Methodology of using fatigue gauges to monitor machinery load

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Abstract. The problem of preventing fatigue damage of machinery critical parts by means of their control with the help of fatigue gauges is considered. The principles of operation and the method of synthesis of fatigue gauges with high sensitivity are described. The technique and results of the stand experiment on the determination of stresses equivalent to the damaging effect of the operating stress spectrum of the vehicle frame are presented using fatigue gauges made of tin foil. It is noted that the monitoring of the parameters of the fatigue gauges can be performed automatically, including using vision devices.

1. Introduction
For the first time in the world to use galvanic copper foil as a means of measuring cyclic stresses acting on the surface of machine parts was proposed in [1, 2]. For the manufacture of such foil developed special modes of electrodeposition. Dark spots (flecks) appearing on the surface of copper sensors are monitored visually with a magnifying glass or microscope.

In [3], it was first proposed to use industrial-grade aluminium foil as fatigue gauges. Slip lines, micro- and macro-cracks appear on the surface of aluminium gauges, which are also monitored with a microscope or magnifying glasses.

A disadvantage of the known fatigue gauges made of copper or aluminium foil is their low sensitivity to small cyclic deformations. For example, if the surface of a steel part experiences cyclic stresses with an amplitude of 167 MPa, then the copper sensor will react after 5 million cycles [2]. If the surface of a steel part experiences cyclic stresses with an amplitude of 62.5 MPa, the aluminium gauge will react after 1 million cycles [4].

Thus, copper and aluminium fatigue gauges are good for studying high-loaded machine parts: gears, shafts, springs and others. But such fatigue gauges are unsuitable for monitoring elements of frames, body parts and machine shafts experiencing relatively low operating stress, since these sensors do not provide for their quick and timely monitoring.

The purpose of the paper is to describe: the principles of operation of fatigue gauges; method of designing fatigue gauges with high sensitivity; method of using fatigue gauges to control the loading of parts or structural elements.

2. Operation principles of fatigue sensors
In [5], it was shown that the study of fatigue gauges should be carried out in a system with a controlled part. Therefore, as a methodological basis for describing the functioning of fatigue gauges, we apply a systematic approach. The fundamental principles of a systems approach are consistency and integrity.
In accordance with the principle of integrity, the fatigue gauge and the tested surface of the part are treated as a single object, as shown figure 1. The surface of the part and the gauge experience the same cyclic deformations: the main deformations of the fatigue gauge $\varepsilon_i^G$ are equal to the main deformations of the surface layer of the part $\varepsilon_i^P$, where $i = 1, 2$.

![Figure 1. Fatigue gauge and the surface of machine part as a system: 1 – part of machine; 2 – fatigue gauge; 3 – adhesive layer.](image)

The essence of the principle of consistency is the requirement to “study the object from different angles, comprehensively, unlike the previously adopted division of research into physical, chemical, etc.” [6]. The principle of consistency was used in [5], where it was noted that all existing effects and manifestations of fatigue are suitable for creating new designs of fatigue gauges and methods for their use and control. This is fundamentally different from the well-known studies that explain the formation of controlled changes in the foil surface only by chemical [1, 2] or only mechanical [3, 4] reasons.

For a more detailed description of the functioning of fatigue gauges, we use the methodological principles of system research formulated in the General theory of systems.

The principle of one centre perception [7] describes the presence of only one centre, which is a backbone, guiding, managing, concentrating "certain activities". And if the system has a complex, “chain” organization, then “it has one higher, common centre” [7]. The principle of one centre is also manifested in the operation of fatigue gauges: it is the deformation of the monitored element of the machine that leads to cyclic deformation of fatigue gauges.

The principle of relative resistance (the law of least): "the stability of the whole depends on the lowest relative resistance of all its parts at any moment." "The structural stability of the whole is determined by its least partial stability" [8]. The law of the minimum is also manifested in the operation of fatigue gauges: fatigue gauges experience the same cyclic deformations together with the surface layer of the part being monitored, but they are damaged and destroyed before the parts.

"The principle of progressive segregation determines the continuous progressive nature of the loss of interactions of elements in the process of differentiation" [9]. “The principle of progressive mechanization is (...) that in the process of developing systems, parts will become fixed with respect to certain mechanisms” [9]. These principles, proposed by L. von Bertalanffy [10], describe the loss of performance of fatigue gauges due to their cracking as a result of a large number of loading cycles while retaining accumulated damage and information inside the resulting fragments.

Background principle: investigating only the background signals or its state, one can judge about the object [6]. In this case, the system is composed of an object, a background, an observer, and their relationships. In relation to the problem, the object is a controlled part, and the background is a fatigue sensor: by changing the state of the fatigue gauge, the observer judges the cyclic stresses that the part
has experienced. At the same time, in the part itself, the fatigue damage occurred may be insignificant and (practically) undetectable.

In the process of research, the decisive role was played by the principle of compatibility. This principle establishes that “the condition for interaction between objects is their relative compatibility property” [11]. It is the ability to create highly sensitive fatigue gauges and correctly choose (if necessary, reduce) the range of amplitudes of cyclic stresses when using gauges, made it possible to solve the tasks quickly, that is, with relatively small numbers of loading cycles.

