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EQUIPMENT COMPLEX FOR ENSURING THE RESEARCH OF THE CHARACTERISTICS OF MULTI-CYCLE FATIGUE USING HIGH LOADING FREQUENCIES

The article describes a complex of testing equipment that ensures implementation of fatigue tests of samples made of metal construction materials within the range of 0.3–44.0 kHz. The considered equipment complex allowed implementation of the following patterns of sample loading: tension-compression and alternating bending over a symmetric cycle.

The article also contains information about the structure of test facilities, matching plants and test samples, as well as the peculiarities of test performance at elevated temperatures. It has been demonstrated that this equipment complex allows realization of random loads characteristic of real conditions of operation of machine parts and elements of engineering structures.

Key words: oscillations, magnetostrictor, concentrator, sample, stresses, fatigue characteristics.

Introduction. The main way to develop methods for calculating fatigue strength is the use of applying various empirical dependencies obtained with the help of a large volume of experimental data. The main downside of this method is the complexity of fatigue tests. It is especially crucial for large test bases, when it comes to hundreds of thousands and millions of load cycles.

As the earlier studies have demonstrated, one very promising method for these goals is using high frequencies of oscillations that allow to ensure a great number of loading cycles over a short period of time and establish regularities of influence of the deformation frequency on cyclic damageability of the studied metals and alloys [1, 2]. Practical implementation of this method requires creation of a complex of testing equipment ensuring determination of fatigue characteristics in a wide range of load frequencies.

Main part. For the implementation of low-frequency (up to 300 Hz) and high frequency (2.8–44.0 kHz) loading, a complex of magnetostriction resonance facilities [3] was designed. The complex allowed to carry out tests of various construction materials (both metal and non-metal) at great test bases in a wide range of frequencies (0.3–18.0 kHz) and temperatures (300–1000°K).

For implementation of tests at high (2.8; 8.8; 18.0 and 44.0 kHz) frequencies, magnetostriction units operating in auto-oscillation mode were used. Block diagram of such units is shown in fig. 1.

Active element of a fatigue plant is a magnetostriction package designed as a closed loop composed of thin sheets of active material (nickel, permendur, etc.). Mechanical oscillations of the package occur under the effect of alternating magnetic field excited by a high frequency oscillator. Effective operation of the magnetostriction converter is ensured by the optimal level of magnetization by constant magnetic field.

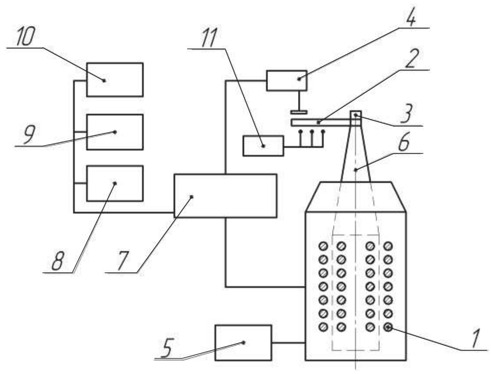

Fig. 1. Diagram of the test stand for excitation of bending oscillations:
1 – magnetostriction converter with excitation and magnetization coils; *2* – sample; *3* – fastening device; *4* – MRTI vibrometer; *5* – magnetization module; *6* –waveguide concentrator; *7* – amplitude stabilization device PSA (ASD); *8* – frequency counter; *9* – oscillograph; *10* – computer with printing device; *11* – temperature controller

In order to increase the oscillation amplitude, the package was connected to a variable cross-section rod (concentrator), which in its turn was connected to the sample. All dimensions of elements of this system were designed with the same individual frequency, which made it possible to obtain maximum value of cyclic loads.

One of the problems affecting correctness of fatigue test results is stabilization of the oscillation amplitude in the process of loading. This issue can be especially critical during the use of the resonance mode, as changes in the oscillation amplitude can be caused both by alteration of the acoustic power supplied to the sample and non-correspondence of the frequency of mechanical resonance of the oscillating system that has an acute characteristic with the current frequency of the oscillator applied in the circuit with independent excitation. Due to this, plants [4–8] with auto-oscillatory operating mode are used, which make it possible to monitor the kinetics of sample damage based on changes in the resonance frequency [9, 10].

The test complex designed by us worked in auto-oscillatory mode and maintained the given parameters of oscillations of sample (fig. 1) with the help of the special amplitude stabilization device PSA, feedback coupling with which was implemented by means of the MRTI vibrometer.

Preliminary adjustment and calibration of the vibrometer were carried out with the help of MBS-2 optical microscope (not shown in fig. 1). Monitoring of the shape and amplitude was performed with the help of the electronic oscillograph connected to the circuit for the period of monitoring.

