Research on a Composite Micro-hose Subjected to Harmonic Loading. Experimental Approach

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Abstract. The article presents an original test rig for investigating the dynamic and static properties of hydraulic hoses. A composite micro-hydraulic hose with an inner diameter of 2 mm was taken as the test object. To carry out hydrodynamic tests in a composite hydraulic micro-hose, a test rig was built. The test stand consists of a hydraulic system whose purpose is to supply the test object with working fluid, and measurement paths that allow observation of hydrodynamic phenomena occurring in the tested hose. In addition, the test stand was equipped with a working fluid temperature stabilization system. The measured values during the measurement series were: pressure at the beginning and at the end of the tested hose (AC and DC components), temperature of the fluid inside the micro-hose at the beginning and at the end, vibrations in three directions at a selected point of the micro-hose, tension force of the micro-hose (DC and AC component), reaction in the supports (DC and AC component), fluid flow rate in the micro-hose, displacement of the movable support differential with the axial deformation of the micro-hose. In the research was determined the influence of the mean pressure value on the amplitude of micro-hose vibrations. Amplitude-frequency spectra were used to analyses the results obtained.

Keywords: Composite · micro-hose · pulsation · frequency · experimental approach

1 Introduction

Hydraulic systems are commonly found across a wide range of industries. They also play a special role ‘in the mechanical engineering industry. Due to their numerous advantages, they are used wherever there is a need to use high power with a compact design [1]. At the same time, new trends in the construction of hydraulic components and systems have been recently noticed. One of the directions of development is the pursuit of miniaturization of hydraulic components. To adapt to the current market demand, hydraulics has formed a new sub-area, which is micro-hydraulics [2] As the name suggests, it is

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characterized by the significantly small size of the components involved, compared to their conventional counterparts. Generally accepted that microhydraulics are characterized by small and very small flows, i.e. flows of less than 50 cm^3/s (3 dm^3/min). In the case of valves, the criterion size is the seat dimension, which is for micro-hydraulic components WN < 6. For pumps and displacement motors, the concept of displacement chamber volume per one full revolution of the shaft is used, which for micro-hydraulic displacement units should be less than 1.2 cm^3/rev. Micro-hydraulic systems are slowly replacing pneumatic and electromechanical systems, which can largely be explained by the fact that they have a large number of useful features, where some of the most important are [3]: small system dimensions; high power transmission and operational reliability; smoothness of movement and cleanliness of the propulsion; low noise level.

Another direction of development is the use of new materials that make it possible to reduce the weight of hydraulic components without changing values of operating parameters (operating pressures). New materials based on plastics and composites are used for the bodies of pumps, valves [4], on hydraulic cylinders [5, 6] or hydraulic lines. In addition to durability, the new materials are also required to be resistant to environmental factors. This is particular important for offshore platforms where hydraulic components are subjected to the action of salt sea water or water mist. [7]. Composite materials are also characterized by very high specific strength, in this respect the most basic composites outclass good steels and their alloys, in addition, their low fiber density contributes into low component weight [8, 9]. Other features of composite components that are also used in hydraulics are: high chemical insensitivity; damage to the element in the form of cracks in the matrix; high strength at low weight; the limit between brittle and plastic states is gradual at lower temperatures; often lower production costs, which results into lower component costs; easy manipulation of physical and mechanical properties; high corrosion resistance; excellent fatigue stability; vibration damping by composite fibers.

The high strength of the new materials and their lightness make them increasingly used for hydraulic components [10]. Composite micro hoses have appeared on the market for use as power hoses in lubrication systems, signal hoses in load-sensing systems or in control and measurement systems [11]. Changing the size of a hydraulic component is often not compatible with maintaining its physical-mechanical properties, and the next problems may involve phenomena that can occur at the microscale but are not noticeable at the macroscale. Therefore, to effectively exploit the capabilities of composite micro-hoses, it is necessary to know their properties and behavior during operation under quasi-steady and variable conditions. Typically, a composite hose is constructed of several layers, 3–6 layers of materials, using a composite fabric layer (such as aramid fibers) to transfer the load. The composite fabric layer is the most important structural factor of composite hoses because it is the layer where the hose gains strength while maintaining high flexibility.

