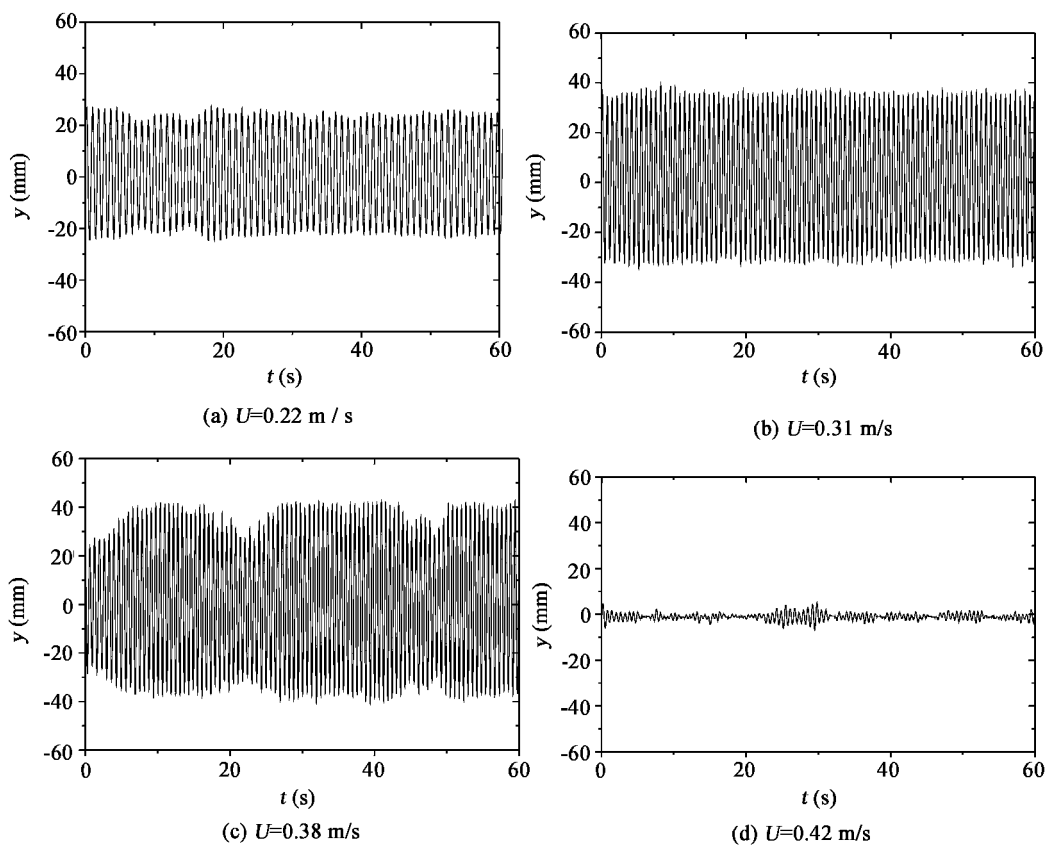


Fig. 2. Typical time traces of the displacement of large gap-to-diameter ratio $e/D = 1.45$ at various velocities of steady current ($M = 2.31$, $\xi = 0.067$).

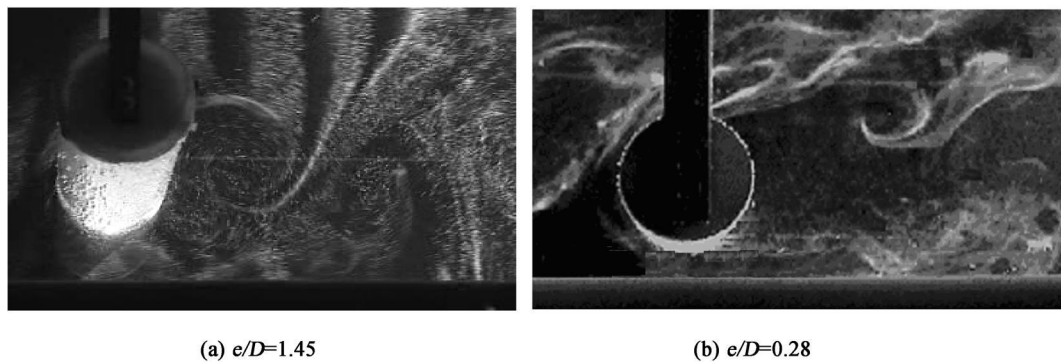


Fig. 3. Vortex shedding from test pipe at various e/D ($Re \approx 1.2 \times 10^3$).