3. Method of synthesis of highly sensitive fatigue gauges

Based on the principle of integrity, using figure 1 and the Hooke's law for uniaxial deformation [12], we will write the following formula:

$$\frac{\sigma^G}{E_G} = \varepsilon^P,$$  (1)

where $\sigma^G$ – stress in the fatigue sensor, MPa; $E_G$ – modulus of elasticity in tension or compression of the material of the fatigue gauge, MPa; $\varepsilon^P$ – deformation of the machine part surface.

Based on the principle of consistency, we use information from the theory of metal fatigue. It is known [13] that the strength characteristic of metals under the action of cyclic loading is the endurance limit or fatigue strength. Therefore, to describe the ultimate stress of the fatigue gauge in expression (1), it is necessary to substitute $\sigma^G = s^G_N$, where $s^G_N$ is the fatigue strength for $N$ cycles.

We will require that the system in question (figure 1) work with minimal deformations of the part surface. To this end, in expression (1) we put: $\varepsilon^P \rightarrow \min$.

The result is a condition for increasing the sensitivity of the fatigue gauge to the cyclic stresses of the monitored part [5]:

$$\frac{s^G_N}{E_G} \rightarrow \min.$$  (2)

Using condition (2), a prediction was made of the applicability of all metals in the periodic table as fatigue gauges [5]. In particular, a forecast was made about the high sensitivity to small cyclic deformations of tin fatigue gauges.

The essence of the method of synthesis of fatigue gauges with high sensitivity is to reduce their endurance limits according to the objective function (2). This can be achieved by annealing the foil [14], by preliminary cyclic deformation [15], by weakening the concentrators [16] and by other methods.

4. Methodology and results of the experiment

For experimental verification of the predicted high sensitivity of tin fatigue gauges, calibration tests were performed. The gauges were glued on steel specimens from st.3sp with a conical working part. Using simple fixtures, the specimens were cyclically loaded under symmetric torsion conditions.

Curve 1 in figure 2 is a calibration curve of a fatigue sensor of tin foil annealed at 200 °C. Curve 2 in figure 2 was obtained under the same conditions for a fatigue sensor made of soft aluminium foil and is a fragment of its calibration curve. The curves are plotted according to the moment of appearance of slip lines on the polished surface of the gauge, visible with an optical microscope at 100x magnification (figure 3a). From figure 2 it can be seen that tin fatigue gauges respond about 100 times faster than aluminium gauges.
Figure 2. Fragments of calibration curves for tin (1) and aluminum (2) fatigue gauges.

Figure 3. Slip lines on the surface of the tin sensor after 5000 loading cycles: a - with constant amplitude $\tau = 25.838$ MPa; b - per stress spectrum.

Paper [17] presents the results of the study of the loading frame of the tractor trailer. The endurance limit of the structure was established experimentally and amounted to $\tau_{-1} = 63.84$ MPa. The most damaging is the mode of movement with a load on broken dirt roads (while the frame durability is 9,600 km, i.e. 2.4 million loading cycles). Computed in work [17], the calculation of the cyclic life of the frame (when summing fatigue damage taking into account the reduction of the fatigue limit based on kinetic diagrams of fatigue) gave a value of 2.4 million cycles. And it is not difficult to determine from the fatigue curve equation given in the paper that the amplitude of cyclic stress equivalent to the damaging effect is $\tau_{\Pi} = 70.007$ MPa. If, however, calculations are made according to the linear hypothesis of summation of fatigue damage, durability will amount to 2.618 million cycles, stress amplitude $\tau_{\Pi} = 69.039$ MPa (which differs from the results of [17] by only 9.08% and 1.38%, respectively).

In this paper, the task of estimating the operational load of the trailer frame is solved with the help of fatigue gauges. At the same time, in order to reduce the duration of the tests, the loading unit was reduced by 2 times (to 5,000 cycles). The highly sensitive fatigue gauges of annealed tin foil proposed by the author were used. Based on the analysis of the results of theoretical calculations and calibration tests (curve 1 in figure 2), the values of the stresses described in [17] were reduced by a factor of 2.88. (On a full-sized object, to reduce the effective torsional stresses, the sensor is displaced to the longitudinal axis of the channel, and if there is a stress concentration, it is removed from the concentrator.) The sequence of reproduction of the unit of operating stresses is presented in figure 4, it was established by random sampling.

Figure 4. Chart of the reproduced stress block.
As a result of the tests, after the first block of stresses, the value equivalent to the damaging effect of the amplitude of the cyclic stress \( \tau_{11} = 25.838 \times 2.88 = 74.4 \text{ MPa} \) was established. This is 6.3% higher than the value obtained from the results of [17] and 7.8% higher than the value obtained by the linear hypothesis of the summation of fatigue damage. This answer is established by comparing the appearance of the sensor surfaces after 5000 loading cycles of the operational stress spectrum and the sensor after calibration tests (figure 3). An MBS-9 microscope was used with a magnification of 100x and direct illumination.

It should be noted that this method of monitoring fatigue gauges is the simplest, but not the only one [18]. It is known to use for this purpose an eddy current control method [19], as well as special computer programs for analysing the state of the surface of a fatigue gauge [20] used in technical vision devices.

5. Conclusion
Based on a systematic approach and a General theory of systems, the principles of functioning of fatigue gauges are formulated. The objective function and the method of synthesis of fatigue gauges with high sensitivity are described.

The technique and results of the stand experiment to determine the stresses equivalent to the damaging effect of the operating stress spectrum of the tractor trailer frame are presented. The use of highly sensitive fatigue gauges made of tin foil ensured a deviation of the obtained results from the calculated ones by no more than 7.8%.

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