Since the quality factor of this auto-oscillatory system is determined solely by the quality factor of the sample, in course of fatigue tests there is a real possibility to study kinematics of accumulation of fatigue damages by monitoring changes in the system oscillation frequency with the help of the frequency meter operating jointly with the computer with printing device.

Water cooling of active and magnetizing coils of converters 1 was ensured in order to prevent them from overheating.

Test plant on the basis of electrodynamic vibratory stand of VE type, block diagram of which is shown in fig. 2, was designed for performance of fatigue tests at low frequencies (up to 300 Hz).

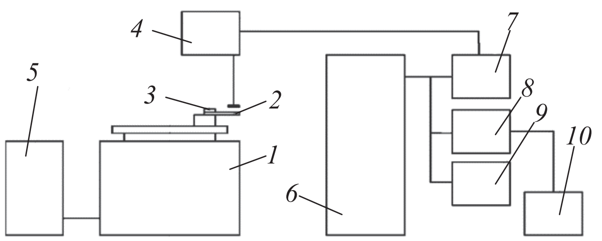

Fig. 2. Diagram of the low-frequency test stand:
1 – VE vibrator; *2* – sample; *3* – fastening devices;
4 – MRTI vibrometer; *5* – magnetizing module;
6 – amplifier; *7* – amplitude stabilization device
PSA (ASD); *8* – frequency counter; *9* – oscillograph;
10 – computer with printing device

Alternate current is supplied to active coils of the table of VE1 vibrator was supplied from the amplifier (working frequencies: 10–5000 Hz).

In other aspects, operation of the low-frequency plant did not differ from operation of high-frequency testing complexes described below.

The above plants supplemented with the system of matching elements (fig. 3) were used for testing of samples under tension-compression.

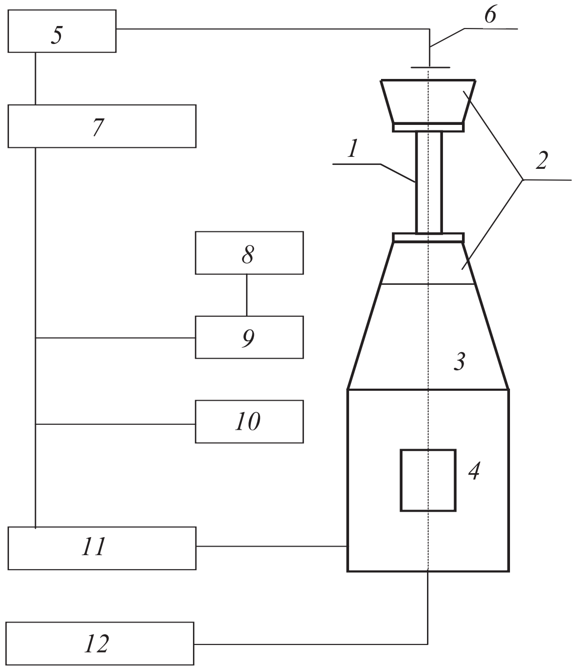

Fig. 3. Block diagram of high-frequency test stands for implementation of longitudinal oscillations:
1 – sample; *2* – matching element; *3* – concentrate;
4 – magnetostriction converter; *5* – MRTI vibrometer;
6 – oscillation amplitude control sensor;
7 – amplitude stabilization device ASD (PSA);
8 – computer with printing device;
9 – frequency counter; *10* – oscillograph;
11 – amplifier; *12* – magnetizing unit

PMS-15-A18 converters (4 kW) made of permendur were used for the plant with the resonance frequency of 18.0 kHz.

Since no magnetostrictors with working frequency below 18 kHz are industrially made, special magnetostriction packages made of nickel plates (NP 2, GOST 492-73, h = 0.2 mm) were specially manufactured for frequencies of 2.8 and 8.8 kHz. Calculation of geometric parameters and resonance frequencies of the converters was carried out in accordance with [11]. Preparation for thermal treatment, thermal treatment and soldering of packages were performed according to the method [12].

Steel plates with threaded shanks were welded to the packages with silver solder Psr 45 for fastening of concentrators on the packages, which made it possible to fasten concentrators of various sizes with the necessary value of amplification ratios quickly and firmly.

Shape, material and dimensions of concentrators were determined on the type and dimensions of samples, oscillation frequency, as well as the necessary value of amplification ratios sufficient for reaching the necessary level of cyclic loads. Ampule-stepwise rod was used as an amplifier of mechanical oscillations (concentrator) for the frequency of 44 kHz, half-wave conical roads [13] – as amplifiers for frequencies of 2.8, 8.8 and 18.0 kHz. Concentrations for resonant frequencies of 8.8 and 18.0 kHz were made of #45 steel, 2.8 kHz – of D16 alloy, for 44 kHz – of VT6 alloy (fig. 4).