In offshore engineering, the most common interests in dynamic responses of a pipeline include its amplitude responses and frequency responses. As submarine pipelines are always installed in the vicin-

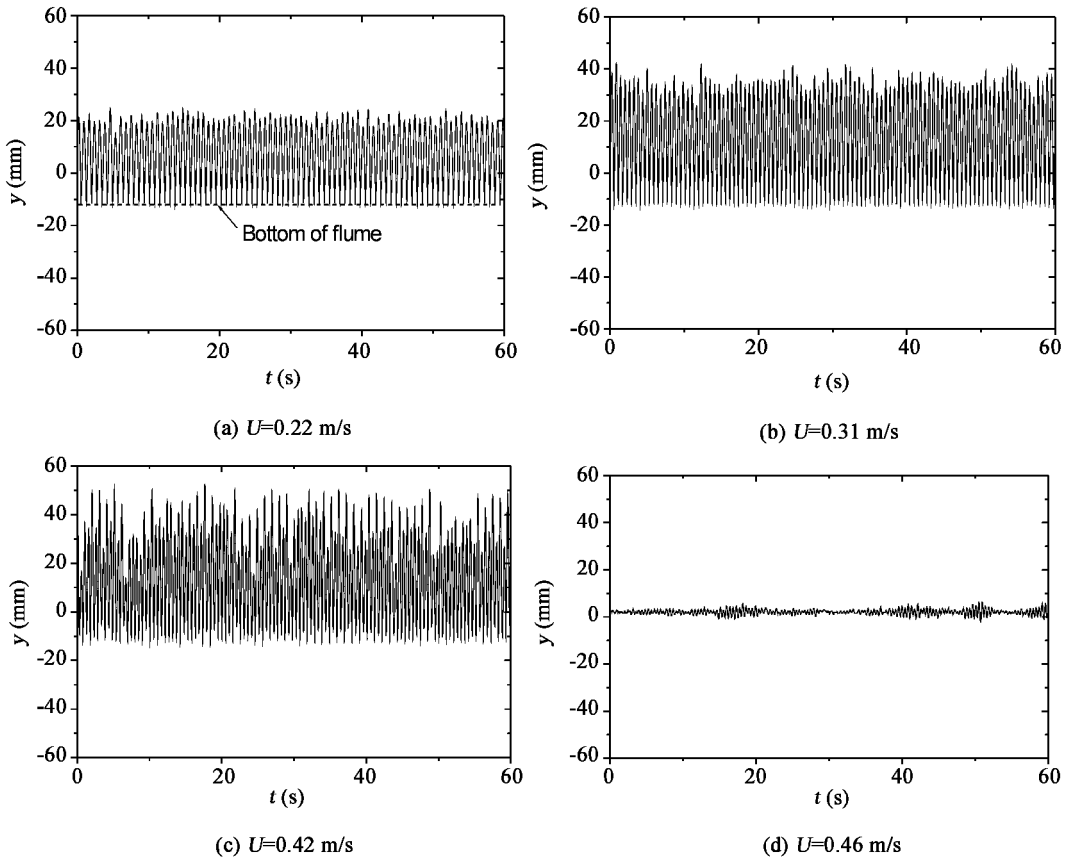


Fig. 4. Typical time traces of the displacement of the pipeline in the vicinity of seabed with $e/D = 0.28$ at various velocities of steady current ($M = 2.31$; $\xi = 0.067$).

ity of seabed, the influences of gap-to-diameter ratio (e/D) need well understanding.

