

The Effect of Functional Loads on Spanning Pipeline VIV Response

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Abstract

During the operation and installation of offshore pipelines high axial force and pressure are included; their effects could not be neglected. In the article, the effect of internal flow velocity and functional loads on VIV response is investigated. On the basis of Hamilton principle, a differential equation is derived to describe the motion of pinned-pinned tensioned spanning pipeline conveying fluid. The VIV response is calculated according to DNV-RP-F105 under different functional loads. The research may provide a reference for the sensitivity study of functional loads on the allowable free spanning lengths.

Keywords: free spanning pipeline, VIV, functional load, internal flow.

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Introduction

The oil and gas industry moves towards harsher and harsher environments often characterized by uneven seabed and deep water. Amplified responses due to resonance between the vortex shedding frequency and natural frequency of the free span may cause fatigue damage. Traditionally, VIV of spanning pipelines is not allowed to occur at any time during the design life of a pipeline system. In recent years VIV has been allowed in a less stringent approach as long as the allowable fatigue damage is not exceeded.

Free spans often become a challenge in pipeline design and operation due to pipeline installation on uneven seabed or seabed scouring effects. The costs related to seabed correction and span intervention are considerable in many projects. Therefore it is relevant to investigate whether such intervention work is necessary or not. The vortex shedding frequency caused by a flow normal to a free span is governed by the Strouhal's number, the pipe outer diameter and the flow velocity. And the natural frequency of the spanning pipeline is a function of the pipe stiffness, end

conditions, length and effective mass. As the flow velocity increases and thereby the shedding frequency reaches one of the natural frequencies of the span, the span starts to vibrate and the vortex shedding along the span gets correlated by the vibration of the span. The vortex shedding frequency and the VIV get locked-in with the natural frequencies of the span over a certain range of flow velocities. Consequently in this way the natural frequencies of span govern onset of VIV.

There are many investigations about the effect parameters of VIV response, especially for axial force. For example, H.S. Choi (2001) and Tao Xu et al. (1999) presented that the natural frequencies significantly change with respect to the axial load, if the axial force is high, the corresponding change of the natural frequency will be considerable. The pipeline structure is traditionally modeled as a beam-column-like structure, while the influences of internal fluid are just taking its weight into account. The researches of pipeline conveying fluid are mainly focus on the stability of pipe with high internal fluid, such as PAMILA A, LAUKKANEN (1991), etc.

In the present study, the aim was to identify the effect of functional loads on spanning pipeline VIV response, including internal flow. A differential equation of tensioned pipes conveying fluid with constant velocity is derived to describe the transverse motion on the basis of Hamilton principle. The significant influences of the functional load parameters on free vibrations are illustrated first. The computational algorithms are familiarized with Housner (1952) in Blevins' book (1990).

Because of the investigation emphasizing on conveying fluid and efficient tension, we apply the DNV-RP-F105 VIV response models for VIV response calculations. And the influences on cross-flow VIV response amplitude and the dominating vibration frequency are studied under different functional loads.

1 Model of tensioned pipeline conveying fluid

Ascribed to the Euler-Bernoulli hypothesis employed in this study, the plane sections normal to centroidal axis remain plane and are normal to deformed centroidal axis. The structural damping and the effect of shear deformation is negligible, and a small angle approximation assumption ($\sin \theta \approx \tan \theta$ and $\cos \theta \approx 1$) is applied. Fig.1 shows a

flexible pipeline under effective axial force, possessing non-negligible bending stiffness EI , and inside flow velocity v .

The strain energy of pipes, which consists of the strain energy due to axial deformation and strain energy due to bending, is given by

$$U = \frac{1}{2} \int_0^L EI (\dot{y})^2 dx - \frac{1}{2} \int_0^L T_e (\dot{y})^2 dx \quad (1)$$

where $(\dot{})$ represents the derivative respect to x , and T_e is the effective axial force.