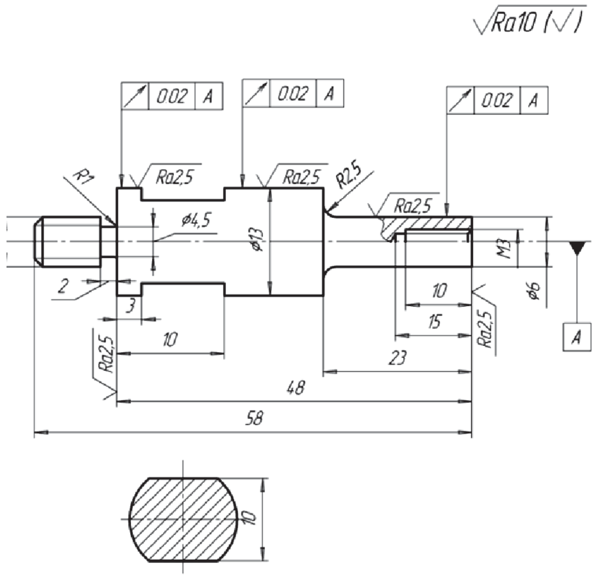

Fig. 4. Ampule-stepwise concentrator for the oscillation frequency of 44.0 kHz

General view of samples for test in the conditions of alternating bending is shown in fig. 5; samples for testing in the conditions of alternating tension-compression – in fig. 6.

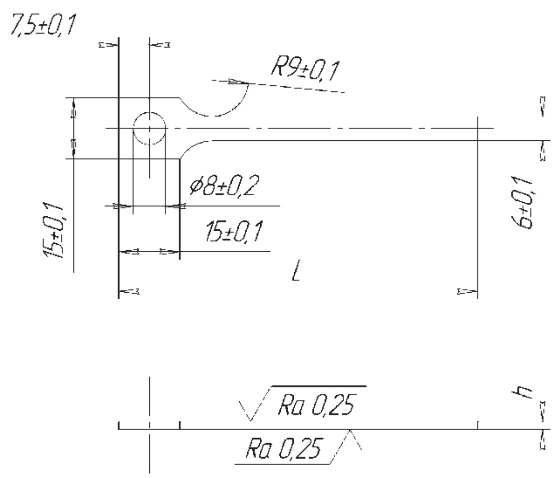

Fig. 5. Samples for loading with alternating bending

In order to reduce the scatter of experimental readings, special attention was paid to the quality and mechanical properties of material used to manufacture the test samples. In order to prevent the effect of scatter of the chemical composition of test results samples were cut out of alloy of the same batch (cast). Removal of a minimum thickness of the layer was provided at the final stage of mechanical treatment during production of test samples in order to prevent the effect of technological heredity; all samples were thermally treated as one batch.

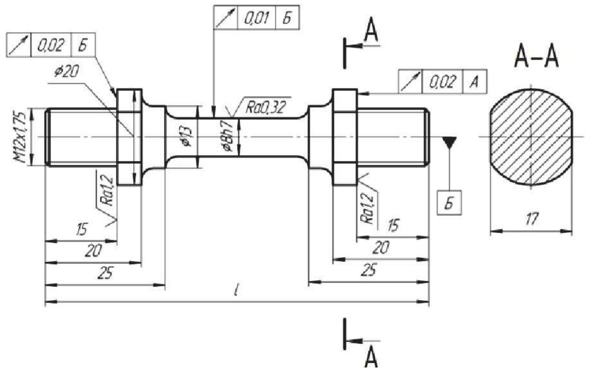

Fig. 6. Samples for loading with alternating tension-compression

Calculation of the loaded state of beam samples was carried out on the basis of the general equation of the technical theory of roads for an untwisted beam with linear axis and small flat cross-section that has the following form Расчет напряженного состояния балочных образцов производился на основании общего уравнения технической теории стержней для незакрученной балки с прямолинейной осью и малым, остающимся плоским поперечным сечением, которое имеет вид (calculation model is shown in fig. 7):

$$\frac{\partial^2}{\partial x^2}\left(EJ\frac{\partial^2 W}{\partial x^2}\right)+\rho F\frac{\partial^2 W}{\partial x^2}=0, \qquad (1)$$

where $J = J(x)$ – is the moment of the cross-section inertia with respect to the central section line; $W = W(x, l)$ – is the deflection.

