Area determination of correct operation of the vibrofuge

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Abstract. The object of the study is a centrifuge, on the rotor of which a pneumatic spring with a mechanical vibrator is fixed. The operation of the pneumatic spring during rotation of the centrifuge rotor and the operation of a mechanical vibrator with varying plant parameters is analyzed. Identified parameters that significantly affect the operation of the plant. The areas of parameters in which the correct operation of the plant is observed are found.

Keywords: centrifuge, vibrations, pneumatic spring, mechanical vibrator, centrifugal force, centrifugal acceleration

Introduction

Nowadays, test studies are included in the life cycle when designing various new technical objects, devices, etc. The main purpose of such tests is to check the response of new technical objects to simulated realistic operating conditions and to ascertain the limits of the values of the loads being subjected.

Specialized test benches are used for carrying out the above operations on products. Test bench - laboratory equipment, which reproduces specialized control tests for any products [1]. In most cases, test benches check products for specific loads. For example, on impact benches, products are tested for impact strength. There are many types of different benches with a wide range of tests, such as speed, acceleration, vibrations, compression, bending, etc., as well as climatic effects [11-13].

In industry, complex benches are also used that can carry out complex tests. The main advantage of such benches is to conduct several tests on an object at the same time, which is faster than conducting each test separately on different benches.

In this work, the object of study is a centrifuge test bench, on the rotor of which a pneumatic “spring” with a mechanical vibrator - “vibrofuge” is fixed. Such a bench can reproduce complex tests on the product — centrifugal forces and vibration forces. Objects that in real conditions are subjected to such loads are mainly used in the design of aircraft, missiles (aviation, aerospace, military industry).

This paper explores the joint operation of a pneumatic "spring" with a mechanical vibrator during rotation of the centrifuge rotor at a constant speed. At certain initial values of speed, dimensions of the plant, the pressure in the chamber of the pneumatic spring, etc., the bench may work properly or incorrectly [14]. In this connection, it is necessary to calculate the range of parameters under which the system works properly, as well as to identify the factors by which the error of the system can be increased. Considering the above about the advantages of the “vibrofuge” complex test bench and its areas of application, the relevance of the work is beyond doubt [15,17].

Literature review

The basis of this work is a centrifuge test bench. High-speed centrifuges with their remote control systems are used for testing technical objects [2], [3]. Such plants, of course, allow for errors in the
work. There are many factors that affect the error of work, but for the most part, predicting the change in radius from the axis of rotation to the test object can significantly reduce the error [4]. To predict the change in radius, it is necessary to implement feedback during the operation of the bench. For this purpose, the use of contactless laser equipment is proposed, for example, a laser tracker [5].

The highest interest is represented in complex tests, which can significantly reduce the financial component of the question of testing technical objects. There are several versions of the stand design for reproducing centrifugal acceleration and vibration forces [6]. However, in this paper, the idea is presented with the addition of a pneumatic spring with a mechanical vibrator.

Within the study of the complex test bench of a centrifuge, on the rotor of which a pneumatic spring with a mechanical vibrator is fixed, the pressure distribution of the gas in the chamber of a closed vessel under the influence of centrifugal force was studied [7]. At certain initial parameters of the system, a vacuum may occur in a closed vessel under load, which can also affect the operation of the plant and increase the error [8].

However, in addition to the study, it is necessary to analyze the operation of the pneumatic spring together with the mechanical vibrator during the rotation of the test centrifuge rotor with different initial parameters of the system. To find out at what parameters the bench works correctly and identifies new factors leading to an increase in error.

**Analysis of joint work of pneumatic spring with a mechanical vibrator when rotating the centrifuge rotor**

In the considered plant, a mechanical vibrator with the following technical characteristics is considered: sinusoidal oscillations, the oscillation frequency is from 5 to 2000 Hz, the maximum force is 5000 N, the maximum speed is 2 m/s. The scheme of the pneumatic spring with a mechanical vibrator during rotation of the centrifuge rotor is shown in Figure 1.

