Dynamic Measurements of Tank Wall Deformations as a New Method for Assessing its Technical Condition

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Abstract. The paper proposes a new approach to assessing the residual resource of the wall of a vertical steel tank by the criterion of low-cycle loading, taking into account its actual deformations. The method is based on the principle of measuring the difference in the power of the luminous flux at the ends of the light tube (light guide) when it is bent. An experiment was carried out using an optical pair (LED and photodiode) and an optical fiber. For this purpose, templates with known radii of curvature were prepared, a prototype of an Arduino-based device was developed and an optical fiber was manufactured, which was subsequently fixed on the wall of a two-hundred-liter metal barrel. As a result of the experiments, a formula was obtained for determining the curvature of the wall depending on the readings of the sensor. The sensitivity of the proposed method is estimated. An algorithm for determining the number of cycles before the formation of fatigue cracks is proposed, taking into account the actual values of the wall deflection.

1. Introduction
Modern industrial trends require a constant increase in reliability indicators. The construction of new critical structures is accompanied by increasing design requirements, in particular, in the field of safety and ecology, which complicates and increases the cost of the project. In addition, the cost of capital construction is constantly increasing, which leads to a situation where maintaining the operation of existing facilities becomes economically more profitable than their reconstruction or construction of new ones.

Continuous monitoring of the state of structures, equipment and facilities, in conjunction with the development of automation and storage of large amounts of data, will make it possible to assess the current state in real time, determine the residual resource and predict the optimal mode of maintenance and / or repair. This state of affairs coincides with the global trend towards the development of digitalization of production.

2. Timeliness
Many steps have already been taken in the field of continuous monitoring of the technical condition of industrial equipment; rather simple methods of continuous monitoring have long been introduced in production. For example, on trunk oil pumping units, the overall vibration level is monitored. Also, more complex control systems are being successfully investigated and developed, such as a system for
automatic diagnostics of gas pumping units [1] and a method for diagnosing oil pumping equipment using continuous strain gauge [2].

Continuous monitoring of the technical condition of structures is more difficult to carry out. Equipment in operation generates vibration, has different temperatures, may require monitoring of the presence of oil, etc. - all this can be the basis for obtaining initial information for subsequent diagnostics. However, the structures do not have such features. Therefore, it is more difficult to determine the parameters by which it is possible to carry out both periodic and continuous monitoring.

Thus, the development of continuous monitoring of the technical condition of an oil storage tank based on the actual position of the wall faces two fundamental problems. The first one is the problem of determining the initial information for diagnostics: the choice of the control parameter and the method of technical implementation of its measurement, while the measurement should be simultaneously technically simply feasible, low-cost and reliable. The second problem is the choice of the method and methodological base for the interpretation of the results.

Further, the presented problem and the method of its solution will be considered in the context of vertical steel tanks for storing oil and petroleum products. In this area, this is extremely important, since over 70% of the tanks operated in Russia have a significant service life, including those exceeding the standard [3]. At the moment, many studies are being carried out aimed at assessing the technical condition of tanks [4-7], which make it possible not only to prevent possible failures, but also to better plan the operating modes of each specific tank, thereby providing the ability to foresee or reduce expensive repairs [8, 9]. However, there is a problem of their automation and carrying out in a continuous format.

3. Statement
To ensure the possibility of continuous monitoring of the technical condition of the tanks, it is proposed to consider the assessment of the actual position of the vertical wall. Under the action of a hydrostatic load, the wall undergoes elastoplastic deformations, which increase as the service life of the tank increases.

Controlling such deformations will allow the durability of the reservoir to be assessed. We note that on tanks, wall deformation during filling can reach more than ten millimeters - for example, on vertical stock tank (20000 m³) it is about 20 mm.

From a technical point of view, wall deformation can be measured using strain gauges. They need to be placed evenly over the entire surface of the tank wall, which causes certain problems, since information from each sensor must be read separately, and as a result, a large number of wires, communication channels and corresponding data processing will be required.

In this study, it is proposed to use an optical fiber as a sensitive element that adjoins the surface of the tank and will allow assessing its deformation. The method is based on the principle of changing the intensity of the light flux passing through the fiber, depending on the degree of its deformation. The method will make it possible to measure the bending (and, accordingly, the deformation of the surface to which the fiber is applied) with high sensitivity.

Further, by evaluating the value of the plastic deformation of the wall, it is possible to obtain the number of cycles before the formation of fatigue cracks and to determine the residual resource of the reservoir [10].

