Resource evaluation method for safe use of gas and oil pipeline sections under conditions of bifrequency loading

A L Shurayts¹, D I Egorov¹

¹JSC «Gipronigaz», Kirova 54, Saratov, Russia

egorov@niigaz.ru

Abstract. The article proposes a mathematical model for predicting gas and oil pipeline section resource under bifrequency loading. Mathematical model for pipeline safety evaluation is formulated. The authors offer a resource-predicting algorithm for gas and oil pipelines.

When evaluating metalwork elements resource, we solve a probabilistic task, in which, construction resource and condition under different exploitation conditions, through certain period of time are to be figured out only with some degree of certainty. In application to gas and oil pipelines, the task of resource is mostly about predicting trouble-free work probability (probability characteristics) for pipeline elements depending on probable exploitation modes and conditions. Validity of prediction is mostly influenced by the source of information about different pipeline elements reliability, as well as processes that cause efficiency loss. Laws of material properties change under conditions of exploitation are applied for resource evaluation. Investigations of these processes lead to the development of exploitation methods for constructive elements reliability increase [1, 2].

The article shows the necessity for development of an evaluation method for gas and oil pipeline safe use [3]. Herewith, the resource evaluation under conditions of bifrequency loading of pipeline sections with consideration of the degree of defect dangers has not been considered in this article.

Curved oil and gas pipeline sections with turning elements, or the so-called curve sections, are the most strained and dangerous sections. Inner pressure loading, in some cases repeated static loading that takes place due to changes in pumping technological mode or fluid temperature mode cause vibration [2]. It appears only in curve sections due to non-stationary hydraulic influence as a result of pressure pulsation at the pipeline inlet from the compressor and the pump, or passing through the two-phase fluid system, especially in the plug mode. The origins of vibration can also be explained by gas flow disturbance at the expense of transitional processes, automatic oscillations in points of interaction between stationary flow and curve elements, branch lines, valves, T-bends, and presence of pipe diameter narrowings.

Bifrequency loading in some cases leads to speeding up of fatigue stress accumulation in the pipeline metal. Works [4, 5] prove experimentally that if relation between vibration frequencies and cyclic inner pressure load is more than 10, then, regardless of the amplitudes and initial phases of the component loads, we can observe, other things being equal, a decrease in metal fatigue resistance under bifrequency loading.

When evaluating the resource of curved pipeline sections with turning elements that work under conditions of non-stationary preloading by inner pressure and vibrations, it is necessary to consider the phenomenon of fatigue under bifrequency loading, because either way it is impossible to make justified decisions regarding destruction prevention.
In our opinion, for gas and oil pipeline working capacity maintenance under conditions of bifrequency loading, harsher rationing of permissible parent metal and pipeline welds defectiveness is necessary, which, consequently, leads to resource prediction.

While complying with Coffin-Manson equation [6] and taking into consideration the influence of the fatigue factor on durability under conditions of gas and oil pipeline bifrequency loading, we accept that:

\[ N_0 = N_2 = \frac{N_p \theta}{D}, \]  
(1)

where \( N_p \) – design number for cycles of oil and gas pipeline element loading by inner pressure in set operation time \( T_o \);
\( N_0 \) – number for cycles of gas and oil pipeline element loading by inner pressure up to limiting condition, i.e. up to appearance of crack in pipeline metal. This is cyclic strength criterion, where the stage of crack appearance is taken with minimal size of 0,25mm [7];
\( N_2 \) – cyclic life under conditions of bifrequency loading;
\( \theta \) — coefficient (dimensionless quantity) of cyclic life decrease under conditions of gas and oil pipeline bifrequency loading;
\( D \) — relative ratio of oil and gas pipeline element metal damage (dimensionless quantity). According to research results [7] and taking into consideration (1) we have:

\[ D = A \cdot N_p \cdot \theta, \]  
(2)

where \( A \) is the coefficient (dimensionless quantity), characterizing metal damage per oil and gas pipeline element preloading cycle, 1/cycle; \( \sigma_{work} \) is the ring-type stress in pipeline metal, caused by inner pressure, MPa; \( n_\varepsilon \) is the coefficient for pipeline metal deformation margin (dimensionless quantity); \( \alpha_\sigma \) is the theoretical coefficient of stress concentration, according to Neuber (dimensionless quantity); \( \chi \) is the coefficient that characterizes pipeline metal plastic properties (dimensionless quantity); \( E \) is the elasticity module, MPa; \( n_\sigma \) is the coefficient of pipeline metal plastic properties (dimensionless quantity); \( \psi_1 \) is the coefficient that accounts for pipeline metal two-dimensional stress state (dimensionless quantity); \( c \) is the metal work hardening index (dimensionless quantity); \( m_c \) is the property that accounts for harsh cyclic loading and corrosive medium influence (dimensionless quantity).

