On the choice of a failure criterion for pumping units based on the results of vibration spectra measurement

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Abstract. The paper presents the results of a study of the possibility of failure prediction (failure) of complex units (for example, pumping units) as a result of the impact of vibration forces. It is shown that the total energy (time integral of the vibration power) at resonance frequencies and in an infinite frequency strip under the condition of the experimental coefficient can be a criterion for the failure of both individual units and the unit as a whole. In this case, the predicted failure time is a function of the calculated measure of destruction” and the accumulated energy.

1. Introduction
The modern approach to diagnostics in general (in particular when applied to energy) is to use the so-called multifunctional technological platform, i.e. sharing methods such as:
- vibration diagnostics,
- parametric analysis (parameters of the working process, PEC - pressure-energy characteristics)

Maintenance principles (strategies):
As a rule, in practice, there are 3 main strategies for maintenance and repair (MR) of equipment, including their combinations in various proportions:
1 - “before the accident” - low value and insignificant equipment;
2 - SPR (scheduled preventive repair) - equipment of average importance and cost;
3 - ACS (actual condition service) - valuable and significant equipment in the technological chain.
The data of both domestic and foreign sources show that if we take the operating costs for SPR as 100%, then the costs for maintenance “before the accident” will be 130%, according to the ACS strategy - 70%.
There are three main directions in vibration diagnostics:
- vibration monitoring,
- modal analysis,
- wavelet analysis (in development).
In order to increase the reliability and safety of machines and mechanisms, as well as to reduce the costs of their operation, condition monitoring and diagnostics systems (CM&D) have become widespread.
Monitoring is the tracking the parameters of working processes within the limits of tolerances (norms). Condition monitoring systems are associated with alarms and protection when parameters are outside the set limits. Condition monitoring systems can provide continuous (real-time) or periodic
monitoring of parameters. Instruments are from simple vibrometers to processor-based spectrum analyzers.

Diagnostics is designed to carry out maintenance or repairs based on the actual condition (ACS) based on in-depth control using monitoring data, or, more simply, identifying equipment defects at various stages of their development.

CM&D is used either in the form of unified systems, or in the form of 2 subsystems.

A greater amount of information is required in order to solve such a complex problem as the assessment of the technical condition of a machine or equipment with the determination of the location of the defect, the identification of the type of defect and the degree of its development, as well as the prediction of changes in the technical condition of an object.

This amount of diagnostic information is contained in the vibration signal. These are the general level of vibration or noise, the levels in certain frequency strips, the relationship between these levels, the amplitude A and the frequency $\nu$, the initial phases of each component, the relationship between A and $\nu$, etc.

Thus, the main goals and objectives of vibration monitoring and diagnostics systems (VM&D) are:

a) the improvement of the reliability and safety of machines and mechanisms;
b) the reduction of operating costs;
c) the maintenance and repair according to the actual technical condition;
d) the prediction of the condition to prevent failures and planning of TR;

Any design has many resonant vibration frequencies (or many modes). Physically, it looks so that when vibrations are excited, the structure will ring at several resonant frequencies.

For the practical implementation of the procedure for the experimental determination of the frequency parameters of a structure, a 2-channel spectrum analyzer and a vibration excitation system are required to deliver a dosed impact on the structure (as a rule, it is a hammer with a piezoelectric sensor for measuring the impact force). As a result, we determine the reaction of the system to external influences, i.e. resonances of the structure.

At present, due to the development of non-destructive testing methods (first of all, vibration diagnostics), much attention is paid to the determination of the predicted service time, or the date of the next state study, of aggregates [1–4]. To do this, it is necessary to determine a criterion that allows assessing the accumulation of fatigue damage in the body of individual nods of the units and, thereby, assessing the failure probability of individual units, and therefore failure of the unit in general.

This can be done considering the contribution of individual vibrational frequencies to the process of the accumulation of a fraction of failure energy and dissipated in the form of heat [5–10].

2. Materials and methods

Let an single-valued correspondence be established between the amplitude-frequency characteristic (AFC) of the vibration spectrum (Fig. 1) and the physical properties of individual nods of the unit so that each “expressed” frequency $\nu_i$ corresponds to the natural frequency of oscillations of this i-th joint.

Let us consider the failure of this joint in the model of accumulation of the sum of instantaneous elastic and viscoelastic deformations $\xi_{mu} + wu$, that is, in contrast to [2], where instant-plastic $\mu$ and visco-plastic $\xi_{wu}$ deformations are decisive for static loads. The rationale for this is that the total stresses during vibrations are far from the limiting ones for elastic deformations [5].
The accumulation of the value $\xi \mu + \nu u$, more precisely, the accumulation of disseminated deformations in the body of an individual joint is associated with the vibration energy in this joint:

$$W_{i,v} = k \cdot A^2 \cdot \cos(2\pi vt) , \quad (1)$$

where $k = k_j/2$, $A$, $t$ - rigidity $j$-joint, instantaneous amplitude and time, respectively.

