Oscillations of Pipelines Laid on Supports in the Conditions of Aerodynamic Resonance

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Abstract. Above-ground laying of field and main oil and gas pipelines is one of the most common methods in the conditions of the North and permafrost soils, as well as at the intersection of ravines, canals, small rivers, in rocky soils, in areas of mine workings and landslides. Under the influence of wind, above-ground pipelines can experience oscillations whose frequency is usually equal to the frequency of the fundamental tone of free oscillations. Oscillations occur not only along, but also across the wind flow. The amplitude of oscillations across the flow is greater than the amplitude of vibration along the flow. At certain values of wind speed, the amplitude of oscillations increases sharply. This phenomenon is called wind resonance. It is most pronounced for pipelines with a circular cross-section.

Pipeline supports perform functions such as fixing communication in the desired position and damping vibrations. In addition, these products exclude the deformation process of communication under the influence of temperature [2].

1. Introduction

At present, the extraction and transportation of hydrocarbons is shifting more and more to the zones of permafrost soils, to the regions of the Far North. Experts believe that in the regions of the Far North it is more expedient to use the above-ground method of pipelining, but the design of the above-ground supports must satisfy both the requirements of economy and environmental safety. The above-ground laying of pipelines is carried out on racks, on pile supports towering above the terrain (figure 1).

Under the influence of wind, above-ground pipelines can experience oscillations whose frequency is usually equal to the frequency of the fundamental tone of free oscillations. Oscillations occur not only along, but also across the wind flow, while, as a rule, the amplitude of oscillations across the flow is greater than the amplitude of oscillations along the flow [1]. At certain values of wind speed, the amplitude of oscillations increases sharply. This phenomenon is called wind resonance. It is most pronounced for pipelines with a circular cross-section.

Pipeline supports perform functions such as fixing communication in the desired position and damping vibrations. In addition, these products exclude the deformation process of communication under the influence of temperature [2].
2. Causes of aerodynamic resonance of pipelines laid on supports

There are several phenomena associated with the vibration caused by the flow. These include the propagation of vortices, elastic instability of a fluid, turbulent vibration, the formation of a vortex in a parallel flow, and acoustic vibration.

Behind the transversely streamlined pipes, a vortex wake forms, which is characterized by nonstationarity of the flow and an active disturbing effect on the pipes. The nonstationarity of the flow created by the vortex wake and the turbulence of the flow can cause the pipes to vibrate.

This propagation of vortices creates variable forces that occur more and more as the flow velocity increases. For a single cylinder, the pipe diameter $D_N$, flow rate $v$ and the frequency of vortex $f_V$ are related by a dimensionless Strouhal number $Sh$:

$$f_V = Sh \cdot \frac{v}{D_N}.$$  \hspace{1cm} (1)

For single cylinders, the number $Sh$, describing the propagation of vortices, is constant; its value is approximately 0.2. Vortices occur in the range of Reynolds numbers $50 \div 5 \cdot 10^5$ and at $Re > 2 \cdot 10^6$ and disappear at intermediate values of $Re$. This gap is due to the shift of the flow separation point in the vortices in the intermediate range near the critical numbers $Re$ [3, 4, 5].

A body in the flow path changes the direction of flow of the jets flowing around it and increases their speed due to a corresponding decrease in pressure. For the midsection of the body begins the reverse process of reducing speed and increasing pressure. At the same time, increased pressure is created on the front side of the body, and reduced pressure on the back side. The boundary layer that flows around the body, passing its mid-section, detaches from the body and under the influence of reduced pressure behind the body changes the direction of movement, forming a vortex. This occurs in both the upper and lower points of the streamlined body. But since the development of a vortex on the one hand hinders the same development on the other hand, the formation of vortices on either side occurs alternately. At the same time, a Karman vortex track of width $a$ is formed behind the streamlined body, having a constant ratio $b/a$, which is 0.281 for the streamlined cylinder.

The frequency of occurrence of vortices can be tied to the frequency of natural oscillations of a vibrating tube, even if the flow velocity increases. The movement of the tube as it organizes the separation of the vortices from the vibrating tube.

Vibrations of pipelines reach significant values. They are a serious obstacle in the work and the cause of the destruction of communication. The frequency of vibration of pipelines depends on the pressure of the gas or liquid, and the frequency of the pulsating flow, the type of supports and the distance between them, the rigidity of the pipeline, its weight, and so on.
To attenuate vibrations, the exclusion of resonant modes, that is, the detuning of the natural frequencies of the aggregate and its individual components and parts from the frequency of the driving force, is essential. The determination of the natural frequencies of individual structural elements is carried out either by calculation or experimentally [4, 5].

When designing elevated systems, one should strive to orient the pipelines along the direction of the prevailing winds and locate them in places that are closed from the effect of transverse wind flows (forest glades, low areas in mountainous areas, etc.). Then, after determining the frequencies of natural oscillations of the pipeline system, they are compared with the frequencies of disturbing forces arising from the actions of the wind load, in accordance with the wind speeds in the area. It is necessary to adhere to the rule that the natural frequencies of the pipeline oscillations differ by at least 20–30% from the frequencies of external driving forces [6, 7].

3. Impact of wind load on main and field pipelines on multi-span supports

When exposed to a wind flow flowing around a pipe with a diameter of $D_N$, located across the flow, the type of hydrodynamic flow varies depending on the numerical value of the dimensionless Reynolds number parameter $Re$:

$$Re = \frac{v \cdot D_N}{\mu},$$

where $q$ is the air density;
$\mu$ is air viscosity (in the CGS system);
$v$ is wind speed, m/s.