Coefficient of cyclic life decrease under conditions of gas and oil pipeline element bifrequency loading \( \theta \), as follows from the experiments [4], has a range, where maximum dilatation, i.e. concentration interval upper boundary with confidence coefficient of 0,95, is 1,25.

\[ \theta = \frac{N_1}{N_2} \]  
(4)

where \( N_1 \) is the cyclic life under conditions of unifrequent (low-frequency) loading correspondingly; \( D_1, D_2 \) is the property of metal damage under conditions of unifrequent and bifrequent loading correspondingly.

At that \( N_p = N_1 \cdot D_1 \) or \( N_p = N_2 \cdot D_2 \).

Thus, we obtain:

\[ N_1 = \frac{1}{A_1}, \quad N_2 = \frac{1}{A_2}, \]  
(5)

or

\[ \theta = \frac{N_1}{N_2} = \frac{A_2}{A_1}. \]  
(6)
Other things equal, according to the formula (2, 3) we obtain:

\[ \theta = \left( \frac{\alpha_{\sigma_2}}{\alpha_{\sigma_1}} \right)^{\frac{1}{1+c}}. \]  

(7)

With \( c = 0.24 \), \( m_c = 0.52 \) we have

\[ \theta = \left( \frac{\alpha_{\sigma_2}}{\alpha_{\sigma_1}} \right)^{0.84} \]  

(8)

or

\[ \alpha_{\sigma_2} = \theta^{1.2} \cdot \alpha_{\sigma_1}. \]  

(9)

Under condition of \( \alpha_{\sigma_1} = 1.62; \; \theta = 1.25 \) the result is \( \alpha_{\sigma_2} = 2.1. \)

Thus, under conditions of bifrequent loading of gas and oil pipeline element the defectiveness upon parent metal and pipeline welds property \( \alpha_{\sigma} \) should be normalized \( \theta^{1.2} \) times harsher in comparison to defectiveness of pipes under conditions of unifrequent loading. Thus, if accepted value is \( \alpha_{\sigma} = 2.1 \) for conditions of unifrequent preloading of gas and oil pipeline elements, then the accepted value for bifrequent preloading is \( \alpha_{\sigma} = 1.7. \)

In general, graphic dependency of \( \alpha_{\sigma} \) from \( \theta \) is demonstrated in Figure 1.

\[ \text{Figure 1. Dependency of } \alpha_{\sigma} \text{ from } \theta \]

While establishing the defect hazard level, one should increase the number of normalized load cycles by \( \theta \) times. Thus, if normalized \( N_1 = 10000 \) cycles, and \( \theta = 1.2 \), then in calculation and evaluation of defect permissibility it is necessary to set \( N_2 = 12000 \) load cycles.

Subject to condition where \( D = 1 \) the result is to be:

\[ A \cdot N_p \cdot \theta = 1. \]

\[ A = \frac{1}{N_p \cdot \theta}. \]  

(10)

Having information regarding numerical value of \( A \), according to formula (10) it is possible to evaluate gas and oil pipeline element resource under conditions of gas and oil pipeline bifrequent loading. However, it is not enough to make a decision regarding gas and oil pipeline safe use resource. It is necessary to indicate the property value of gas and oil pipeline elements defect-free performance probability (expected frequency of failures), while predicting.

