Experimental investigation of elastic properties degradation in aluminum samples under cyclic loading

A O Torgovanov¹ and G V Moskvitin¹

¹ Blagonravov Mechanical Engineering Research Institute of Russian Academy of Sciences, 4, Maly Kharitonyevsky Pereulok, Moscow 101990, Russia

E-mail: torgovanovAO@mail.ru

Abstract. This research focuses on experimental study of fatigue resistance to vibration. At this time, there are no absolute criteria to accurately estimate fatigue of one or another structure despite the significant amount of studies in this area. A method for predicting the remaining life by studying the changes in the first self-resonant frequency of an aluminum sample depending on the number of loading cycles.

1. Introduction
Static or quasi-static loads are relatively rare in modern engineering applications. In this regard, the calculator is stimulated to turn to the repeated and cyclic loads’ study. Nowadays, most engineering structures and mechanisms include parts that are subject to cyclic or pulsating loads during operation. As a result of the action of such loads, cyclic or pulsating stresses arise, which quite often cause fatigue failure [1]. Often, a failure can occur suddenly without noticeable signs of its approach. Furthermore, during the “rest” when the stresses cease to act, there is no “recovery” or disappearance of the effects of preliminary cyclic loading, i.e. damages during fatigue accumulates and, as a rule, are irreversible.

Fatigue can be characterized as a process of gradual fracture, consisting of the nucleation of a crack and its growth to a size at which an unstable propagation of the crack begins. There is hitherto no generally accepted point of view on the details of the processes of nucleation and propagation of cracks at the microscopic level. It is assumed that the nuclei of fatigue cracks, from which cracks subsequently form, which often propagate before failure, occur as a result of the movement of dislocations [2], which leads to the appearance of thin slip bands on the surfaces of crystals.

To conduct a fatigue tests under cyclic or pulsating loading, in general, a vibration test system is required, which consists of a vibration stand, an amplifier, an accelerometer, a controller, and a laser vibrometer. A test specification and an object of study (sample) are also required.

2. Preparing the experiment
To fix the sample to a vibration stand (model: Data Physic V400LT), depending on the task, special equipment that prohibits movements and rotations in the area of the sample base is required. At the same time, the equipment must transmit the movement of the vibrating stand and ensure reliable fastening of the sample throughout the test. For these tests, a metal tooling was chosen (figure 1), which is rigidly attached to the table of the vibration stand with a screw. The sample is fixed by the clamping part of the equipment with two screws, thereby creating an equivalent built-in support. The
geometry of the clamping surfaces allows the sample to move in the vertical direction without creating additional stresses and impacts.

Figure 1. Mounting the sample to the vibration stand

An experiment requires data recording for further processing of the results in Matlab software. During the tests, the readings of the accelerometer fixed on a snap and the readings of a laser vibrometer (vibration velocity sensor), which tracks the speed of movement of the sample at a given point, are of interest. LabVIEW 2009 (Laboratory Virtual Instrumentation Engineering Workbench) was chosen for the task being set. The geometric characteristics of the tested samples (190x20x1 mm) are presented in figure 2. Material: D16T aluminum.

Figure 2. Sample geometry

In the course of the work, the dynamic characteristics of the samples were determined: natural frequency $\omega$ and damping coefficient $\zeta$, using experimental, analytical methods and FEM (technique of finite elements). Experimentally, the characteristics were obtained by measuring the vibrational velocity of the sample in the resonant mode, followed by the Fourier transform and the attenuation experiment (envelope selection). To find the natural frequency, the solution was analytically considered based on the Krylov functions [3]. To calculate the FEM, the Abaqus program was chosen. The results of calculations and measurements are presented in Table 1. The table shows that all values
are approximately equal and the relative calculation error does not exceed 5%. The average value of the natural frequency of the samples has been taken as 29.4 Hz.