4. Theoretical
In this case, the algorithm for determining the technical condition of the reservoir in real time, and, in particular, the residual resource, can be as follows:

- Obtain information about the deformation of the tank wall using an optical fiber.
- Convert the readings on the fiber (luminous flux) to the bending radius of the fiber (therefore, to the radius of curvature of the wall).
- Determine the number of cycles to the formation of fatigue cracks from the data of plastic deformation of the wall.
The number of cycles to fatigue cracking can be determined using the Coffin-Manson equation

\[
\varepsilon_a = 1.75 \frac{\sigma_u - \sigma_m}{E} N_p^{0.12} + \frac{1}{2} \ln \left( \frac{1}{1 - \psi} \right)^{0.6} N_p^{0.6}
\]

where \(\varepsilon_a\) is the amplitude of total deformation per cycle; \(\sigma_m\) is the average stress of the cycle; \(\sigma_u\) is the ultimate strength of the material under static tension; \(E\) is the modulus of elasticity; \(\psi\) is the relative narrowing of the cross-sectional area of the sample under tension; number of cycles before the formation of fatigue cracks \(N_p\).

The deformation of the wall in the vertical plane can be estimated as a first approximation as

\[
\varepsilon = \frac{0.5t}{\rho} = 0.5tr
\]

Solving equations (1)-(3) together, it is possible to determine the residual life, that is, the number of cycles before the formation of fatigue cracks \(N_p\).

5. Findings

To implement the idea, a light guide was made based on silicone and heat-shrinkable tubes, as well as a photodiode and an LED (Figures 1 and 2). The first experiments were carried out on a photoresistor, but its large error of readings forced to abandon its use in favor of an optical pair (photo and LED). For bench experiments, an 840 mm long fiber was fabricated; an additional 100 mm long fiber was fabricated for commissioning.

![Figure 1. Light guide circuit.](image)

To test the possibility of using the light guide to control the wall position, an electronic board was made (Figure 3), which includes an Arduino Uno microcontroller, an external 16-bit analog-to-digital converter (ADC) with a built-in ADS1115 signal amplifier to improve the measurement accuracy, an optocoupler with peak emission / reception wavelength of 940 nm, resistors for limiting currents, module KY-026, sensitive to the infrared spectrum (later it was decided to abandon it due to the negative effect on the external ADC). The microcontroller was programmed in C ++ in the Arduino IDE.
Figure 3. Electrical diagram of the developed electronic board for determining the wall deformation using a light guide.

The light guide must be tightly and rigidly mounted on the outer wall of the tank along its entire height. An example of installing a fiber on a model barrel is shown in Figure 4.

Figure 4. An example of installing a light guide on a barrel for storing petroleum products.
To assess the possibility of implementing the proposed method, experimental studies were carried out to determine the readings of an electronic device from a bend of a fiber. Templates with known radii of curvature were prepared, the light guide was matched to the template (that is, its radius of curvature \( s \) determined), the voltage across the photodiode and the readings obtained after digitizing the values were determined (Figure 5).

![Figure 5](image-url)

**Figure 5.** Dependence of the fiber curvature on the readings of the experimental setup.

The approximation of the results made it possible to obtain the following dependence (sensor readings \( P \); bending radius \( \rho \), m); the coefficient of determination \( R^2 \) is 0.9792)

\[
\rho = \frac{1014}{P - 1528}
\]  

(3)

The dependence of the radius of curvature of the wall \( \rho \) (m) on the voltage (mV) across the photodiode was also obtained

\[
\rho = \left(1.4 \sqrt{U} - 5.4\right)^{-1}
\]  

(4)

The coefficient of determination \( R^2 \) was 0.977 for (4), which is a fairly high indicator and confirms the reliability of the model obtained.

The graph of the dependence of the radius of curvature \( \rho \) of the light guide on the voltage \( U \) at the photodiode is shown in Figure 6.
Figure 6. Dependence of the radius of curvature of the wall on the voltage on the photodiode.

The change in the radius of curvature of the wall during the loading-unloading cycle must be converted into the total deformation amplitude per cycle by algebraic calculations.

An important step is to predict the error of the proposed method on an oil storage tank.

The method error is affected by possible deviations in the operation of the ADS1115 signal amplifier with a built-in analog-to-digital converter. Its error less than 0.1% [11].

Analysis of Figure 5 shows that the relationship between the curvature of the fiber and the obtained data is linear, which is confirmed by the high value of the coefficient of determination ($R^2 = 0.9792$) when approximated. According to formulas (1) and (3), we find that the relationship between $r$ and $\varepsilon$ is linear, thus, the error in determining $\varepsilon$ is also 0.1%, which ensures high accuracy in further determining the number of cycles before the formation of fatigue cracks $N_p$.

6. Conclusion

The presented study proposes a method for determining the technical condition of a tank for storing oil and oil products. The method is based on the use of a light guide, which makes it possible to determine elastoplastic deformations of the tank wall with high sensitivity. Elastoplastic deformation is used to calculate the number of cycles until the formation of fatigue cracks, the residual life and the general technical condition of the reservoir.

It is quite obvious that this method is easily automated and provides the possibility of its application in real time, which opens up opportunities for increasing the degree of digitalization in the industry and conducting an assessment of the technical condition on a deserted basis.
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