The paper presents a unique experimental rig for studying hydrodynamic phenomena in composite hoses. Experimental results of flexural vibrations of a composite microhose for various average pressures inside the pipe are presented. The analysis of the dynamic behaviour of hydraulic composite components can be useful for designers and users of these components.

2 Object Under Study. Test Site

2.1 Description of the Test Object

The test object is a meter long 2020N-012V30 hydraulic microhose from Parker [12], it is a thermoplastic, three-layer composite hose. The hose consists of three layers. The inner layer is made of thermoplastic polyamide, which is a polymer with better physical and physicochemical properties than other materials used for the base layers of hydraulic lines. Polyamide is characterized by high mechanical strength, resistance to a wide temperature range, abrasion and tensile resistance, low coefficient of friction, UV resistance, broad chemical resistance, light weight, lack of electrical conductivity and thermoplastic. Another, middle layer is a high-strength synthetic composite fiber, which acts as a reinforcement for the hose. The layer of composite fiber significantly improves the physical and mechanical properties of the hose, so that the maximum working pressure of the hose is 50 MPa, and the minimum burst pressure oscillates around 200 MPa.

The last layer of the hose is made again of polyamide and is the outer layer of the hose, tasked to protect the hose from mechanical factors such as abrasion. Unlike the base layer of the hose, the polyamide surrounding the outer layer is punctured, resulting in the presence of a significant number of micro-holes. Water vapor, air and other gaseous products can get inside the tube and accumulate in the reinforcement area, creating areas of lower strength resistance. This phenomenon shows itself by means of the appearance of bubbles or blisters in the area. Puncturing the tube layer is very important, because puncturing the tube cover allows trapped gases and vapors to get out.

2.2 Description of the Test Stand

A test stand was configured for carrying out preliminary vibration tests of a composite hydraulic micro-hose (Fig. 1). This test stand consists of a hydraulic system designed to generate fluid flow rate and pressure in the tested object, and measurement tracks that allow observation hydrodynamic phenomena occurring in the tested tube.

Hydraulic system

The task of the hydraulic system, which was made specifically for the purpose of the conducted scientific tests, was to enable fully controlled flow of the working fluid through the test object. The hydraulic station makes it possible to control the value of the average pressure, flow rate and temperature of the working fluid. The hydraulic stand is shown in Fig. 2.

Driven by an electric motor (1), a multi-piston pump (2) feeds the system and the tested hose with mineral oil. Tested hose (7) is placed in the test stand (Fig. 2). The working fluid is supplied to the test hose by the overdriving the directional control valve (5). Adjustable throttling valves (6) and (8) are used to set the flow rate and average pressure in the test line in accordance with the test program. In addition, the system was equipped with a safety valve (3), oil filter (11). An important component of the system is the oil cooler (10), as it allowed to stabilize the temperature of the working fluid during the tests. The Manometer (4), located in the hydraulic power unit, was used to roughly control of the average pressure.

