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최신 DnV 규정에 의한 해저 파이프라인의 자유 경간 해석

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Developments of Free Span Analysis of Offshore Pipelines by New DnV Code

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ABSTRACT: *Two different methods of free span analysis of offshore pipelines by DnV codes were introduced and compared in order to calculate the allowable free span lengths of the offshore pipelines. The allowable span lengths of the offshore pipelines for installation, hydrotest and operation conditions by static and dynamic span analysis were determined. Static analysis was performed by ASME codes and dynamic span analysis was performed by both 1981 DnV code and 1998 DnV code. Comparison of two codes were carried out. A new design procedure to calculate the allowable span lengths was developed with new DnV code.*

1. INTRODUCTION

In general, when a fluid flows across the unsupported portion of pipeline, the flow separates, vortices are shed, and periodic wakes are formed. Each time a vortex is shed, it alters the local pressure distribution and the pipeline experiences a time-varying force at the frequency of vortex shedding. The pipeline will oscillate at a frequency of vortex shedding. The vortex shedding frequency is suddenly approach to the natural frequency of the pipeline and this phenomena is called a lock-in. Then the oscillation will result fatigue damages on the pipeline and can eventually lead to catastrophic failure. Symmetrical vortices are shed when the flow velocity is low. The pipe will start to oscillate in-line with the flow direction. As the flow velocity increases further, the cross-flow oscillation begins to occur due to the asymmetric vortex shedding.

Two different DnV codes were utilized in order to analyse the allowable free span length, they are DnV code "Rules for Submarine Pipeline System" (DnV 1981) and DnV code Guideline #14, "Free Spanning Pipelines" (DnV 1998). The free span analysis is typically involved static and dynamic analyses.
For static analysis, it was performed by ASME B31.4 (ASME, 1998) and ASME B31.8 (ASME, 1999) for installation, hydrotest, operation conditions. For dynamic analysis, it was performed for in-line and cross-flow motions and it was also applied under three conditions, installation, hydrotest and operation conditions. But the most notable difference between DnV 1981 and DnV 1998 is simply whether fatigue analysis is involved or not. Additionally, more factors, such as partial safety factors related to stability parameter, natural frequency and stress range, axial load and deflection load etc. are also considered. Therefore, it can be summarized that DnV 1998 is such an improvement of DnV 1981 and also provided more reliable and reasonable design procedures.

2. STATIC ANALYSIS

The allowable span length for static analysis of the pipeline can be determined according to ASME B31.4 (ASME, 1998) and ASME B31.8, (ASME, 1999).

- Installation : empty pipe subject to a 1-year return period significant wave and associated current loading
- Hydrotest : flooded pipe with hydrotest pressure subject to a 1-year return period significant wave and associated current loading
- Operation : operated pipe with the product subject to a 100-year return period significant wave and associated current loading

<u>Design Criteria</u>

Combined Von Mises Stress	= 0.9 SMYS
Longitudinal Stress	= 0.8 SMYS

where SMYS is specific minimum yield strength of the pipelines.

From the equation for Von Mises combined stress, the allowable longitudinal stress can be calculated by following formula :

$$\sigma_L^2 - \sigma_L \times \sigma_h + \sigma_h^2 = (0.9 \times SMYS)^2 \quad (1)$$

σ_h = Pipe hoop stress due to external hydrostatic head (compressive)

The longitudinal stress, σ_L , is given by :

$$\sigma_L = \frac{P_i A_i}{A_s} - \frac{P_e A_e}{A_s} + \frac{T_r}{A_s} \pm \frac{MD}{2I} \quad \text{for unrestrained pipe} \quad (2)$$

$$\sigma_L = -\frac{(P_i - P_e) A_i}{A_s}(1-2\nu) - Ea\Delta T + \frac{T_r}{A_s} \pm \frac{MD}{2I} \quad \text{for restrained pipe} \quad (3)$$