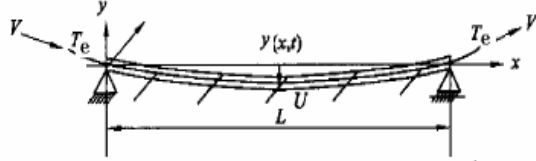


Figure 1: spanning pipeline model

All kinetic energy terms are caused by the pipe movement, and by the motion of the internal fluid flow relatively to the displacements. The kinetic energy of pipe consists of the kinetic energy due to pipe motion and internal fluid motion as follows:

$$K = \frac{1}{2} \int_0^L m_i [v^2 + (\dot{y} + vy)^2] dx + \frac{1}{2} \int_0^L m_p \dot{y}^2 dx \quad (2)$$

The first term is the elastic potential energy of the pipe due to elongation, the second term is due to the tensile force, $(\dot{})$ represents the derivative with respect to time t , m_i and m_p are the masses of internal flow and pipeline, respectively.

The virtual work is zero for free vibration, i.e.

$$\delta W = 0 \quad (3)$$

The Hamilton's principle is

$$\delta \int_{t_1}^{t_2} (K - U) dt + \int_{t_1}^{t_2} \delta W dt = 0 \quad (4)$$

Substituting Equations (1) (2) and (3) into Equation (4), and applying Hamilton's principle, the equations of motion for the transverse vibration and the pinned end boundary conditions are derived:

$$\begin{cases} EI y'''' - (m_i v^2 + T_e) y'' + 2m_i v \dot{y}' + (m_i + m_p) \ddot{y} = 0 \\ y(0, t) = y(L, t) = 0 \\ y''(0, t) = y''(L, t) = 0 \end{cases} \quad (5)$$

The resolution of this equation can express as a summation of symmetrical and anti-symmetrical spatial vibration modes in the form of sinusoidal functions as:

$$y_j(x, t) = \sum_{n=1,3,5,\dots} a_n \frac{\sin n\pi x}{L} \sin \omega_j t +$$

$$\sum_{n=2,4,6,\dots} a_n \frac{\sin n\pi x}{L} \cos \omega_j t \quad (6)$$

Substituting Equations (6) into Equation (5) and considering the transform of Fourier series i.e.

$$\cos \frac{n\pi x}{L} = \sum_{r=1,2,3,\dots} \frac{1 - (-1)^{n+r}}{\pi(r^2 - n^2)} \frac{\sin r\pi x}{L} \quad (7)$$

We can obtain the coefficients of $\sin(\omega_j t)$ and $\cos(\omega_j t)$.

According to the algorithms same as Housner (1952) and written in terms of matrix, the natural frequency equation for pinned-pinned tensioned pipe conveying fluid can be obtained from

$$\{[K] + \omega_j [B] - \omega_j^2 m\} \{a\} = 0 \quad (8)$$

Where the elements of matrixes are:

$$K_{rs} = \begin{cases} EI \left(\frac{r\pi}{L} \right)^4 - (m_i v^2 - T_e) \left(\frac{r\pi}{L} \right)^2 & r = s \\ 0 & r \neq s \end{cases} \quad (9)$$

$$B_{rs} = \begin{cases} \frac{-8m_i v}{L} \frac{rs}{s^2 - r^2} & r = 1, 3, 5 \dots \& s = 2, 4, 6 \dots \\ \frac{8m_i v}{L} \frac{rs}{s^2 - r^2} & s = 1, 3, 5 \dots \& r = 2, 4, 6 \dots \end{cases}$$

$$\{a\} = \{a_1, a_2, \dots, a_n\}^T \quad (10)$$

For the in-air natural frequency the mass is $m_i + m_p$, and for the still-water natural frequency it is

$$m = m_i + m_p + m_a \quad (11)$$

which m_a is the added mass.

2 Functional loads of free spans

During installation, the pipeline may have residual tension due to the lay-barge method. During operation, the pipeline may have operational load due to the operational pressure and temperature. The functional loads of spanning pipelines which shall be considered are:

- weight of the pipe and internal fluid
- external and internal fluid pressure
- thermal expansion and contraction
- Residual installation forces.

As Equation (8) is shown, the natural frequencies are a function of the pipe stiffness, length and effective mass. The stiffness of the pipeline consists of material stiffness and geometrical stiffness. The geometrical stiffness is governed by the effective axial force. This force is equal to the true steel wall axial force with corrections for the effect of external and internal pressures as

$$T_e = N_e + P_e A_e - P_i A_i$$

$$N_e = H_e - \Delta P_i A_i (1 - 2\mu) - A_s E \Delta T \alpha_e \quad (12)$$

where H_e is effective lay tension; P_i and P_e are internal and external pressures, ΔP_i is internal pressure difference relative to laying, A_s is the cross-section area of pipelines; A_i and A_e are the internal and external cross-section areas of the steel pipe, respectively; ΔT is the temperature difference relative to laying, α_e is the temperature expansion coefficient and μ is the Poisson's ratio.