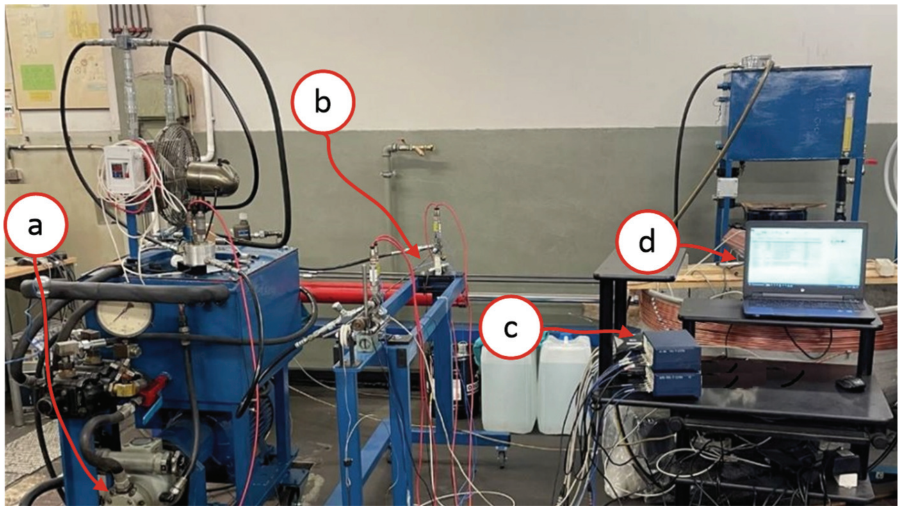

Fig. 1. Test stand: a - piston pump; b - tested hose; c – conditioners; d - measurement devices.

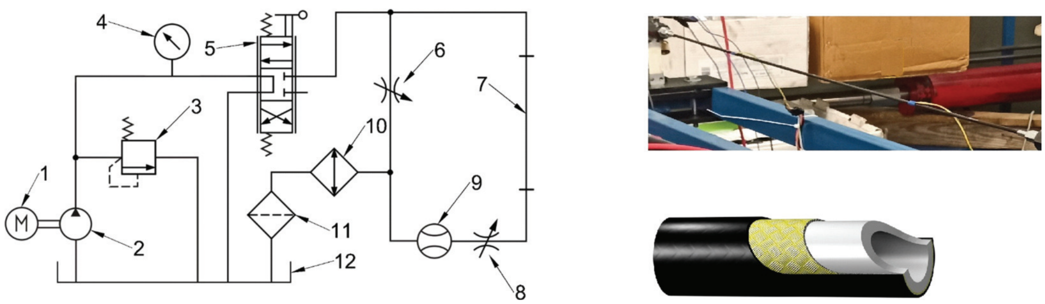

Fig. 2. Schematic diagram of an open hydraulic system: 1- motor; 2 – pump; 3 - safety valve; 4 - pressure gauge; 5 - hydraulic directional control valve; 6 - adjustable throttle valve; 7 - hose under test; 8 - adjustable throttle valve; 9 - flow meter; 10 – cooler; 11 – filter; 12 – tank.

Measuring lines

The schematic of the measurement path shown in Fig. 3. The task of the measuring part is to record hydrodynamic phenomena occurring during the test of the composite hose. The measuring tracks are divided into two segments according to their purpose. The first, provides us with the reading and recording of the hydrodynamic properties of the working fluid flowing through the test object, and the second - the response of the hose to the flow. Due to this solution, it is possible to observe the hydrodynamic phenomena of the fluid in the tested hose and see their effect on the test object.

The first segment consists of sensors for temperature (3, 13), static pressure (4, 12) and dynamic pressure (5, 11) of the fluid, they perform the function of receiving the basic physical parameters of the working fluid. They are located directly in front of and directly behind the test stand.

The second segment includes two temperature sensors (8, 10), which measure the external temperature of the test object at 250mm from the hose nut. A piezoelectric accelerometer (9) is located halfway along the test hose. An inductive displacement sensor (24) that measures the changes in the length of the hose under load (pressure inside the hose and pre-tension). The tested hose is preloaded through weights and the