![Figure 1](image)

**Figure 1.** The scheme of the pneumatic spring operation together with a mechanical vibrator during the rotation of the centrifuge rotor

In the diagram during the rotation of the rotor (pos. 4), the centrifugal force acts on the mechanical vibrator (pos. 3) at a distance r (radius from the axis of rotation). In turn, the mechanical vibrator acts on the piston of the cylinder (pos. 2). A hollow cylinder (pos. 1) is conditionally considered instead of a pneumatic spring. The length of the cylinder chamber is L. From the cylinder chamber, in turn, the gas force acts on the piston in the opposite direction of the centrifugal force [16].

During the operation of such a scheme, the piston, perceiving the centrifugal force and vibration forces, performs displacement. It is necessary to calculate these displacements at certain initial parameters of the system [9]. Through the laws of the dynamics of mechanical systems and taking into account the indicated forces in Fig. 1, we obtain the following equation:

\[
M \frac{d^2L}{dt^2} = F_{cf} + F_{vibr} - pS. \tag{1}
\]
In terms of Eq. 1, the total mass of a mechanical vibrator and piston, kg, \( \frac{d^2L}{dt^2} \) is the acceleration of the mechanical system (mechanical vibrator, piston), m/c2, \( F_{cf} \) and \( F_{vib} \) are the centrifugal force of rotation of the rotor and vibration force, respectively, H, \( pS \) is the force acting on the piston from the inside of the cylinder chamber, where \( p \) is the gas pressure in the chamber, \( S \) is the piston area [18].

Given the fact that the displacement of the piston cylinder chamber pressure and volume changes and taking into account the law \( pV = \text{const} \), we obtain the following equation:

\[
pS L = (p + dp)S(L - dL).
\]

Taking into account the resulting expression Eq. 2, it is necessary to derive the value of \( dp \) (added pressure, at piston displacement):

\[
 dp = \frac{pL}{L - dL} - p.
\]

The following formula can be used to calculate the centrifugal force \( F_{cf} \):

\[
 F_{cf} = M \omega^2 r,
\]

where: \( \omega \) – rotation speed, rad/s, \( r \) – rotor length, m.

Expression Eq. 5 defines the law of motion of a mechanical vibrator:

\[
 F_{vib} = Fs \sin(\omega_f t).
\]

In expression Eq. 5, \( F \) is the maximum force of the vibrator acting on the piston, N; \( \sin(\omega_f t_i) \) is the law of motion, \( \omega_f = 2\pi f \), where \( f \) is the frequency, Hz. \( t_i \) is the current time, s, which is a calculation step.

The current time is determined from the expression \( t_i = t_{i-1} + dt \), where \( t_{i-1} \) is the time in the previous calculation step, \( dt \) is a constant, a permanent calculation step.

The acceleration \( \frac{d^2L}{dt^2} \) is calculated from the expression Eq. 1:

\[
 \frac{d^2L}{dt^2} = \omega^2 r + \frac{F}{M} \sin(\omega_f t) - \frac{pS}{M}.
\]

For convenience, we denote \( \frac{d^2L}{dt^2} \) by \( a \). From the acceleration we calculate the increment of the speed of the mechanical system:

\[
 dv = adt.
\]

The speed increment of movement of the mechanical system is the speed at the current time of calculation, m/s. Given the fact that the movement of a mechanical vibrator is caused by a sinusoid, the speed of movement of the mechanical system at each time point of the calculation changes:

\[
 v_i = v_{i-1} + dv,
\]

where \( v_{i-1} \) – movement speed at the previous time of calculation (at the initial moment of time the speed of the movement is zero), m/s.

Expressions Eq. 8 and 6 can be used to calculate the movement speed and acceleration of the mechanical system. From here, it is possible to calculate displacements at each instant of time, therefore, the values of the piston displacement in the cylinder chamber:

\[
 dL = v_{i-1} dt + \frac{a(dt)^2}{2}.
\]

Using the MatLab software package, all expressions from Eq. 1 to 9 can be adapted to the program code with which piston displacement values are calculated and a corresponding graph of these displacements can be plotted [10]. The initial parameters in the program code are the following: \( M = 25 \) kg, \( L = 0.5 \) m,
\( \omega = 50 \text{ rad/s}, r = 2.5 \text{ m}, F = 5000 \text{ N}, S = \frac{\pi}{4} d^2 \) (\( d = 0.320 \text{ m} \) – piston diameter), \( f = 50 \text{ Hz}, dt = 0.02/12 \text{ sec} \). The results of the calculations are presented as a graph in Figure 2.