where P_i = Pipe internal pressure

P_e = Pipe external pressure

A_i = Pipe sectional area of flow

A_e = Pipe sectional area with OD

T_r = Residual tension in pipeline

A_s = Steel cross sectional area

ν = Poission ratio of pipe steel

E = Modulus of elasticity of pipe steel

α = Coefficient of thermal expansion

ΔT = Temperature difference

Ws = Submerged weight of pipe

F_h = Hydrodynamic force per unit length on span

D = Pipe OD

I = Moment of inertia of pipe section

and the bending moment in the pipeline is :

$$M = (Ws^2 + Fh^2)^{0.5} L^2/8 \quad (4)$$

From the above equations for the moment, the allowable static span length, L, can be determined by satisfying both the combined stress criteria and the longitudinal stress criteria. Sample calculated values are shown in Table 1.

3. DYNAMIC ANALYSIS BY DnV CODE 1981

The determination of the allowable span length is based on the avoidance of the vortex-induced vibration (VIV). Hence, to calculate the allowable span lengths which is to prevent VIV, first of all, criteria set out in DnV "Rules for Submarine Pipeline Systems" (DnV 1981), Section 2.2 were used to obtain the maximum allowable span length due to the vortex-induced vibration.

Design Criteria

Onset of In-line VIV

Onset of Cross-flow VIV

Parameters of VIV

The natural frequency, f_N , of pipe span under zero tension is calculated by

$$f_N = (C_f / L^2) \times (EI / m_e)^{0.5} \quad (5)$$

where C_f = Constant depending on span end conditions

m_e = Effective mass of pipeline

L = Span length

The end condition of the span is considered to be fixed-pinned. Two parameters control the vortex-induced vibration : reduced velocity, V_R, and stability parameter K_S. The reduced velocity determines whether the vibration occurs or not, while the stability parameter determines the magnitude of the amplitude of the vibration.

- Reduced Velocity, V_R

The reduced velocity is a non-dimensional parameter that determines the velocity range for which the vortex shedding will occur. It is defined as

$$V_R = V / (D_c \times f_N) \quad (6)$$

V = Current speed normal to the pipe axis

D_C = Outside diameter of pipe including coatings

The reduced velocity for onset of cross-flow motion depends on Reynolds number and for the onset of in-line motion depends on stability parameter. The reduced velocity can be obtained from the figure in DnV 1981.

- Stability Parameter, Ks

The stability parameter is controlling the motions. It is defined as

$$K_S = 2 Me\,\delta / (\rho\, D_C^2) \quad (7)$$

Me = Effective mass per unit length of the pipe

δ = Logarithmic decrement of structural damping

ρ = Mass density of surrounding water

Once the stability parameter is calculated, the amplitude of the vibration can be estimated from the figures in DnV 1981.

Allowable Span Lengths due to Dynamic Loading

Substituting for reduced velocity into the natural frequency equation, the allowable span length, La , to prevent VIV is given by

$$L_a = \sqrt{\frac{V_R \cdot C_f \cdot D_C \cdot \sqrt{\frac{E \cdot I_s}{m_d}}}{V}} \tag{8}$$

Both the allowable span length due to in-line and cross-flow can be obtained using different V_r and m_e conditions. The results obtained by sample calculation is presented in Table 2.

4. DYNAMIC ANALYSIS BY DnV CODE 1998

Criteria set out in DnV Guidelines #14, "Free Spanning Pipelines" (DnV 1998) are to be used to obtain the allowable span length due to the vortex-induced vibration.

Design Criteria

Fatigue due to in-line VIV

Onset of cross-flow VIV

Natural Frequency of Span under Axial Tension and Deflection Load

DnV 98 guideline uses more realistic equation for the natural frequency calculation. The natural frequency, fo , of span under axial tension and deflection load is calculated

$$f_o = C_f \left[\frac{EI}{m_1 L_e^4} \left[1 + C_2 \frac{S_{eff}}{\pi^2 \frac{EI}{L_e^2}} + C_3 \left[\frac{Q_h L_e}{\left(\pi^2 \frac{EI}{L_e^2} + C_2 S_{eff} \right)} \frac{L_e}{D_C} \right]^2 \right] \right]^{1/2} \tag{9}$$

where L_e = Effective span length (DnV98, sec. 3.7.4)

S_{eff} = Effective axial force (DnV98, sec. 3.4.3)

Q = Deflection load per unit length (submerged weight for cross-flow or static current loading for in-line)

The equation (9) is an approximate solution based on the Multi span Projects 1997 (Mork and Verley, 1997). The exact solution of the span under axial tension can be found in resent work (Choi, 2001).

