Radial waves of pipeline pressure at the hydraulic shock

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Abstract. The mathematical model of shock loading of a pipe, in which on an inner surface impulses of radial tension of pressure are instantly put, is offered. These impulses lead to distribution in a pipe as the falling waves of tension of compression, and an interference of the falling and back waves of tension, which are formed, on a free surface. The system of differential equations together with boundary and entry conditions for the description of the intense deformed condition of material of a pipe, and considering process of distribution in it radial waves of pressure is offered. The method of characteristics is applied to obtaining the decision of this system. The method is developed and the equations for definition the intense deformed condition of material of a pipe of the pipeline are received at a hydraulic shock. It is established that the interference of these waves has essential quantitative shock on nature of voltage variation and, as a result, can lead to possible destruction of the pipeline. It is shown that when loading a pipe shock pressure, its stress-strain state can be considered settled approximately after triple run by a wave of tension in the direction from loaded to a free surface and back.

1. Introduction

Even since emergence of the pipe manifold there was a concept of hydraulic shock. The Russian scientific Zhukovsky N.E. was engaged in this research (1847-1921). Of course, and to it considered this problem, but he the first developed the theory of hydraulic shock.

In pipelines pipes of different diameters therefore increase of shock pressure happens upon transition of a shock wave from pipes of bigger diameter on pipes to smaller diameter [1-3] are used. Besides, in the presence of waves of pipeline pressure there can be resonance conditions, i.e. coincidence of frequency of own and forced oscillations of a fluid column in the pipeline. This process is observed in deadlock points of the pipeline, for example, in internal pipeline systems of buildings. Thus, the destroying influence of hydraulic shocks repeatedly amplifies.

The probability of emergence of hydraulic shocks increased in modern pipelines in connection with implementation of long heat conductors of a large diameter with a large number of latches and control valves. At refusal of any element of system of heat supply, for example, at fast closing of a latch, there can be a sharp change of speed of water in a heat network, which is followed by a hydraulic shock. Emergence of a hydraulic shock, as a rule, results breaks in the most weakened places of pipeline system which owing to wear is incapable to sustain dynamic loads of shock character. Hydraulic shocks, fluctuations and pressure pulsations, the increased vibration of pipelines repeatedly increase the speed of internal corrosion processes, promote accumulation of fatigue micro cracks in metal, especially in places of concentration of tension (welded seams, scratches, factory defects, etc.) are also the main background of emergence of emergencies [4, 5].

According to operational experience [6] causes of destruction of pipelines in 60% of cases are hydraulic shocks, differential pressures and vibrations, about 25% are the share of corrosion processes, 15% - of the natural phenomena and force major circumstances.
Carrying out the researches connected with the analysis and detection of features of course of deformation processes in pipes at high speeds of influence is caused by need of ensuring durability of pipelines under the influence of pulse and shock loads. An effective scientific method of studying of shock loading of pipelines is mathematical modeling, based on models of the physical processes interconnected among themselves, which are taking place in thermo elastic and viscous-plastic medium of materials of which pipes are made.

Increase of reliability of pipelines is an actual task and can be reached, including, and based on new solutions of problems of an assessment of durability of pipes at differential pressures, up to a hydraulic shock, in pipelines.

2. Formulation of problem

Let us consider process of loading of the pipeline of outside radius $R_k$ in which on an inner surface of radius $R_0$ the impulses of tension of radial pressure arising, for example, in case of a hydraulic shock are instantly put. Such loading of the pipeline can bring, as directly to destruction of a pipe [7], and to destruction of armature of the pipeline, for example, to loss of longitudinal stability a pipeline lock spindle that will lead to impossibility of overlapping of an emergency site of the pipeline [8]. The decision of a task is passed in cylindrical coordinate system $ROZ$, which axis $Z$ matches a pipe axis.