Figure 2 - Piston displacement with respect to time

Figure 2 clearly shows the nature of the displacement of the piston under the influence of centrifugal and vibration forces. The maximum swing of the piston at the beginning of the graph is 0.0159 m. At \( t = 0.2 \text{ sec} \), the displacements do not exceed 0.3 cm. To calculate the transition process and the steady-state operation error, a graph is plotted at the middle points in Figure 3.

Figure 3 – Displacement of the midpoints

The steady-state error of 0.1\% is 0.00051 m. The transition process is 0.54 seconds. The presence of a steady-state error leads to errors of the tests performed on technical objects.

When varying the parameters of the plant, it was found that the most “sensitive” parameters were the speed of rotation of the centrifuge rotor and the maximum force of the mechanical vibrator. For example, when reducing the rotor speed to 25 rad/s, the nature of the piston displacements is as follows (Figure 4).
It can be seen from the fig. 5 that the time of the transition process has increased significantly to 3.4 seconds. And the lower the speed, the higher the transition process, which means the incorrect operation of the system with high errors [19-21].

By varying the rotor speed and maximum vibrator effort, it is possible to calculate the areas of these values at which the plant correctly works (Figure 6).
In Figure 6, the solid line and the entire right area of the graph are the values at which the bench operates stably. The dashed line and the area of the graph to the left of this line are the values at which the bench works incorrectly, the time of the steady-state exceeds 5 seconds [22]. In the area between the dashed and solid lines, correct operation is observed, where the steady-state time is less than 5 seconds.

Results
According to the analysis of the pneumatic spring (conventionally instead of a pneumatic spring, a closed cylinder with a piston is taken as the basis) and a mechanical vibrator during the rotation of the test centrifuge rotor revealed the following:
1. The plant can work correctly with certain initial parameters - the length of the rotor and the cylinder chamber, the rotation speed of the rotor, the initial air pressure in the cylinder chamber, the strength of the mechanical vibrator;
2. the most "sensitive" parameters - the rotation speed of the centrifuge rotor and the maximum force of the mechanical vibrator;
3. at changing the system parameters - different times of the transition process (Figure. 2 and 4);
4. the point relative to which the piston carries out displacements after the steady-state regime shifts from the initial position of the piston without load (Figure 3);
5. the values of the rotation speed of the centrifuge rotor and the maximum force of the vibrator at which the plant works stable (Figure. 6) are calculated.

Conclusion
In this work, the object of study is a test bench centrifuge, on the rotor of which a pneumatic spring with a mechanical vibrator is fixed. Such a test bench is capable of carrying out complex tests for centrifugal acceleration and vibration forces. Such tests are performed on objects that are part of the construction of missiles, airplanes, etc.

The calculation of the piston displacements in the chamber of the pneumatic spring (conventionally hollow cylinder) makes it possible to detect the shift of the point (from the initial position without load), with respect to which the piston moves from the mechanical vibrator and the centrifugal force. This suggests that the results when testing over objects may be with an error. The error can reach several percentages depending on the initial characteristics of the plant. But this is without taking into account that during the rotation of the rotor the pressure in the cylinder is redistributed.

In this paper, we analyzed the operation of the pneumatic spring and mechanical vibrator during rotation of the test centrifuge rotor:
1. the forces arising during the operation of the plant are analyzed (Figure 1);
2. taking into account the acting forces, expressions from Eq. 1 to 8 are compiled and formula Eq. 9 for calculating piston displacements is derived;
3. for calculating displacements and plotting graphs (Figure 2-6), the derived expressions are adapted to the program code of the MatLab software package;
4. the graphs in Figure 2 and 4 differ from each other due to a change in the speed of rotation of the centrifuge rotor;
5. varying the values of the centrifuge rotor speed and the maximum force of the mechanical vibrator, areas in which the plant works correctly or incorrectly are identified (Figure 6).

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