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Determining the limits of piping vibration

Key words

Vibration, stresses, pipeline.

Słowa kluczowe

Drgania dopuszczalne naprężenia, rurociąg.

Summary

This paper presents a method for determining the acceptable limits of piping vibration and their natural frequency. Acceptance criteria for the vibration values are taken as the limit of the allowed deformations of the pipeline caused by these vibrations and the limit of stress caused by these deformations. On the base of document *The Pipeline and Compressor Research Councils*, under the title "Controlling the effect of pulsation and Fluid Transients in Piping Systems" a computer program setting these values based on given piping parameters was developed.

Introduction

Today's industrial systems consist of machines (motors, compressors, pumps, etc), static equipment (reactors, columns, filters) and pipelines, which are a kind of "bloodstream" of a company. Maintenance strategies focus

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primarily on machines and equipment, leaving out issues related to the operation of pipelines but as research shows [1, 3], these are elements that are often damaged the most. These studies indicate that damaged pipelines account for over 30% of all failures of industrial plants. The three major causes are leaking seals (22%), corrosion and erosion (21%), and vibration (6%). The first two causes are commonly known and prevention is described. The vibrations of pipelines are treated in terms of an unavoidable evil, and actions are mainly focused on the installation of additional supports. It should be noted, however, that for every three damages caused by corrosion or erosion, one damage of a pipeline results from vibrations. In addition, there is still no common guidance on the limits of vibration, in contrast to machines, where the values are standardised and widely used [4].

The Chair of Construction, Maintenance of Vehicles and Machines in University of Warmia – Mazury in Olsztyn developed a procedure and software to determine the diagnostic relations for pipelines, enabling the determination of vibration limits values , depending on the length and diameter of pipeline spans, and to calculate the frequency of the natural frequency of pipelines [2]. This program was developed based on the content of a document under the title "Controlling the effect of pulsation and Fluid Transients in Piping Systems." Developed by The Pipeline and Compressor Research Councils [1].

The method allows one to determine the allowable piping vibration in various configurations [2]. Criteria for acceptable vibration levels are based on admissible deformation of the pipeline caused by these vibrations, and the admissible stress caused by these deformations.

Determination of the permissible vibration takes place in two stages:

1 – The designation of the stress generated in the pipeline, depending on the strain-induced vibrations; and,

2 – The vibration limit value determination based on the designated stress per unit displacement (deformation) of the pipeline and the fatigue strength of the material.

Additionally, the method includes a procedure for the designation of the natural frequency of vibrations of the pipeline.

Determination of the permissible vibration and natural frequency can be done graphically, using the appropriate nomogram [1] or digitally, using developed software.

The presented method is applicable under the following assumptions:

- Pipeline span vibration is occurring at frequencies equal to or less than the first natural frequency of spans.
- The calculation of the stresses and natural frequencies are made using the assumed Young's modulus $E = 20x10^{4}$ Mpa.
- The span of a pipeline does not contain a concentrated mass, and the weight of the medium and insulation is negligible.
- The maximum stresses occur at the theoretical maximum bending moment.

- The span of the pipeline contains only one dimension of the pipe.
- Vibration limits are calculated for elongation 100 μ-strain *(1/10^6 percent of deformation)* peak-peak, and stress concentration factor less than 5.

Description of the method

Dynamic stresses arising as a result of transverse vibrations of pipelines are connected with the dynamic bending moment M.

$$S = \frac{MD}{2I} \tag{1}$$

where:

S – stress [Pa],
D – outside diameter of pipe [m],
I – moment of inertia of the pipe [m ^{4}],
M – bending moment [Nm .

The bending moment is related to the piping vibration mode shape.

$$M = -EI\frac{d^2y}{dx^2} \tag{2}$$

where:

E – *Young*'s modulus [N/m^2],
$\frac{d^2y}{dx^2}$ – the second derivative of a vibration mode shape.

After substituting Equation (2) to (1) we get the following:

$$S = \frac{-ED}{2}\frac{d^2y}{dx} \tag{3}$$

Dynamic tension is thus a function of the pipe material, its diameter and the second derivative form of vibration. The character of vibration depends on the configuration of the pipeline and boundary conditions.

Example:

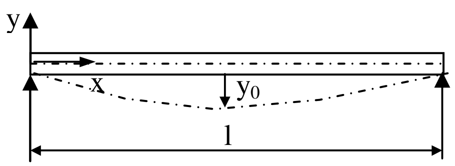

Fig. 1 Pipeline model
Rys. 1. Model rurociągu

For the pipeline shown in Figure 1, the vibration mode shape for the first mode resonance is a sine wave:

$$y = y_0 \sin\frac{\pi x}{l} \tag{4}$$

$$\frac{d^2 y}{dx^2} = y_0 \frac{\pi^2}{l^2} \sin\frac{\pi x}{l} \tag{5}$$

where

y_0 – *the* maximum displacement [m],
l – the length of span [m]t.