3 VIV response analysis procedure

For the sake of simplification in this study, after the natural frequencies for pinned-pinned tensioned pipe conveying fluid are acquired from the above motion equation, we calculate the influences on cross-flow VIV response amplitude and the dominating vibration frequency under different functional loads according to DNV guideline RP-F105.

DNV-RP-F105 uses a so-called Response Models approach to predict the vibration amplitudes due to vortex shedding. These response models are empirical relations between the reduced velocity defined in terms of the still-water natural frequency and the non-dimensional response amplitude. Response model shown as Fig.2, is measured in the physical or numerical tests, and have been reviewed by Nielsen, F.G. et al (2002) Fyrileiv, O. et al. (2004), Mørk, K.J. et al (2003), etc.

The cross-flow response frequency is obtained based on the updated added mass coefficient (C_a , CF-RES) due to cross-flow response using the following equation:

$$f_v = f_{n,CF} \sqrt{\frac{(\rho_s / \rho) + C_a}{(\rho_s / \rho) + C_{a,CF-RES}}} \quad (13)$$

Where $f_{n,CF}$ is the n -order frequency in the still water with added mass C_a (defined as 1.0), A_y / D is the normalized cross-flow VIV amplitude, V_R represents reduced velocity and f_v is dominating vibration frequency.

ρ and ρ_s is density of water and pipes. And added mass coefficient is a function of reduced velocity $V_R = U / f_n D$, see Fig.3. f_n is the n -order frequency in the air.

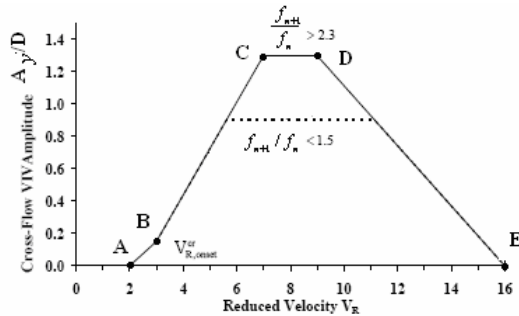


Figure 2: Cross-flow VIV response model in RP-105

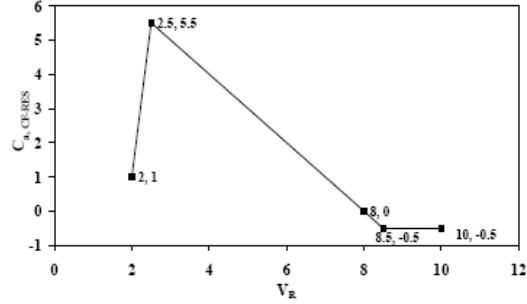


Figure 3: Added mass coefficient (C_a , CF-RES) model

Typical steps required for VIV analysis in a deterministic method are outlined below:

1. Determine natural frequency. For the real case, a finite element method needs to be applied.
2. Estimate a frequency distribution of velocity.
3. For each level of current velocity, determine the response amplitude

4 Case studies

The spanning pipeline will be a single pipe whose cross section is shown as Fig.4. Carrier pipe is a steel pipe with coating. It may have concrete coating outside of 3PE coating. The pipe data for the pipeline is given in Tab.1.

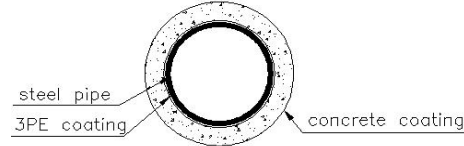


Figure 4: Single Pipe Cross Section Configuration

Outside Diameter of Steel Pipe	mm	220.0
Nominal Wall Thickness	mm	10.0
Steel Grade	API 5L X65	
Anti-corrosion Coating Thickness	mm	2.0
Anti-corrosion Coating Density	kg/m ³	960
Concrete Coating Thickness	mm	40
Concrete Coating Density	kg/m ³	2540
Young modulus	Pa	2.06e+11
Inner flow density	kg/m ³	908.2
the inertia coefficient		1.0
Outer current velocity U	m/s	0.8
Pipeline length	m	20.0

Table 1: Pipeline parameters.