The Stress-Strain State (SSS) of material of a pipe is defined by tension radial $\sigma_R$ and district $\sigma_\nu$ and corresponding deformations $\varepsilon_R$, $\varepsilon_\nu$ and axial deformation $-\varepsilon_Z$ caused by this tension. The movement equation for a ring element of mass of a pipe registers so [7]:

$$\rho \frac{\partial V_R}{\partial t} = \frac{\partial \sigma_R}{\partial R} + \frac{\sigma_R - \sigma_\nu}{R};$$

(1)

where $\rho$ – pipe material density; $V_R$ – radial speed of particles.

Deformations $\varepsilon_R$, $\varepsilon_\nu$ and speed $V_R$ are connected among themselves by compatibility conditions:

$$\frac{\partial \varepsilon_R}{\partial t} = \frac{\partial V_R}{\partial R}; \quad \frac{\partial \varepsilon_\nu}{\partial t} = \frac{V_R}{R}.$$  

(2)

As indicial equations for material of a pipe, the generalized Hooke's law, which for conditions of the considered task registers so, is used:

$$\frac{\partial \varepsilon_R}{\partial t} = \frac{1}{E(T)} \left( \frac{\partial \sigma_R}{\partial t} - \mu \frac{\partial \sigma_\nu}{\partial t} \right);$$

$$\frac{\partial \varepsilon_\nu}{\partial t} = \frac{1}{E(T)} \left( \frac{\partial \sigma_\nu}{\partial t} - \mu \frac{\partial \sigma_R}{\partial t} \right),$$

$$\frac{\partial \varepsilon_Z}{\partial t} = -\mu \frac{\partial \sigma_R}{\partial t} + \frac{\partial \sigma_\nu}{\partial t};$$

(3)

where $E(T)$ – the variable module of elasticity depending on temperature $T$ of the transported environment:

$$E(T) = E^* - k_1 T,$$

where $E^*$, $k_1$ – the material constants defined from experiment.

Boundary conditions of a task were accepted in a look:

$$\sigma_R(R_0,t) = \sigma_{R_0}, \sigma_R(R_k,t) = 0,$$

where in quality $\sigma_{R_0}$ the shock pressure in the pipeline arising when closing a lock [9] was accepted.

The given entry conditions correspond not to a tension of material of a pipe. The equations (1)–(3) represent system of quasi-linear differential equations in partial derivatives of first order of hyperbolic type which together with boundary and entry conditions unambiguously and
completely are described by the stress-strain state of material of a pipe and distribution of radial waves of pressure in it. The decision of system was passed by method of characteristics [10]. Expressions of communication between required functions along the characteristic directions have an appearance:

– along the characteristic of \( dR=0 \):

\[
\begin{align*}
    &\frac{d\varepsilon_v}{dt} = \frac{\sigma_v - \mu \sigma_R}{E} dt; \\
    &\frac{d\sigma_v}{dt} = \frac{R \sigma_R - \mu \sigma_v}{E} dt; \\
    &\frac{d\varepsilon_R}{dt} = -\mu \frac{\sigma_R + \sigma_v}{E} dt;
\end{align*}
\]

– along the characteristic of \( dR \pm = \pm \sqrt{\frac{E(T)}{\rho (1-\mu^2)}} = \pm a dt \):

\[
\pm dV_R + \frac{1}{a \rho} d\sigma_R \pm \frac{\sigma_R - \mu \sigma_v}{\rho R} dt - a \frac{\mu V_R}{R} dt = 0.
\]

Let us consider the forward front of wave of tension extending in the radial direction along the characteristic \( R = at \). Using a hypothesis of continuity of material in the course of deformation and momentum conservation law, received the conditions of a dynamic and kinematic continuity connecting tension, speed and deformation upon transition through a forward front of wave:

\[
\begin{align*}
    &V_R + \frac{1}{a \rho} \sigma_R = 0; \\
    &V_R + a \varepsilon_R = 0.
\end{align*}
\]

From the generalized Hooke's law

\[
\sigma_R - \mu \sigma_v = \varepsilon_R E.
\]

Substituting (5) and (6) in (4), received the ordinary differential equation connecting tension and time on a forward front of wave;

\[
\frac{d\sigma_R}{dt} = -0.5 a \frac{\sigma_R}{R} \left(1 + \mu - \mu^2 \right).
\]

Speed of particles on the forward front and deformation district tension - from the equation is defined from the equations (5), and (6).