The maximum displacement and stress occurs in the middle of the span (x=l/2):

$$\frac{d^2 y}{dx^2} = -y_0 \frac{\pi^2}{l^2} \sin\frac{\pi}{2} = -y_0 \frac{\pi^2}{l^2} \tag{6}$$

Substituting into Equation (3) we obtain

$$S = -\frac{ED}{2}(-y_0 \frac{\pi^2}{l^2}) \tag{7}$$

and after transformation

$$\frac{S}{y_0} = \frac{E\pi^2 D}{2l^2} \tag{8}$$

Assuming that the displacement y_0 will be expressed in millimetres, the diameter of pipe D in millimetres and span length L in meters and assuming a value of Young's modulus for low-carbon steel E=20x10^4 MPa we obtain the following:

$$\frac{S}{y} = 0.314\frac{D}{L^2} \tag{9}$$

By introducing the variable K, the coefficient of stress depends on the configuration of the pipeline.

$$\frac{S}{y} = K\frac{D}{L^2} \tag{10}$$

where, for a simply supported beam as in the example, K = 0.986. The values of the stress factors for other configuration of the pipeline are shown in the nomogram.

Calculation of natural frequency spans of pipelines

The frequency of the natural vibrations of pipeline spans is derived from the frequency dependence of the total.

$$f = \frac{\lambda k}{2\pi l^2}\sqrt{\frac{E}{\gamma}} \tag{11}$$

where

l – length of the span [m],
E – Young's modulus [Mpa],
Γ – density [kg/m^3]
f – *freq*uency [Hz],
k – radius of gyration [m], and

$$k = \sqrt{\frac{I}{A}} \tag{12}$$

where

I – moment of inertia of the pipe [m4],
A – m2 cross-sectional area of the pipeline.

Equation (12) can be transformed into the following form:

$$k = \frac{D\sqrt{1+(\frac{d}{D})^2}}{4} \tag{13}$$

where

d – internal diameter of the pipe[m],
D – outer diameter of the pipe [m].

For pipes with a diameter greater than 50.8 mm and the size of the pipe characterised the US system as a "schedule" of less than 160, it is assumed that

$$k \cong 0.34D \tag{14}$$

Substituting Equation (14) into Equation (11) and assuming that the diameter of the pipeline will be expressed in millimetres and the length of span in meters, and assuming the value of Young's modulus for low-carbon steel is E = 20x10 ^{4} MPa and the density of steel is equal to 7800kg/m3, we obtain the following:

$$f = 0.274\lambda \frac{D}{L^2} \tag{15}$$

The Lambda coefficients for different piping configurations are shown in the nomogram [1]. According to ASME standards, maximum allowable alternating stress intensity for 10 ^{6} cycles for low-carbon steel is equal to 89.6 MPa for the vibrant cycle (zero – peak) and 179.3 MPa for the shuttle cycle (peak-peak). For Young's modulus E = 20x10 ^{4} MPa, the allowable stress intensity is equivalent to 433 µ-strain strain (zero – peak) or 866 µ-strain (peak – peak). Elongation of 100 µ-strain stress is equivalent to 20.7 MPa (peak – peak) on the fatigue SN curve. Comparing this amount (20.7 MPa) to 179.3 MPa (peak – peak) for 10 ^{6} cycles, it can be seen that the ratio of these two values is 8.66. This ratio expresses the product of the safety factor and stress concentration for welded steel pipe. The maximum stress concentration factor is usually equal to 5. Taking into account this value of the coefficient of stress concentration, the safety factor is equal to 1.74. Based on analysis of over 400 cases of damaged piping, it was found that damage to the steel, low-carbon pipelines is rare, if measured dynamic stress level is less than 100 µstrain (peak – peak). On the other hand, if this level is less than 200 µstrain (peak – peak) damage occurred frequently.

Taking into account that the increase of elongation equal to 100µstrains is equivalent to stress equal to 20.7 Mpa, it is possible to estimate the allowable amplitude of the vibration of the pipeline on the basis of the following formula:

$$y_{all} = \frac{20.7}{S / y} \text{ [mm]} \tag{16}$$

Example of diagnostic relations.

1) For a simple span of the pipeline (Fig. 1) with a diameter D = 48.3 mm and length L = 5m, the span vibration frequency f = 12 Hz and the maximum value of vibration in mm peak-peak is 1.7 mm
2) For spans of the same configuration, a different diameter and length (diameter D = 48.3 mm and span length L = 2.5 m) of natural vibration frequency f = 48 Hz and the maximum value of vibration in mm peak-peak is 0.42 mm.

Summary

Even though the vibrations of pipelines are one of the major causes of their failures, there are no [4, 5, 6] – in contrast to the machinery and equipment – guidelines for calculating the allowable vibration. This paper presents a procedure that allows the determination of vibration limit values depending on the length and diameter of pipeline spans and allows one to calculate the frequency of free vibrations of pipeline spans. Criteria for acceptable vibration levels are based on admissible deformation of the pipeline caused by these vibrations and admissible stress caused by these deformations.

Literature

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Wyznaczanie wartości dopuszczanych drgań instalcji rurociągowych

S t r e s z c z e n i e

W pracy zaprezentowano metodę wyznaczania wartości dopuszczalnych drgań instalacji rurociągowych oraz częstości drgań własnych. Kryteriami przyjęcia danej wartości drgań za dopuszczalne są przyjęte za dopuszczalne odkształcenia rurociągu spowodowane tymi drganiami oraz dopuszczalne naprężenia wywołane tymi odkształceniami. Na podstawie materiałów The Pipeline and Compressor Research Councils, pod tytułem “Controlling the effect of pulsation and fluid transients in piping systems” opracowano program komputerowy wyznaczający te wartości na podstawie zadanych parametrów instalacji rurociągowej.