Destruction of linear part of pipeline under influence of high-frequency pressure change

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Abstract: The article deals with the vibrations of the pipe surface, connected with the change in pressure, which can lead to the destruction of the linear part.

1. Introduction
It follows from experience in the operation of main pipelines that most of the damage occurs suddenly, without apparent external causes. It is believed that this kind of destruction is associated with a variable load and has a fatigue nature [1-4]. Consequently, the problem of ensuring the reliability must be associated with dynamic processes in the gas pipeline.

2. Materials and methods
The fact is that the changing in the gas pressure along the length of the pipeline can cause considerable stresses. Deformations caused by these stresses negatively affect the reliability of the pipeline [14]. In this connection, the establishment of a relationship between the change in pressure and stresses arising in the pipes walls, caused by deformations as a result of dynamic processes, is an important task in solving problems of increasing the reliability [10-13].

Let us consider the oscillations of a cylindrical surface in a thin shell model.

Figure 1. A model of a thin cylindrical shell
Let us introduce \( u, v, \omega \) - the variables denoting the displacement of the shell surface of the cylinder. The equations system of forced oscillations under the action of internal pressure will have the following form [2]:

\[
\begin{align*}
\frac{\partial^2 u}{\partial \xi^2} + \frac{1 - \mu}{2} \frac{\partial^2 u}{\partial \varphi^2} + \frac{1 + \mu}{2} \frac{\partial^2 v}{\partial \xi \partial \varphi} - \mu \frac{\partial \omega}{\partial \xi} &= 0 \\
\frac{1 + \mu}{2} \frac{\partial^2 u}{\partial \xi \partial \varphi} + \frac{1}{2} \frac{\partial^2 u}{\partial \varphi^2} + \frac{1 - \mu}{2} \frac{\partial^2 v}{\partial \varphi^2} - \frac{\partial \omega}{\partial \varphi} &= 0 \\
\frac{\partial u}{\partial \xi} + \frac{\partial v}{\partial \varphi} - \omega - k \nabla^4 \omega &= \frac{\rho r^2}{B} \frac{\partial^2 \omega}{\partial t^2} + P(t)
\end{align*}
\]  

(1)

where \( \xi = \frac{x}{r}, \quad k = \frac{h^2}{12r^2}, \quad B = \frac{E h}{1 - \mu^2} \)

\( x \) – distance from the cylinder edge to the considered point;
\( r \) – cylinder radius;
\( \varphi \) – angle between the axial plane and the considered point;
\( h \) – shell thickness;
\( E \) – modulus of elasticity of the shell material;
\( \mu \) – Poisson's ratio of the shell material;
\( \rho \) – shell weight per area unit;
\( t \) – time.

Assuming the load as a periodic one: \( P(t) = P \sin \omega t \), let us expand it to series:

\[
P = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} P_{mn} \cos \alpha_m \xi \sin \varphi
\]

(2)

where \( \alpha_m = \frac{m \pi r}{l} \)

\( P_{mn} \) - Fourier coefficients;
\( l \) – shell length;
\( m \) – number of half-waves in direction \( l \);
\( n \) – number of waves around the circumference of the cross section.

After solving the equations system by the method described in [2], let us express the amplitude of forced oscillations:

\[
A = A_\omega \sin \omega t
\]

\[
A_\omega = \frac{16P}{\pi^2 \rho h} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{1}{mn(\omega_{mn}^2 - \omega^2)} \cos \alpha_m \sin \varphi
\]

(3)

where \( m, n = 1, 3, 5... \)

\( A_\omega \) – maximum amplitude of forced oscillations;
\( \omega_{mn} \) – natural oscillation frequency of the system.

However, in reality, the pressure amplitude is a random variable with an unknown distribution density.

The paper [3, 5] shows a histogram and a reconstructed function of the pressure distribution density in gas pipeline \( f(P) \). To do this, daily fixed pressure values throughout the year were sampled. According to the results, the general form of the function can be approximated by the expression:

\[
f(P) = P^\alpha e^{-\beta P}
\]

(4)

where \( \alpha, \beta \) – coefficients obtained by approximating the experimental results [3];
\( P \) – pressure in the gas pipeline.
Consequently, the amplitude of the forced oscillations taking into account the random distribution of the pressure amplitude will have the following form:

$$
A_\omega = \frac{16P}{\pi^2 \rho h} \int_0^\infty p^{a+1} e^{-\beta P} \sum_{m=1}^\infty \sum_{n=1}^\infty \frac{1}{m \omega_{mn}^2 - \omega^2} \cos \alpha_m \sin \varphi \quad (5)
$$

$$
m, n = 1, 3, 5...
$$

Taking $m = 1$, corresponding to the lowest frequency [3], the expression for $\omega_{mn}^2 = \omega^2$ can be written:

$$
\omega_n^2 = \frac{P_{cr}}{\rho h r} \left( n^2 + \frac{1}{2} \frac{m^2 r^2}{l^2} \right) \left( 1 - \frac{P^*}{P_{cr}} \right)
$$