![Figure 1](image_url)

**Figure 1.** Phase plane Rot

Fig. 1 is provided algorithm of the decision. In part I of the plane Rot waves of tension of compression extend. The AB line corresponds to the direction of distribution of a forward front wave of compressing tension. The BC line corresponds to the direction of distribution of a back wave of stretching tension.
In part II Rot of the SSS plane of pipe material is defined by an interference of waves of compression and stretching. Tension at the front of a back wave unloads pipe material in process of distribution of its front to the loaded surface.

Total to the SSS at the front of a back wave it is provided as [11]:

\[ X^\Sigma II(Z, \frac{2R-Z}{a}) = X^P II(Z, \frac{2R-Z}{a}) + X^C I(Z, \frac{2R-Z}{a}), \]

where \( X^\Sigma II \) – total values of characteristics of the SSS of pipe material at the front a reflected wave as a result of its interaction with the falling wave; \( X^P II \) – amplitude values of characteristics of the SSS of pipe material on the forward front of a reflected wave; \( X^C I \) – the corresponding parameter of a state in the considered point before arrival of the front of a reflected wave to it.

As boundary conditions for part I of the phase plane Rot equality of radial tension to shock pressure on an inner surface of a pipe was accepted, for part II of the phase plane equality of radial tension to zero on a free surface of a pipe was accepted. Similar reasoning carried out and for the subsequent parts of the phase plane.

3. Results of modeling

The decision was passed by replacement of the differential equations describing changes of the stress-strain state of material of a pipe along the characteristic directions, the finite difference equations and the organization of a cycle of iterations for all required sizes, which are not entering under a differential sign on each step of numerical integration in number. For the decision, Rot the grid (Figure 2) which is rigidly fixed in the plane was used Rot.

In Fig. 3 distributions of radial tension to different instants of time are provided (at \( \sigma_{R0} = 250 \text{ MPa}, R_0 = 0.1 \text{ m} \)): curve 1 \(- t = 15 \mu s \); curve 2 \(- t = 30 \mu s \); and a curve 3 \(- t = 45 \mu s \).

4. Results and discussions

The instants presented on Fig. 3 correspond to the run period a wave from the loaded surface to the free. The analysis of these dependences shows that the interference of waves has shock on nature of change of radial tension in a pipe. It is visible that subsequent changes of radial tension have the
fading character. Thus, when loading a pipe as the shock pressure, its SSS it is possible to consider settled approximately after triple run by a wave of tension in the direction from loaded to a free surface and back. Similar conclusions can be drawn and on change of district tension. The different designs of drives of locks reducing differential pressure when overlapping of the transported environment in the pipeline are applied to reduction of effects of hydraulic shocks. In the works we offer a design of the 2-speed drive of the lock [12, 13] allowing to reduce twice shock pressure, and in work [14] – the self-governed drive providing continuous reduction of speed of overlapping of a working flow. However, any design of the drive cannot guarantee integrity of the pipeline therefore, it is periodically necessary to carry out monitoring of durability of pipes of the existing pipelines in process of their wear.

5. Conclusions
The method is developed and the equations for definition of the SSS of material of a pipe of the pipeline at a hydraulic shock are received and is established that at a hydraulic shock in a pipe the radial waves of tension leading to an interference of the falling and back waves extend. It is established that the interference of these waves has essential quantitative shock on nature of change of tension and, as a result, can lead to possible destruction of the pipeline.
It is shown that when loading a pipe as the shock pressure, its SSS it is possible to consider settled approximately after triple run by a wave of tension in the direction from loaded to a free surface and back.

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