At $Re > 50$, an alternating vortex path forms behind the obstacle, alternating alternately from one or the other edge of the pipeline. The frequency of vortex formation (in Hz) as in equation (1).

For a pipeline considered as a rod with a constant cross section on two supports, the natural frequency $f_i$, corresponding to the i-th form of natural oscillations, is determined by the equation [8]:

$$f_i = \frac{10^{-3}}{2\pi} \cdot \frac{k_i^2}{L} \cdot \sqrt{\frac{E \cdot I}{m_s}},$$

where $k_i$ is the I-th root of the frequency equation in accordance with [8];
$L$ is the length of the pipeline between the supports, m;
$I$ is moment of inertia, mm$^4$;
$E$ is the modulus of elasticity;
$m_s$ is the linear mass of the pipeline, taking into account the insulation and the working substance, kg.

The main means of ensuring the vibrational strength of the pipeline is the detuning of the natural frequencies $f_i$ from the frequencies of disturbing loads $f_v$. The following conditions must be met [6]:

$$\frac{f_v}{f_i} \leq 0.75 \quad \text{or} \quad \frac{f_v}{f_i} \geq 1.3.$$

Based on the analysis of the calculations performed for various pipelines laid on supports, the characteristic resonant wind speeds and vibration amplitudes were determined.

For a field methanol pipeline, with an outer diameter of $D_N = 114$ mm, the condition for the onset of resonance is the speed range from 5 to 7 m/s, in the range of natural oscillation frequencies from 9.40 to 13.05 Hz (figure 2, a, b).

For a field gas pipeline with an outer diameter $D_N = 273$ mm, the condition for the onset of resonance is the speed range from 14 to 20 m/s, in the range of natural oscillation frequencies from 10.40 to 14.45 Hz (figure 3).
Figure 2. The vibration amplitude of the methanol pipeline depending on: a) the time at the resonant wind speed; b) wind speed.

For a field gas pipeline with an outer diameter of $D_N = 325$ mm, the condition for the onset of resonance is the speed range from 13 to 18 m/s, in the range of natural oscillation frequencies from 7.65 to 10.62 Hz (figure 4).

Figure 3. Vibration amplitude of the field gas pipeline $D_N = 273$ mm depending on wind speed.

For a field pipeline, with an outer diameter $D_N = 219$ mm, the condition for the occurrence of resonance is the speed range from 13 to 18 m/s, in the range of natural frequencies of oscillations from 11.39 to 15.81 Hz (figure 5, a, b).

For the main pipeline, with an outer diameter $D_N = 820$ mm, the condition for the occurrence of resonance is the speed range from 13 to 18 m/s, in the range of natural oscillation frequencies from 3.04 to 4.22 Hz (Figure 6, a, b).

4. The distance between the supports from the condition of preventing aerodynamic resonance

The distance between the supports of pipelines is calculated based on the anticipated external forces and moments. Friction, internal pressure and compensation, as well as the weight of the pipeline and the substance being transported, dust, wind, ice, etc. are taken into account. If the temperature value is set different from +20 degrees, it is necessary to use special factors.
Figure 5. The vibration amplitude of the field oil pipeline depending on: a) the time at the resonant wind speed; b) wind speed.

Figure 6. The vibration amplitude of the field oil pipeline depending on: a) the time at the resonant wind speed; b) wind speed.

Obviously, with this approach, the calculations will be individual. Installed when designing the distance between the supports should not exceed the values obtained from the calculations. However, their reduction is permissible when it comes to installing a support near a branch, a locking device, etc.

Additional calculations are required if pipeline supports are to be installed on foundations. It should be borne in mind that, as a rule, no calculation is made of the conditions for the occurrence of wind resonance and the determination of the critical wind speed when designing pipelines.

A wind load in the presence of resonance causes a bending moment not only in the horizontal, but also in the vertical plane, so it is necessary to check whether there is room for the adopted gasket for wind resonance and select the distance between the supports from the condition of its prevention. The required distance between the supports is determined on the basis of the criterion that, with a critical wind speed of more than 25 m/s, there is no wind resonance for above-ground pipelines [3]. The results of the calculations are shown in table 1.

Table 1. Calculation results by reducing the length of the spans between the supports.

| Pipeline Type                     | Distance between supports after adjustment, m | Applicable distance range, m |
|-----------------------------------|---------------------------------------------|------------------------------|
| Main oil pipeline (D N = 820 mm)  | 13,79                                       | 18,0-20,0                    |
| Field oil pipeline (D N = 219 mm) | 4,68                                        | 5,0-7,0                      |
| Field gas pipeline (D N = 273 mm) | 5,32                                        | 7,0-9,0                      |
| Field gas pipeline (D N = 325 mm) | 6,34                                        | 9,0-11,0                     |
| Methanol pipeline (D N = 114 mm)  | 3,55                                        | 4,0-6,0                      |
It should be noted that in this case the rigidity of the pipeline will increase and, accordingly, the natural frequencies of its vibrations will increase [9-12].

5. Summary
Based on the analysis of the calculations, it was shown that for each pipeline with an outer diameter \( D_N \) from 114 to 820 mm, its own range of resonant speeds, with different ranges of natural frequencies of oscillations. At the same time, an increase in the distances between the supports is impractical, since it will lead to a decrease in the critical wind speed and, accordingly, an increase in the risk of aerodynamic resonance. As the calculations showed, the optimal distances between the supports of above-ground pipelines are much less than those used in practice. Reducing the distances between the supports leads to an increase in the rigidity of the pipeline, its natural oscillation frequencies and, therefore, increases the value of the critical wind speed and contributes to the detuning from aerodynamic resonance.

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