For the investigation of the effects of gap ratio upon pipeline responses, three values of e/D are chosen, i. e. $e/D = 1.45$, 0.28 and 0.10 . Based on the recorded displacement data of the test pipeline at the corresponding velocities of the current, as depicted in Figs. 2 and 4, the dimensionless amplitude ratios (A_{\max}/D) and frequency ratios (f/f_n) can be obtained, A_{\max} being the maximum value of pipe vibration amplitude. Fig. 5 shows the amplitude and frequency responses of the pipeline for various values of e/D . Some experimental data by Govardhan and Williamson (2000) and those by Anand (1985) are also shown in the figure. In the experiments by Anand (1985), $M = 5.3$, and in those by Govardhan and Williamson (2000), $M = 10.3$ and $\xi \approx 0.001$. It is noted that in the experiments by Govardhan and Williamson (2000) and those by Anand (1985), the test pipes are wall-free ones, i. e. the boundary effects are negligible.

It can be seen from Fig. 5 that, for the case of $e/D = 1.45$, the dimensionless amplitude ratios (A_{\max}/D) are comparable with those for the wall-free cases in Govardhan and Williamson (2000) and Anand (1985). Their frequency ratios (f/f_n) are all higher than 1.0 in the lock-in regions. Unlike

in the cases of wall-free pipes, for the pipes in the vicinity of seabed boundary, e.g. $e/D = 0.28$, 0.10, both the width of the lock-in ranges in terms of V_r and the dimensionless amplitude ratios A_{\max}/D increase with the decrease of e/D . It is shown that larger vibration amplitudes need larger values of V_r for unlocking the vibration frequency from the vortex shedding frequency. That is, larger vibration amplitudes may require larger V_r to unlock from the vibration frequency, so as to restore the Strouhal frequency. With the increase of V_r , the variation of f/f_n with V_r comes closer to the Strouhal law, as shown in Fig. 5(b), which indicates that the vortex shedding frequency will control the vibration frequency.

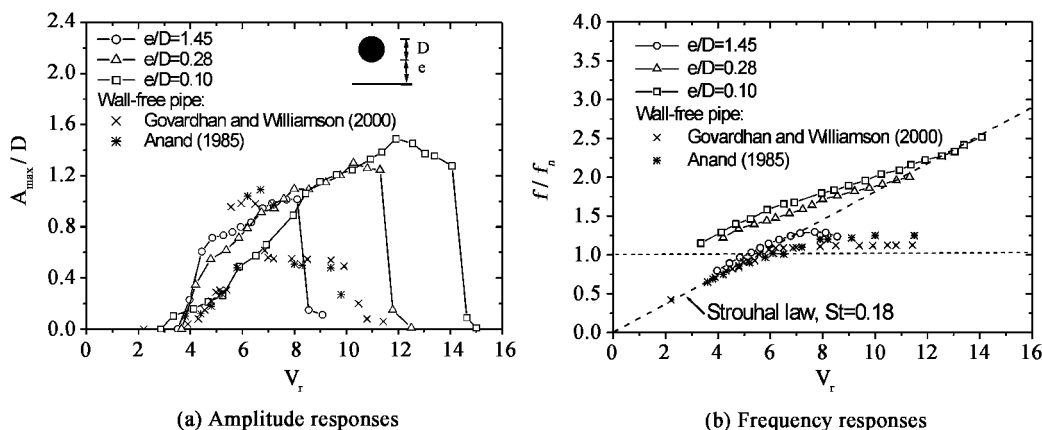


Fig. 5. Responses of pipeline for various values of e/D .

3.2 Effect of the Stability Parameter

As described in the section of similarity analysis, i. e. section 2.1 the dynamic response of a pipeline will also be relative with the stability parameter K , which is a combined mass-damping parameter defined by Eq. (5). In this section, the influence of K on the pipeline responses will be further investigated.