(6)

were $P^*$ - compression pressure of a cylindrical shell;

$P_{cr}$ –the critical load of a cylindrical shell, determined by the formula of Mises [2]:

$$
P_{cr} = \frac{Eh}{r^3} \left( n^2 + \frac{1}{2} \frac{m^2 r^2}{l^2} \right) \left( \frac{h^2}{12(1-\mu^2)} + \frac{n^4 r^4}{l^4 \left( n^2 + \frac{1}{2} \frac{m^2 r^2}{l^2} \right)^2} \right)
$$

(7)

To carry out further analysis, let us rewrite expression (5) in a more convenient form:

$$
A_\omega = \frac{16}{\pi^2 \rho h} \sum_{n=1}^\infty \frac{\cos \alpha \sin n \varphi}{n} \int_0^\infty p^{a+1} e^{-\beta P} dP \quad (8)
$$

$$
B = \frac{P_{cr}}{\rho hr} \left( n^2 + \frac{1}{2} \frac{m^2 r^2}{l^2} \right); \quad \delta = \frac{1}{P_{cr}}
$$

During normal operation of the pipeline, the frequency range is far from resonant frequency $B(1 - \delta P^*) \gg \omega^2$. Consequently, expression (8) can be simplified:

$$
A_\omega \approx \frac{16}{\pi^2 \rho h} \sum_{n=1}^\infty \frac{\cos \alpha \sin n \varphi}{n} \int_0^\infty p^{a+1} e^{-\beta P} dP
$$

(9)

Taking into account the fact that $\delta P^* \ll 1$, formula (9) can be written in the following form:

$$
A_\omega \approx \frac{16}{\pi^2 \rho h} \sum_{n=1}^\infty \frac{\cos \alpha \sin n \varphi}{n \cdot B(n)} \int_0^\infty p^{a+1} e^{-\left( \beta - \delta P^* \right) P} dP
$$

(10)

It follows from formula (10) that even if the given dynamical system is far from the resonance range, there is still pressure range $P \approx \frac{P^*}{P_{cr}^{1-\beta}}$, where the amplitude of the oscillations will increase with finite probability under condition $e^{-\left( \beta - \delta P^* \right) P} \approx 1$, as a power function of pressure. The pressure fluctuation limits usually reach 10% of the working pressure [5-7]. It is known that such fluctuations, being high frequency, cause small amplitudes of stresses and can not affect the process of appearance of short cracks.

The appearance of short cracks occurs during low-frequency action at large pressure drops during stopping and start-up of the gas pipeline. In this case, the resulting stresses caused by internal pressure drops can be compared with static stresses which are linearly dependent on the pressure [4]:

$$
\sigma_{st} = \frac{P(D - h)}{2h}
$$

(11)

In the case of high-frequency dynamic loads, as shown above, cases are possible in which the strain amplitude grows like a power function together with dynamic stress $\sigma_{\omega}$.

$$
\sigma_{\omega} = \frac{A_\omega}{r_0} \left[ 1 + \left( \frac{3v^2}{1-v^2} \right)^{0.5} \right] E \approx A_\omega^{0} \left[ 1 + \left( \frac{3v^2}{1-v^2} \right)^{0.5} E \right] P^{2+\alpha}
$$

(12)
Consequently, a situation is possible where the stress caused by high-frequency pulsations will be comparable with low-frequency pulsations $\sigma_\omega \approx \sigma_{st}$.

In this case, the high-frequency load will cause the germination of short cracks. Crack length $a_i$, at which the avalanche failure mode begins to develop, will be determined by the expression [4, 8, 9]:

$$a_i = \frac{2}{\pi} \left( \frac{k}{\alpha \sigma_\omega} \right)^2 \cdot 10^3 \text{mm}$$  \hspace{1cm} (13)

where $k$ – stress intensity factor [4],
$\alpha$ – coefficient in the stress formula [4].

For $\bar{\sigma}_\omega \approx 7.5 \text{ MPa}$, $k \approx 1 \text{ MPa} \sqrt{\text{m}}$, crack length, after which achieving the avalanche destruction of the material begins at high-frequency oscillations, will be $a_i \approx 0.5$ mm by formula (13).

3. Conclusion

Thus, a random distribution of pressure inside the pipe can change the fracture mechanism. As it was shown, random pressure fluctuations do not lead to crisis situations under normal conditions. However, in a dynamical system, a critical condition can be realized, in which avalanche failure can be realized. In the theory of destruction, such situation is defined as self-organized criticality.

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