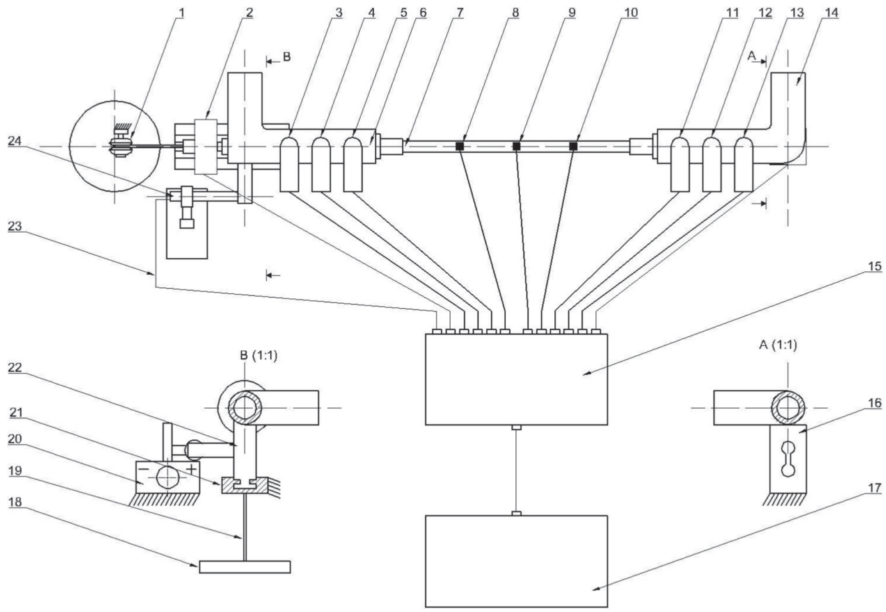

Fig. 3. Schematic of the measurement track: 1 – roller; 2 - force sensor; 3 - temperature sensor; 4 - static pressure sensor; 5 - dynamic pressure sensor; 6 - angle connector; 7 - composite micro hose under test; 8 - NTC thermistor; 9 - piezoelectric accelerometer; 10 - NTC thermistor; 11 - dynamic pressure sensor; 12 - static pressure sensor; 13 - working medium temperature sensor; 14 - angle fitting; 15 - signal conditioner; 16 - strain gauge beam; 17 – computer; 18 - load rack; 19 – wire; 20 - magnetic holder; 21 – rail; 22 - angle fitting stand; 23 - electrical hose; 24 - displacement sensor.

hose tension force is measured by the force sensor (2) and strain gauge beam (16). The force sensors measure the constant and variable components.

All measuring sensors were connected to two signal conditioners (15), which were connected to a computer (17). The task of the signal conditioners was to take input current, voltage and frequency signals and then give the proportional signals in output format. The data (after conversion from analog to digital) were sent to a computer, which recorded the results of the measurements and presented them in the form of graphs to make it easier to read and analyze the data.

3 Methodology and Findings

3.1 Methodology

The fundamental problem of hydrodynamic testing in a hydraulic microhose is the impossibility of locating measuring sensors inside hoses, that have such small nominal diameters that it is not feasible to locate the sensor inside in such a way that the sensor does not affect the characteristics of the tested object. One way to observe hydrodynamic phenomena in such small objects, is to locate measuring sensors directly in front of and directly behind the tested hose. This method, makes it possible to observe differences in the results, caused by physicomechanical phenomena, acting on the working fluid during its flow through the tested element.

The tests conducted on the vibration of the hose during hydrodynamic flow focused on three main measurement tracks used in the test stand. The first was the tension force, which was applied to the system to stabilize the test object and observe the change in stretch and deformation in the axis parallel to the direction of flow of the working fluid.

The second test track used an accelerometer to measure vibration, which allowed the determination of the vibration of the hose caused by the pulsatile flow of the working fluid. The amplitude-frequency spectrum made it possible to determine the components of the hose vibration spectrum and analyze the contribution of each component.

The third measurement track focused on measuring the axial displacement of the tested hose along its axis. This made it possible to record the axial displacement resulting from the pulsation of flow and pressure inside the tested hose. The use of an amplitude spectrum made it possible to determine the amplitude of the displacement pulsation, and the simultaneous use of an axial force sensor allowed the determination of the force causing this displacement.

The use of measuring devices, such as accelerometers or temperature sensors, directly on the surface of the tested hose allows to observe its motion and changes in internal energy. Additional force sensors in the axis of the hose, as well as in its base, allow monitoring the axial loads on the hose caused by the pulsating flow of the working fluid. All these measurement results provide valuable information about behavior of the hose during the flow of the working fluid.