Table 1. Dynamic properties of samples.

|                          | Analytical | FEM   | Experiment |
|--------------------------|------------|-------|------------|
| Frequency $\omega_1$, Hz | 29.7       | 29.71 | 28.64      |
| Motion at end of specimen $v(l)$, mm | 35         | 33.2  | 35±2       |
| Tension in the building-up support area $\sigma(0)$, MPa | 155        | 159   | -          |

During the work, vibration tests were performed at various accelerations of the vibration stand in the range from 1 g to 2 g. Figure 3 shows the result of one of the tests with a duration of 7.7 hours with an acceleration of 1.5 g and an average natural frequency of 28 Hz.

![Figure 3. Vibration Test at 1.5g](image)

3. Results Processing

The average duration of a fatigue test with an acceleration of the vibration stand of 1.5 g for 10 samples was 7.5 hours (7.7*10^5 cycles). In all experiments, a decrease in the first natural frequency of the samples is noted. The strongest drop occurs shortly before fracture, that is, by the time cracks appear in the area of specimen fixation. Also, in all tests, an increase in the vibration velocity of the samples was observed depending on the number of cycles. Each experiment can be divided into 3 intervals with intrinsic features, such as the interval of stable resonant frequency, the interval of the onset of a decrease in the resonance frequency, and the interval of active manifestation of other harmonics:

1. At the beginning of the experiment, all samples behave almost identically. The natural frequency is stable and does not change. During this period of time, the accumulation of fatigue damage, the initiation of microcracks, a microscopic change in the structure of the samples, which does not affect
the sample as a whole. At the end of the first interval, it was decided to choose the drop in the first natural frequency by more than $0.1\%$ of its value at the beginning of the experiment, which is more than just the measurement and processing error. On average, in time this amounts to $40\%$ of the entire sample resource or $3.08\times10^5$ cycles.

2. The second interval is characterized by a continuing smooth drop in frequency and the development of microdefects. In this case, the readings of the acceleration and vibration velocity sensor of the sample continue to be harmonious.

3. During the experiment, it was noticed that, approaching destruction, other harmonics begin to appear actively in the sample. This is due to the large appearance of internal and external cracks. The amplitudes of some frequencies reach a level close to half of the amplitude of the first frequency. Also, the readings of the laser vibrometer are strongly distorted and not so similar to the sinusoidal signal. This behavior of the samples begins to be observed after $6.93\times10^5$ cycles (90\% of the resource). If the amplitudes of the external frequencies are more than 10\% of the 1st eigenfrequency, then the sample has reached the 3rd interval - the approaching destruction of the sample.

Based on the data obtained, it is possible to construct a fatigue curve (figure 4), which displays the beginning of the second interval (the beginning of the frequency drop) depending on the number of cycles and stresses in the termination. The geometry of the fatigue curve is equivalent to the geometry of the classical Weller curve. Using the data obtained, it is possible to predict the current resource of the samples, knowing their initial first natural frequency.

![Figure 4. Fatigue curve](image)

4. Conclusion
In the course of the work, tests were carried out on the fatigue strength of the samples. The experiment was supported by analytical and FEM calculation. It is worth noting that from the FEM calculation, the maximum tension does not arise at the termination itself, but a little further, whereas in the analytical solution, the maximum tension arises in the termination. This remark is due to the geometry of the plate, which is not taken into account by the analytical solution. The fillets near the building-up support area (figure 2) are stress concentrators and the place where cracks begin to grow. This remark is confirmed by experiment. A method for analyzing test results which consists in obtaining the dependence of the resonant frequency of the sample on the number of cycles has been proposed. The entire experiment can be divided into 3 intervals with intrinsic features, such as the interval of stable resonant frequency, the interval of the onset of a decrease in the resonance frequency, and the interval of active manifestation of other harmonics. At the end of the analysis of the results, a fatigue curve was constructed for the beginning of the second interval, which requires further study and addition.
References

[1] Serensen S, Kogaev V and Shneyderovich R 1975 Bearing Capacity and Machines Elements Strength Calculation. Manual and Reference Guide. Edited by S.V.Serensen. (Moscow: Engineering) 488 119

[2] Collins J 1984 Material Damage in Structures. Analysis, Prediction, Prevention. (Moscow: MIR) 624 47

[3] Biderman V 1980 Theory of mechanical vibrations. The manual for high technical schools. (Moscow: Higher School) 408 149