In this section, the numerical examples will be given for the vibrations of tensioned pipes conveying fluid. In Fig.5, the first natural frequencies are plotted depending on a constant internal velocity v and $T_e = 10\text{kN}$, and Fig.6 is shown the first frequencies versus efficient tension at

$v=5\text{m/s}$. A three dimension graph is shown in Fig.7 as the first frequency is a function of the effective tension and internal flow velocity.

The results show that the natural frequencies of spanning pipeline increase with the internal flow speed or compression decrease, and increasing tension will lead to enlarge the frequency. The transported fluid becomes more significant on pipelines with high tension than those with low tension.

After natural frequency is determined, the VIV response is calculated according to basic cross-flow response model in DNV-RP-F105 under different functional loads. Firstly, VIV response amplitude and the dominating vibration frequency are calculated at constant internal flow velocity $v=3\text{m/s}$, while applying a series of T_e . Then the tension is fixed at 10kN , the effect is studied with internal flow velocity varying from 2m/s to 10m/s .

T_e (kN)	$f_{n=1}$ (Hz)	$f_{n=1,CF}$ (Hz)	A_y/D	f_v (Hz)
1.00	0.789	0.726	0.400	0.622
10.0	0.825	0.759	0.352	0.646
15.0	0.844	0.777	0.327	0.658
20.0	0.863	0.794	0.305	0.671
30.0	0.899	0.828	0.264	0.696
50.0	0.968	0.891	0.194	0.741
60.0	1.001	0.921	0.165	0.763
70.0	1.032	0.950	0.144	0.784
100.0	1.122	1.032	0.108	0.844

Table 2: VIV response applying a series of T_e and constant $v=3\text{m/s}$

v (m/s)	$f_{n=1}$ (Hz)	$f_{n=1,CF}$ (Hz)	A_y/D	f_v (Hz)
2.0	0.8373	0.7706	0.3359	0.6542
3.0	0.8367	0.7700	0.3367	0.6538
4.0	0.8358	0.7692	0.3378	0.6532
5.0	0.8346	0.7681	0.3393	0.6524
6.0	0.8332	0.7668	0.3411	0.6515
7.0	0.8315	0.7653	0.3432	0.6504
8.0	0.8296	0.7635	0.3457	0.6491
9.0	0.8274	0.7615	0.3485	0.6477
10.0	0.8249	0.7592	0.3517	0.6461

Table 3: VIV response applying a series of v and constant $T_e=10\text{kN}$

The key results are show in Table 2 and Table 3, and Figs.7~9 present the tendency of response amplitudes at a series of tension and transported fluid velocity. The results

show that the VIV response is influenced by the structural natural frequencies changing with functional loads.

Because V_R falls in line BC in Fig.2, dominating vibration frequency decrease and amplitude increase while increasing T_e , and the reverse tendency is acquired when increasing transported fluid velocity v . It should be noted that the normalized cross-flow VIV amplitude and dominating vibration frequency presented in Tab.3 change only 4.7% and 1.3% from $v=2\text{m/s}$ to $v=10\text{m/s}$, respectively. However, there is obvious change with different axial force.