3.2 Implementation of the Tests

Preliminary vibration tests of the hydraulic line were carried out on a composite micro-hydraulic line. These tests took place to obtain information on the dynamic properties of the line, in particular, its flexural vibration forced by pulsating flow. During the test, a constant tension force of 1 kg was applied to the hose along its axis. The average static pressure of the system was a parameter that have been changing between measurement series, while the temperature of the working fluid, the speed of the motor driving the pump and the flow rate were constant for each measurement series.

To carry out preliminary vibration tests of the composite hose, two measurement series were carried out, during which selected quantities were measured using the sensors of the measurement system with a measurement duration of one second. The sampling frequency was 19200 Hz. The tests were carried out for a hydraulic system flooded with RENOLIN VG 46 oil from FUCHS.

In the tests was used a piston pump driven by an electric motor with a speed of 960 rpm. The flow rate parameter was set to 1 dm^3/min, and the temperature of the working fluid oscillated in the range of 45–50 °C. Measurements were made for two values of static pressure, read from a sensor placed directly behind the test subject. The average pressure for the first series of measurements was 5 MPa, and for the second it was 10 MPa.

3.3 Test Results

During the preliminary hydrodynamic testing of the composite hose, its vibration was tested using a triaxial piezoelectric accelerometer, which was glued directly to the surface of the hose at the midpoint of its length. This sensor measured the axial accelerations of the hose in three axes (Fig. 4): along the axis of the hose (x-axis); perpendicular to the hose axis in the vertical direction (y-axis); perpendicular to the hose axis in the horizontal direction (z-axis).

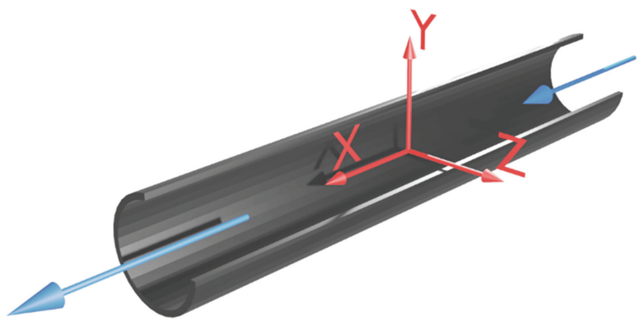

Fig. 4. Axes of triaxial piezoelectric accelerometer.

The test results are shown below using the amplitude-frequency spectrum of the test object's axial accelerations. In Figs. 5, 6, 7, 8, the spectrum for the second measurement test (measurement series) is upshifted by 0.2 m/s2.

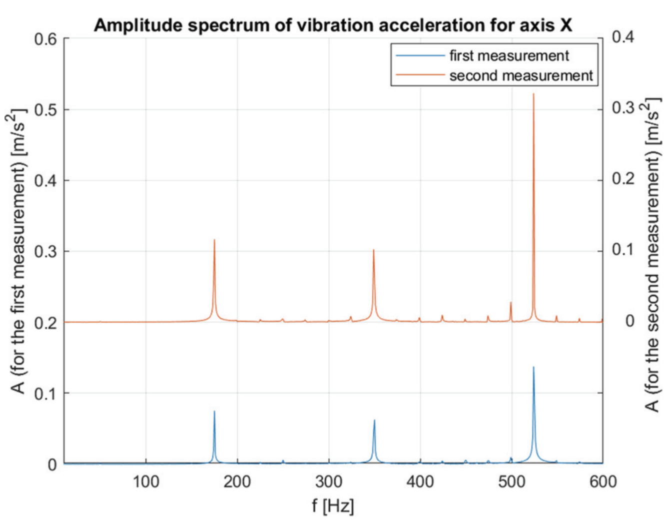

Fig. 5. Acceleration amplitude spectrum for two measurement series in the x-axis.