As it was pointed out above, the resource prediction task comes to predicting gas and oil pipeline element defect-free performance probability, while taking into consideration probable modes and conditions of use. The following algorithm is proposed for solving the opposite task, i.e. the expected safety characteristic is defined through given resource.
According to [3], theoretical stress concentration coefficient, that characterizes parent metal and pipeline welds defectiveness value, has a correlation with reliability coefficient for material $K_1$ as follows:

$$K_1 = \alpha_\sigma^{0.39}$$ (11)

Herewith, $K_1$ has analytic dependency on pipeline working capacity coefficient $K_3$ as follows:

$$K_1 = \frac{K_3 \cdot m}{K_r} \cdot \left(1 + \frac{1}{n}\right) - 1$$ (12)

where $m$ is the pipeline working conditions coefficient (dimensionless quantity); $K_r$ is the reliability coefficient based on pipeline utilization purpose (dimensionless quantity); $n$ is the reliability coefficient based on pipeline loading (dimensionless quantity).

Let us use safety characteristic $\gamma$, given in [8, 9], that appears as follows:

$$\gamma \cong \frac{1}{\alpha_d} \cdot \left(1 - \frac{1}{K_3}\right)$$

where $\alpha_d$ is the durability variability (variation) coefficient; $\alpha_p$ is the loading variability (variation) coefficient.

Herewith

$$\alpha_d = 0.61 \cdot \left(1 - \frac{2}{K_1 + 1}\right)$$ (14)

Safety characteristic $\gamma$ is, actually, a durability and loading properties normal distribution quantile. It directly characterizes gas and oil pipeline defect-free performance probability [10].

Thus, taking into consideration (5) – (8), the result is that stress concentration coefficient is calculated according to formula:

$$\alpha_\sigma = \left[\frac{K_3 \cdot m}{K_p} \cdot \left(1 + \frac{1}{n}\right) - 1\right]^{2.564} = \left[\frac{m(1+1)}{1-\gamma \cdot \alpha_d} \cdot K_p - 1\right]^{2.564}$$ (15)

Therefore, calculation of $\alpha_\sigma$ when $\gamma$ is given allows to evaluate coefficient $A$ using formula (2), and subsequently, to predict gas and oil pipeline element resource defining the pipeline’s safe use conditions.

For practical calculations of $\gamma$ we recommend to use the following algorithm:

- $N_0$, $\theta$ are defined, and coefficient $A$ is calculated using formula (10);
- Calculation of $\alpha_\sigma$ is performed using formula (3) $\alpha_\sigma$;
- Calculations of $K_3$, $K_1$, $\alpha_d$ are performed using formulas (11), (12), (14) correspondingly;
- Calculation of $\gamma$ is performed using formula (13), and comparative assessment with acceptable $\gamma_{acc}$ value is carried out.

References

[1] Perov S N, Argafenin S I, Skvortsov Yu V and Tarasov Yu L 2008 Reliability assurance of pipeline system: a monograph (Samara: SNTS Publishing House)
[2] Kharionovskiy V V 2000 Reliability and lifespan of pipeline constructions (Moscow: Nedra)
[3] Sultanov M Kh, Shurayts A L and Egorov D I 2016 Methodology for assessing the safe operation life for oil and gas pipelines Scientific and technical journal Industrial Safety in Industry 6 68–70
[4] Sultanov M Kh and Egorov D I 2015 Estimation of no-failure operation at two-frequency loading of pipeline Scientific and technical journal Problems of collecting, preparing and transporting oil and oil products 4(102) 194–8
[5] Sultanov M Kh and Gavrilin A V 2012 Cyclic longevety of pipe steel samples at two-frequency loading Problems and methods of ensuring reliability and safety of the oil, oil products and
gas transportation system: materials of the scientific-practical conference 23/08/2012, Ufa

[6] Serensen S V, Kogaev V P and Shneyderovich R M 1975 Bearing capacity and calculation of machine parts for durability. Manual and reference book ed S V Seresnen (Moscow: Mashinostroenie)

[7] Sultanov M Kh 2005 Longevity of main oil product pipelines (Moscow: Nedra)

[8] Rzhanitsyn A P 1978 Calculating theory of reliability for building constructions (Moscow: Stroyizdat)

[9] Reliability and efficiency in engineering. Reference book. Volume 10: Reference data on operating conditions and reliability characteristics 1990 ed V.A. Kuznetsov (Moscow: Mashinostroenie)

[10] Shor Ya B and Kuzmin F I 1968 Tables for analysis and control of reliability (Moscow: Sovetskoye radio)