The reduced velocity for the onset of in-line VIV can be obtained from DnV Guideline #14, Fig. 8-1 or Para 8.2.6. The reduced velocity for the cross-flow motion can be obtained by Multispan Project, 1997 (Mork and Verley, 1997)

For DnV 98, additional terms are involved, they are axial force and deflection term as shown in the equation (9). But these two terms are not considered for DnV 81.

In-Line VIV

- *PART A* : Span length calculation by in-line VIV
  1) Find the onset value for the reduced velocity from Fig. 8-1 in DnV 98.
  2) Calculate the natural frequency corresponding to the reduced velocity. Since partial safety factors are applied, the values of V_R is smaller than the values of V_R used in DnV 81.
  3) Calculate the effective axial force from 3.4.3. in DnV 98.
  4) Match the two natural frequencies equation to obtain the effective span length
  5) Calculate the allowable span lengths from 3.7.4. in DnV 98.

- *PART B* : Fatigue calculation with a span length obtained from part A
  1) Find stress range by the in-line response model.
  The stress range S us calculated by the in-line VIV response model :

  $$S = 2\ S_{A\text{-}ID}\ R_{I\theta}\ (A_Y/D)\ \lambda_{max}\ \Psi_{mod}\ \gamma_s\ \Psi_R \tag{10}$$

  where $S_{A\text{-}ID}$ = unit stress amplitude (stress due to unit diameter in-line mode shape deflection)

  $R_{I\theta}$ = amplitude reduction factor accounting for the turbulence intensity and flow angle

  (A_Y/D) = non-dimensional in-line VIV response amplitude

  γ_s = safety factor to be multiplied on the stress range

  Ψ_R = factor depending on the free span scenario

  λ_{max} = transformation factor to be taken as :

  λ_{max} = 1 in case of a constant amplitude response

  $\Gamma(1+m/2)^{1/m}$ in case of a narrow-banded Gaussian process

  2) If the stress range is less than the cut-off (threshold) stress (ex. API RP 2A X' of SN curve), fatigue analysis is not required.
  3) If fatigue damage is below the allowable damage ratio (ex. h = 0.1), do not use the in-line allowable span length.
  4) Otherwise, in-line allowable span length must be used for the pipeline design.

Fatigue Criteria

The fatigue damage assessment is to be based on the accumulation law by Palmgren-Miner :

$$D_{fat} = \sum \frac{n_i}{N_i} \leq \eta \tag{11}$$

where D_{fat} = accumulated fatigue damage

η = allowable damage ratio

Σ = summation over all stress fluctuation in the design life

N_i is the number of cycles to failure at stress range S_i defined by the SN curve :

$$N_i = C \cdot S_i^{-m} \tag{12}$$

where m = fatigue exponent

C = characteristic fatigue strength constant

n_i is the number of cycles corresponding to the stress range S_i given by :

$$n_i = F_v T_{life} \tag{13}$$

where F_v = dominating vibration frequency of the considered pipe response

T_{life} = time of exposure to fatigue load effects (i.e. design life)

For practical applications the following approximate fatigue damage criterion applicable to both in-line and cross-flow VIV is recommended :

$$D_{fat} = \frac{T_{life}}{C} \times \int_0^{\infty} \max(f_v S(V_R^*; \alpha_*; KC^*)^m) dF_{Uc} \leq \eta \tag{14}$$

where S = stress range determined from the response models

dF_{Uc} = long-term distribution function for the current velocity

Cross-Flow VIV

1) Find the onset value for the reduced velocity.

