Hydrodynamic Causes of Vibration in the Pipe Bend of Process Pipelines

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Abstract. Hydrodynamic vibrations can occur both in pump piping at local resistances and in the pump, for example, when it’s operated outside the working area. Vibrations occurring in the hydraulic section of the pumps and associated pipings are transmitted to the mechanical section and can lead to breakdowns. Oscillations of pump piping can be caused by both hydrodynamic reasons and vortex formation at local resistances, and resonance with the natural frequencies of the piping. In some cases, the vibration of pipelines exceeds the permissible norms by 1.5-2 times. The range of vibration frequencies of a hydrodynamic nature directly depends on the flow rate of the working medium. As the latter decreases, the range also decreases. In any elbow of the pipeline, with a sufficient flow rate of the liquid, vortex formation occurs, which is the cause of forced vibrations. The values of the Strouhal number characterizing hydrodynamic phenomena in unsteady flow regimes for the flow of liquids in local resistances of pipelines have been studied very little.

1. Introduction
Vibration of pumping units is one of the most important reasons for their failures. At the same time, the least studied and most difficult to predict is the vibration of hydrodynamic origin, which occurs both in the pump, for example, when power plants operate at low and high flows, and in the pump piping. Vibrations arising in the hydraulic part of the pumps are transmitted to the mechanical part (bearing units, housing, foundation, etc.). This process can be accompanied by both minor vibrations of the unit without significant consequences, and destruction of bearings, foundations, volute bends of large pumps, or, for example, beating and displacement of shafts, as well as an increase in vibration in the piping to critical values [1, 2].

Oscillations of pump piping can be caused both by hydrodynamic reasons and vortex formation at local resistances, and by resonance with the natural frequencies of the piping. In some cases, the vibration of pipelines exceeds the permissible norms by 1.5-2 times and, being transmitted to the pumping unit, can serve as one of the most important reasons for its increased vibration [2-6].

In addition to material consequences due to the destruction of equipment and a temporary emergency shutdown of pumping, there is also a risk of environmental damage during the spill of the pumped product, as well as for the operating personnel of pumping stations, since, as practice shows, vibration can increase the permissible values provided for by sanitary and hygienic standards.
Determination of the conditions for the occurrence and the possibility of predicting the hydrodynamic vibration of pipelines for piping of pumping units is an urgent task for pipeline transportation of oil and oil products.

2. Hydrodynamic vibrations in the “pump – piping” system
Speaking about vibration, one should understand that in addition to natural frequencies, that is, those with which the body will vibrate after perturbation without external force or with its constant influence, there are also frequencies of forced vibrations of mechanical, electrical and hydrodynamic origin. If the ratio of excitation to natural frequencies is within the range from 0.75 to 1.3, resonance occurs, that is, the frequency-selective peak response of the oscillatory system with a sharp increase in amplitude, and the closer to 1, the stronger this disturbance [7].

In addition to the acting static loads (weight, temperature, internal pressure and mounting tension loads) during vibration, cyclic stresses arise, the magnitude of which is determined by the amplitude of vibration displacements and the form of bending vibrations of the pipeline [2, 3, 8].

There are vibrations, the origin of which is associated with power units and pipelines. It is worth noting that their interactions are interconnected, so it is impossible to consider the general vibration state of the pipeline separately from the units and vice versa.

3. Vibration sources in the pipeline
The main causes of vibration in a pipeline are of a hydrodynamic nature. In bent pipelines, bends, tees due to a change in the flow velocity vector, centrifugal forces arise, directed from the center of curvature to the outer wall of the pipeline. This process is accompanied by an increase in pressure at the outer wall and a decrease on the inner one, which leads to a diffuser effect near the inner wall and a confusor effect near the outer one (when passing from a curved section to a straight one, the opposite picture is observed, figure 1). Diffuser effects result in flow separation from both walls. The separation from the inner wall occurs due to inertial forces, which in the curved section force the flow to move towards the outer one. The formed vortex zone spreads far and wide, significantly reducing the cross section of the main flow. The appearance of centrifugal forces and the presence of a boundary layer at the walls explains the appearance of a secondary cross-flow in a bent pipe, i.e. the formation of a paired vortex, which is superimposed on the main flow, parallel to the channel axis, and gives the lines a helical shape [9].

This effect is accompanied by the appearance of an impulse of force on the body, which leads to the formation of vibration, as well as noise.