In the following two series of experiments, the damping ratios are chosen to be $\xi = 0.037$, 0.016, respectively, and the mass ratio $M = 3.87$. Thus, the corresponding values of $K = 0.180$, 0.078 respectively. Fig. 6 shows the amplitude and frequency responses of the pipe with $e/D = 0.66$ for various values of the stability parameter. At a lower value of K , the lock-in range in terms of V_r becomes wider, and the dimensionless amplitude ratio A_{\max}/D becomes larger, as shown in Fig. 6 (a). This indicates that, with the decrease of the stability parameter, the vibration of the pipeline becomes easier to occur and its amplitude response becomes more intensive. However, the pipeline frequency responses are affected slightly by the stability parameter, as shown in Fig. 6(b).

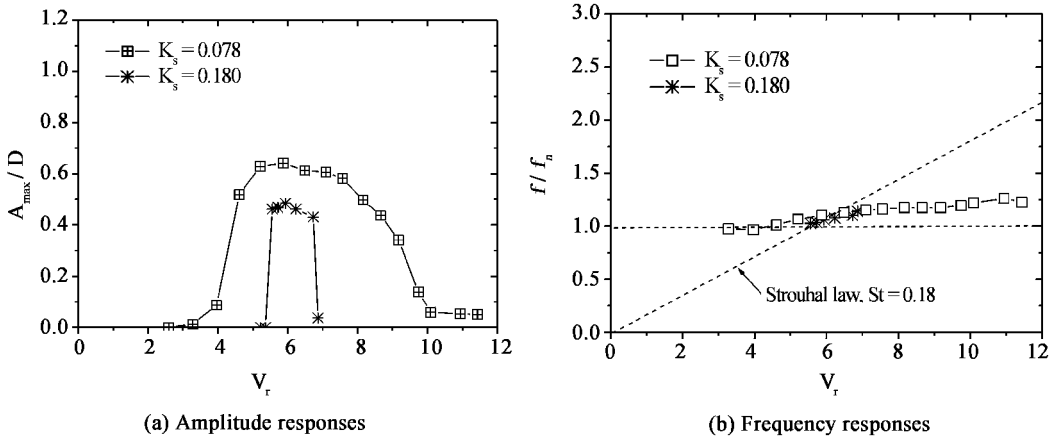


Fig. 6. Responses of pipeline for various values of stability parameter.

4. Concluding Remarks

For the investigation of the influence of close proximity of a submarine pipeline to seabed on the vortex induced vibrations of the pipeline, a similarity analysis is made on the vibration of a pipeline in a current, and on this basis, a new experimental apparatus is designed. The effects of the gap-to-diameter ratio and those of the stability parameter on the amplitude and frequency responses are investigated respectively. A comparison is also made between the present experimental results of the amplitude and frequency responses for the pipes in the vicinity of seabed boundary and those for wall-free pipes given by Govardhan and Williamson (2000) and Anand (1985). The following conclusions can be drawn:

(1) The close proximity of a pipeline to seabed has much influence on vortex shedding and vortex induced vibrations of the pipeline. The flow field visualization with hydrogen bubbles indicates that the wake vortices become much more irregular with the decrease of the gap between the pipe and boundary. With the decrease of the gap-to-diameter ratio, both the width of the lock-in range in terms of V_r and the dimensionless amplitude ratio A_{\max}/D increase.

(2) For the vortex induced vibrations of the pipes close to the seabed boundary, the dimensionless frequencies f/f_n are larger than those obtained according to the Strouhal law. When the reduced velocity V_r increases, the variation of f/f_n with V_r comes closer to the Strouhal law, indicating that the vortex shedding frequency will take control of the vibration frequency at high values of V_r .

(3) Moreover, the stability parameter also affects the vortex induced vibration of a pipe. With the decrease of the stability parameter, the vibration of a pipeline becomes easier to occur and its amplitude response becomes more intensive. Nevertheless, the pipeline frequency responses are affected slightly by the stability parameter.

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