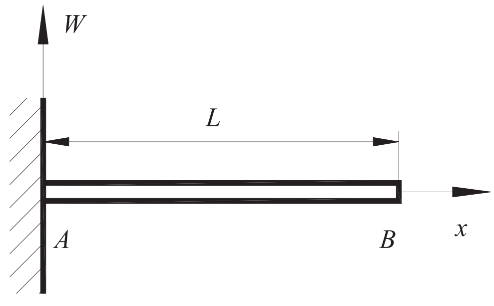

Fig. 7. Calculation model

In study of the beam oscillations without consideration of the shift and inertia, in case of anchorage at $x = 0$ and $x = 1$ boundary conditions will have the following form:

– anchorage $W = 0, \quad \frac{\partial W}{\partial x} = 0$;

– free end

$$M = EJ\frac{\partial^2 W}{\partial x^2} = 0,$$
$$Q = \frac{\partial M}{\partial x} = \frac{\partial}{\partial x}\left(\frac{\partial^2 W}{\partial x^2}\right) = 0. \tag{2}$$

If J = const and F = const the original equation is written as follows

$$\frac{\partial^4 W}{\partial x^4} - k^4 W = 0, \tag{3}$$

where

$$k = \frac{4\omega^2 \rho F}{EJ}. \tag{4}$$

For a hammer beam in these border conditions, the solution has the following form:

$$W(0) = \frac{\partial W}{\partial x}(0) = \frac{\partial^2 W}{\partial x^2}(l) = \frac{\partial^3 W}{\partial x^3}(l) = 0, \tag{5}$$

frequency equation

$$ch(kl)\cos(kl) + 1 = 0, \tag{6}$$

the roots of which are kl = 1.875 (first oscillation mode), kl = 4.694 (second oscillation mode).

Beam deflection function is described by the following dependency:

$$W = A\left(U(kx) + \frac{B}{A}V(kx)\right), \tag{7}$$

Where $\frac{B}{A} = -\frac{U(kl)}{V(kl)}$ or $\frac{B}{A} = -\frac{T(kl)}{U(kl)}$,

$$S(x) = 0.5\left(ch(kx) + \cos(kx)\right),$$
$$T(x) = 0.5\left(sh(kx) + \sin(kx)\right),$$
$$U(x) = 0.5\left(ch(kx) - \cos(kx)\right),$$
$$V(x) = 0.5\left(sh(kx) - \sin(kx)\right).$$

– Krylov's functions.

It is known that in case of excitation of constant cross-section hammer beam oscillations of any mode, absolute values of the loads in the anchorage always exceed the ones acting in the region of deflection antinodal. In practice, samples with increased area of cross-section in the anchorage region [14] are used to shift the point of fatigue destruction from the anchorage, which alter rigidity of the near-root section of the sample. Moreover, comparison of experimental and calculated frequencies of oscillating objects, such as turbine blades [15] revelated that the actual oscillation frequency of a blade anchored to the disk is always less than the frequency that was calculated theoretically based on condition of absolute rigidity of anchorage. Imperfection of anchorage is due to such factors as the friction force, quality of treatment of mating surfaces, elastic interaction of bodies, etc.

In order to account for the influence of anchorage compaction on stress-strain behavior of samples, calculation-experimental determination of the anchorage rigidity ratio was used, with the help of which the boundary conditions for the section adjacent to anchorage were adjusted.

In order to do this, it is necessary to determine experimentally the frequency of resonance oscillations of the beam, its thickness, coordinates of the characteristic points (free end of the sample and nodes of oscillation for higher forms) and calculate the value of the wave coefficient K. By measuring the deflection value (amplitude) at the edge of the sample (x = 0) and thus finding one of the unknown variables, i. e. $A = W0$, we can find the last variable – the constant B, expressing it in the same way as A through the oscillation amplitude of the characteristic points of section $x = b$ of the oscillating beam $W(b)$.

In this case

$$B = \frac{J}{T(kb)}\left(W(b) - W_0 S(kb)\right), \tag{8}$$

If b is the coordinate of the oscillation node, then $W(b) = 0$ and

$$B = -W_0\frac{S(kb)}{T(kb)}. \tag{9}$$

Based on the above dependencies, calculation of stress-strain behavior of beams samples was performed together with their inspection using strain gauging for frequencies of 0.3 and 2.8 kHz with the help of the MathCad application package. The difference in the stress values did not exceed normal stress gauging errors for normal measurement conditions.

Further development of the complex for fatigue tests at high loading frequencies consisted in ensuring the possibility to determine fatigue characteristics of metal samples under elevated temperatures (300–1000°K). For this purpose, the test complex was additionally fitted with a heating element with temperature controller (11, fig. 1), which allowed maintaining the sample temperature within 300–1000°K.

Development of the fatigue destruction of test samples was controlled on the basis of changes in microhardness, dislocation density and electrical resistance of samples [16].

Conclusions. This complex can be used to simulate tests within a wide range of frequencies and temperatures, implement various random loads characteristic of actual operating conditions, while various feedbacks will make it possible to monitor various test parameters (sample temperature, frequency spectrum, oscillation amplitude, etc.) in real time, measure and analyze them.

It is practicable to use such equipment at enterprises and in organizations involved in engineering of machine parts and construction elements, as well as creation of new materials working under cyclic loading.

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