4. The influence of vortex formation in a pipeline bend to the resulting vibration
The object of research (figure 2) for analyzing the hydrodynamic causes of vibration for vortex formation is a section of a pipeline with a diameter of 108 mm and a wall thickness of 3.5 mm with a bend with a 90° rotation angle. To study the emerging vibration, the water supply Q in the pipeline was varied from 165 to 15 m³/h with a step of 15 m³/h. The vibration analyzer “Diana-8” was used as a device, and the software “Atlant” was used for data processing. Before the turn, the section has a length of 4.4 m and the pipeline is freely fixed at the ends. This leads to additional noise on the readings. At the same time, the site is in almost complete isolation from vibrations caused by a running pump. Analysis of hydrodynamic vibrations is reduced to the analysis of vortex formation, since it is the main cause of vibrations in this case. The most important in this case will be the readings from horizontal sensors 1 and 2 (figure 2), since the vortex is observed precisely in these places in the fluid flow, which is confirmed by works [2, 3, 9]. Consider the results of the experiment using the example of flow rates of 165 m³/h and 75 m³/h (figure 3, 4).
For all the measurements carried out according to the obtained peak values for vertically located sensors, 3 values of the natural frequencies of the pipeline vibrations can be distinguished, which are repeated regardless of the pipeline supply: 11.921 Hz, 28.610 Hz and 59.604 Hz.

Let's compare the graphs of horizontal sensors 1 and 2, combining them, respectively, for flows of 165 m$^3$/h and 75 m$^3$/h. Since the last sensor is located in the vortex flow zone, the hydrodynamic frequencies stand out brighter on it (figure 5).

In general, with a decrease in supply, the frequency range becomes narrower and smaller in value (the first range is in the range of 16.7 - 47.7 Hz), which indicates the hydrodynamic frequencies in the pipeline. This range also includes two natural frequencies of 11.921 Hz and 28.610 Hz, which have a significant effect on the amplitude of oscillations.

5. Dependence of the frequencies of hydrodynamic vibration in process pipelines from the flow and pipeline parameters

The resulting turbulence in the pump piping affects its operation. If the frequency range of vortex formation in the pipeline coincides with the exciting frequencies of the pump, it will be possible to observe the beat - the process of increasing the amplitude of stationary harmonic oscillations.

It is known that the frequencies of vortex formation depend on the velocity $\nu$ of the liquid and the diameter of the pipeline $D$. Based on the experimental data, in the first approximation, we find the Strouhal number $Sh$, which characterizes the process of the arising vibration:

$$Sh = \frac{f \cdot D}{\nu} = \frac{f \cdot \pi \cdot D^3}{4 \cdot Q} = \frac{11,921 \cdot 3.14 \cdot 0.101 \cdot 3600}{4 \cdot 165} = 0.210,$$

where $f$ is the frequency of vortex formation, Hz.
Figure 3. Obtained results of measurements of vibration velocity at Q = 165 m$^3$/h.

Figure 4. Obtained results of vibration velocity measurements at Q = 75 m$^3$/h.
Figure 5. Combined graphs of readings of sensors 1 and 2 transversely at: a) \( Q = 165 \text{ m}^3/\text{h} \); b) \( Q = 75 \text{ m}^3/\text{h} \).

Reynolds number:

\[
\text{Re} = \frac{\nu \cdot D}{\nu} = \frac{4 \cdot Q}{\pi \cdot D \cdot \nu} = \frac{4 \cdot 165}{3600 \cdot 3.14 \cdot 0.101 \cdot 1 \cdot 10^{-6}} = 578083 ,
\]

where \( \nu \) is the kinematic coefficient of viscosity of the working fluid.

The resulting range of Strouhal numbers depending on the Reynolds number is shown in figure 6.

Figure 6. Dependence of the Strouhal number on the Reynolds number.

6. Summary

The hydrodynamic causes of vibration in the pipeline are currently poorly studied. This is a vast area that requires research, since the range of their frequencies may be within the range of frequencies of disturbing forces, the source of which is the pumping-power unit. In this case, beating of both the pumping and power plant and the pipeline in the supports may occur, since this is a mutually communicating system. Moreover, the increased vibration adversely affects the health of the working personnel, which makes the issue of studying the hydrodynamics in the pipeline very important.

The range of vibration frequencies of a hydrodynamic nature directly depends on the flow rate of the working medium. As the latter decreases, the range also decreases. In this case, in any bend of the pipeline, with a sufficient fluid flow rate, vortex formation occurs, which is the cause of forced
vibrations. The Strouhal number $Sh$, which characterizes the vortex formation process, decreases with increasing Reynolds numbers $Re$.

7. References

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