Introducing here the parameter $c$, characterizing the fraction of the energy going to the mechanical failure - the accumulation of disseminated cracks (then the fraction of the energy dissipated in the form of heat will be equal to $1-s$), we will write the parameter defining the fracture dynamics:

$$W_{i,v} = c \cdot k \cdot A^2 \cdot \cos(2\pi vt) , \quad (2)$$

Then the share of energy in the spirit of the above mentioned remark in the range $v \in (v_j - \Delta v_j, v_j + \Delta v_j)$ is:

$$W_{i,v_j} = \int_{v_j-\Delta v_j}^{v_j+\Delta v_j} W_{i,v} \cdot dv . \quad (3)$$

The energy accumulated by $i$-th vibration by the moment of failure $t_p$ will be presented by integral equation:

$$W_{i,v_j} = \int_0^{t_p} \int_0^{v_j+\Delta v_j} W_{i,v} \cdot dt \cdot dv . \quad (4)$$

However, it is clear that the failure of this elastic unit of the aggregate is the result of the accumulation of deformations (energies of the form (3)) not only due to vibrations $v_i$, but also vibrations of other frequencies. This circumstance forces us to extend condition (4) to the entire range of vibration frequencies:

$$W_{i,v} = W_{i,v_j} + \left[ \int_0^{v_j-\Delta v_j} W_{i,v} \cdot \varepsilon \cdot dv + \int_{v_j-\Delta v_j}^{v_j+\Delta v_j} W_{i,v} \cdot \varepsilon \cdot dv \right] = \int_0^{t_p} \int_0^{v_j+\Delta v_j} W_{i,v} \cdot \varepsilon \cdot dv , \quad (5)$$
where $\varepsilon_\nu$ – a measure of the influence of frequency fluctuations $\nu$ on the destruction of a given $i$-th joint.

Moreover, if we take the influence $\varepsilon_\nu$ of the frequency $\nu$ as maximum and equal to 1, then we have (4) at the time of failure.

3. Results and Discussion
We believe that the proposed failure criterion will describe the process of accumulation (irreversibly) of the deformation fraction of vibration energy and will be a convenient parameter for statistical processing of a large number of unit failure tests when monitoring the vibration condition. This can be done in the following way: earlier we found the possibility to construct an energy criterion for failure of the form:

$$
\sum_{j=1}^{M} W_{t_j,\nu_j} = \int_{0}^{t_j} dt \int_{\nu_j - \Delta \nu}^{\nu_j + \Delta \nu} W_{t,\nu_j} \cdot d \nu = C_i. \quad (6)
$$

The constant $C_i$ is a certain average experimental value (Fig. 2). Then the measure of failure in terms of [2] should be

$$
\Pi_i(t) = \frac{W_{t_j,\nu_j}}{C_i}, \quad (7)
$$

the equality or proximity of which the unit should ensure the accumulation of disseminated vibrodestruction, sufficient for destruction (failure).

On the other hand, its equality or closeness to 1 for the $i$-th node, indicating a high probability of failure in the predicted time $t_p$, is a rare event in real aggregate systems in which the failure of an aggregate is a superposition of accumulated defects in many nodes. Then the probability, or measure of failure of an aggregate of nodes, as is known for Bayesian events (conditionally, we accept this hypothesis a priori as common [1]) is equal to:

$$
P_c = 1 - \prod_{i=1}^{N} 1 - \Pi_i \quad (8)
$$

The latter probability is always greater than any maximum of $\Pi_i$. A system failure is a failure of at least one node (1, 2, 3).

After conducting $M$ tests, we determine the average (6) and (7), accumulated by the moment of failure:

$$
\Pi_{\text{average}} = \frac{\sum \Pi_i}{M}, \quad C_{\text{average}} = \frac{\sum C_i}{M}. \quad (9)
$$
Figure 2. Destruction measure $\Pi_c$ (a) and accumulated energy $W_p$ (b) depending on time $t$, $t_p$ – failure time

For a numerical assessment of the performance of the proposed criterion, we consider the installation (Fig. 3).
4. Conclusion

Thus, we will find the measure of failure in the whole system (8). In the case of the adequacy of the developed method for the assessment of vibration destruction, the obtained $P_C$ should be close to 1 (by the time the unit fails or by the time the vibration amplitude goes beyond the permissible limit, or another criterion for the inadmissibility of further operation of the unit). In the latter case, (9) it acquires a meaning corresponding to this criterion.

To assess the applicability of this approach to predict the failure time of a node / unit / system (destruction, failure to complete a technological task, etc., which is determined by the conditions of a specific technical and (or) technological scheme of the system in general), it is necessary to develop the corresponding parametric dependencies (Figure 1, 2). Modern tools (vibration analyzers-collectors) allow doing this in automatic mode.

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