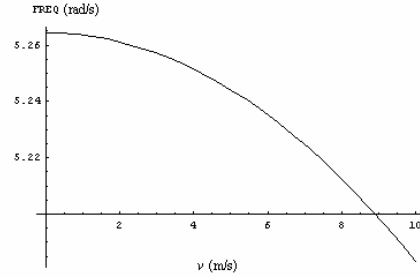


Figure 5: Natural frequencies of first mode versus v under $T_e=10\text{kN}$

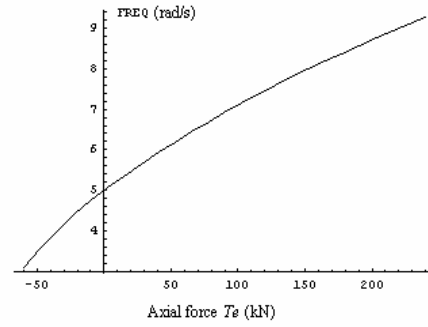


Figure 6: Natural frequencies of first mode versus T_e under $v=5\text{ m/s}$

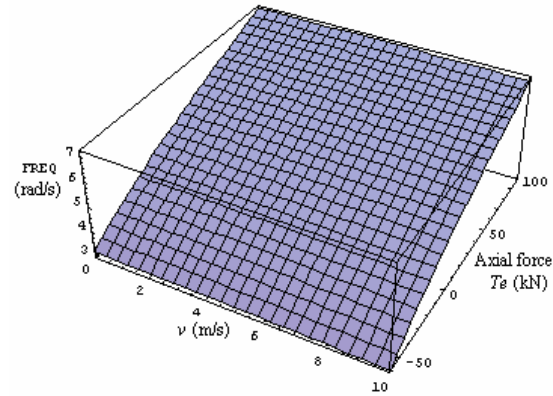


Figure 7: 3D graph of the first frequencies as a function of T_e and v

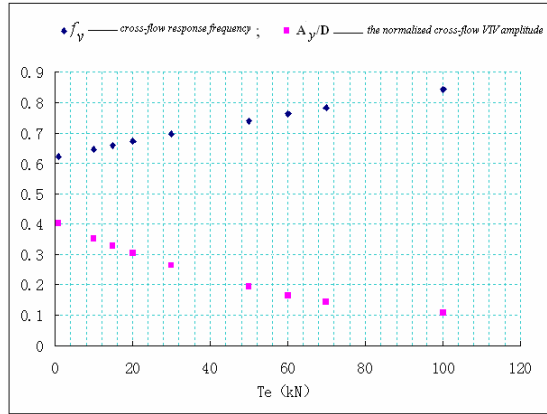


Figure 8: VIV response amplitudes and dominating vibration frequencies via T_e with constant internal flow velocity $v=3\text{m/s}$

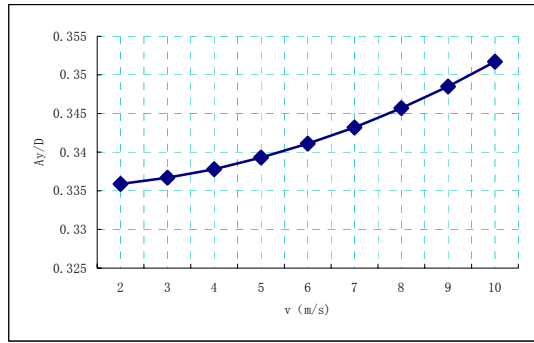


Figure 9: VIV response amplitudes via internal flow velocity v for constant $T_e=10\text{kN}$

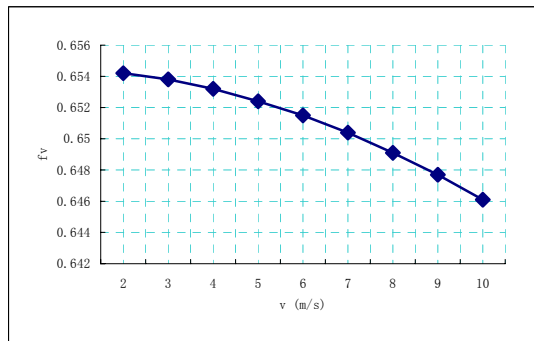


Figure 10: VIV dominating vibration frequencies via internal flow velocity v for constant $T_e=10\text{kN}$

5 Conclusions

In the present study, a differential equation of tensioned pipes conveying fluid with constant velocity is derived to describe the transverse motion on the basis of Hamilton principle. The significant influences of the functional load parameters on free vibrations are illustrated first. Then

using the terms of effective axial force, the influence of functional loads on spanning pipeline VIV response is studied according to DNV-RP-105. The results show that natural frequencies of spanning pipeline increase with the internal flow speed or compression decrease, and an increment in the tension also can lead to larger frequencies. And the transported fluid reveals more significance on the high extensible pipelines than the low extensible ones. The response calculations must account for the functional loads i.e. the effective axial force. Internal flow velocity is less important than other factors for VIV response, because the speed in reality is not high enough.

The research may provide a reference for the sensitivity study of functional loads (tension and compression force, internal flow velocity, and pressure) on the allowable free spanning lengths, and further provide some useful information for submarine pipeline design.

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