2) Repeat for the steps 2) to 5) in in-line VIV Part A

The fatigue criteria is not used for the span length obtained form the cross-flow VIV. Sample calculated values are shown in table 3.

5. COMPARISON OF CALCULATED RESULTS

A sample design data used for the calculations is as follows :

Water Depth : 120 m

Current speed : 0.21 m/sec for installation and hydrotest

0.42 m/sec for operation

Pipeline : 12.75" OD x 0.500" wt, Grade API 5L X-42

	Installation	Hydrotest	Operation
ASME codes	110	46	58

Table 1 Allowable span length(m) by static analysis

	Installation	Hydrotest	Operation
In-Line	52	51	34
Cross-Flow	86	79	56

Table 2 Allowable span lengths(m) by DnV 1981

	Installation	Hydrotest	Operation
In-Line	46 (no fatigue)	35 (no fatigue)	20 (no fatigue)
Cross-Flow	115	34	31

Table 3 Allowable span lengths(m) by DnV 1998

For the 3 conditions of in-line VIV, the calculated stress range was below the cut-off stresses and no fatigue damage is expected. Therefore the allowable span length of cross-flow can be used for the design.

In-Line

According to DnV 98, partial safety factors is applied for calculation of stability parameter which results smaller value of stability parameter comparing with the value obtained from DnV 81. Thus, obtained V_R is small.

For installation case, the values of in-line V_R from DnV 81 and DnV 98 are 1.8 and 1.4, respectively. So the allowable span length is decreased by reduced V_R and increased by residual tension. But the effect of V_R is dominant, thus, reduced value of allowable span length was obtained by DnV 98.

For Hydrotest case, the values of in-line V_R from DnV 81 and DnV 98 are 2.1 and 1.67, respectively. So the allowable span length is decreased by reduced V_R and it is decreased further, because of internal test pressure, in other words, the pipeline is under compression. Therefore, the final allowable span length is reduced by large amount.

For operation case, the values of in-line V_R from DnV 81 and DnV 98 are 1.8 and 1.6, respectively. So the allowable span length is decreased by reduced V_R and it is decreased further, because of operational pressure and temperature, in other words, the pipeline is under compression. Thus final allowable span length is reduced a lot.

Cross-Flow

For installation case, the values of cross-flow V_R from DnV 81 and DnV 98 are 5 and 3.4, respectively. So allowable span length is decreased by reduced V_R but increased by residual tension. The increment by tension is dominant for long span as in this case.

Therefore, it is resulted long allowable span length.

For Hydrotest case, the values of cross-flow V_R from DnV 81 and DnV 98 are 5 and 3.5, respectively. So the allowable span length is decreased by reduced V_R and it is decreased further, because of internal test pressure(the pipeline is under compression). But the reduction in span length is much fast for longer span, since the effect of axial load is significant. Therefore, very short allowable span length is calculated.

For operation case, the values of cross-flow V_R from DnV 81 and DnV 98 are 4.8 and 3.5, respectively. So the allowable span length is decreased by reduced V_R and it is decreased further, because of operational pressure and temperature(the pipeline is under compression). But the reduction in span length is much fast for longer span, since the effect of axial load is significant as previous case. Therefore, very short allowable span is calculated.

6 CONCLUSIONS

DnV code 1998 is fairly new codes which is different from the previous design codes, DnV code 1981.
In DnV 98 code, fatigue analysis is involved in part of in-line vibration. The fatigue analysis is to ensure an adequate safety against fatigue failure within the design life of the offshore pipeline. If the fatigue damage due to the in-line vibration is significant, the in-line VIV criteria should be used to determine the allowable span length. If the fatigue damage is insignificant as the results obtained in this work, then the cross-flow VIV criteria can be used to obtain the allowable span length.
The other difference between two methods is that axial and deflection load are involved for the calculation of natural frequency. The effect of deflection load is quite insignificant but the axial load affects very sensitively for final results.
From the results of cross-flow, obtained by DnV 98, very long span length is calculated for installation and very short span length is found for hydrotest and operation.

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