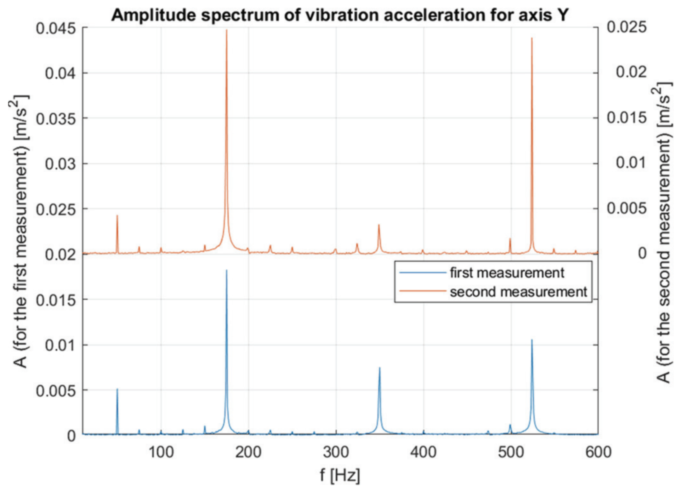

Fig. 6. Acceleration amplitude spectrum for two measurement series in the y-axis.

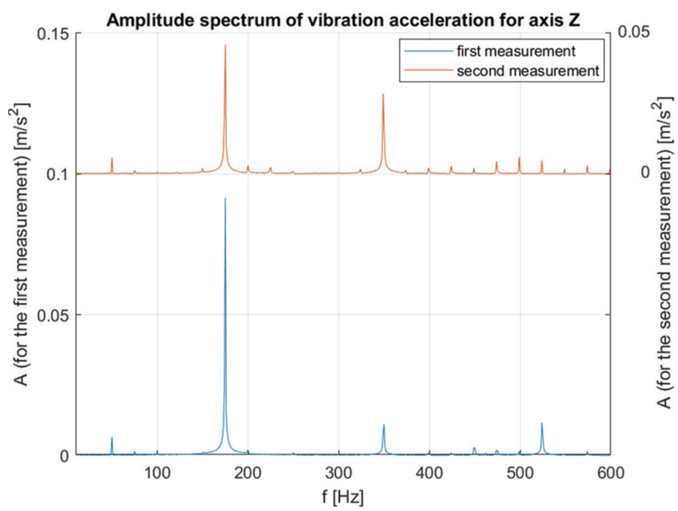

Fig. 7. Acceleration amplitude spectrum for two measurement series in the z-axis.

It was decided to use frequency characteristics instead of time waveforms in the presentation and analysis of measurement results. Frequency characteristics are a convenient form of presenting the dynamic characteristics of test objects. Such analysis of measurement data makes it possible to directly determine the vibration characteristics of an element.

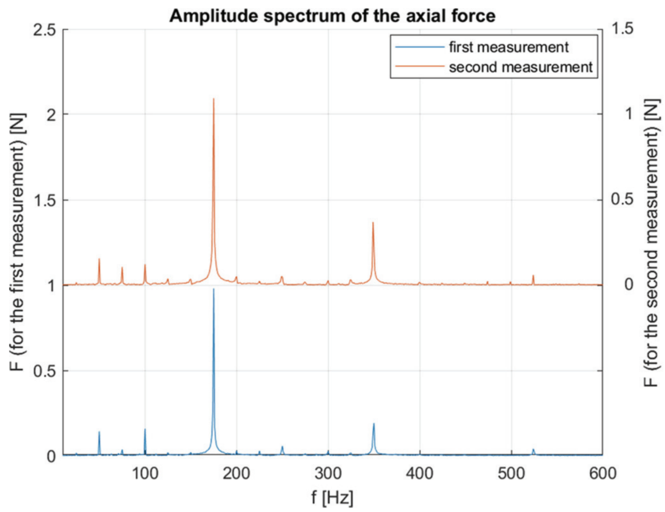

Fig. 8. Amplitude spectrum of the axial force for two measurement series.

4 Discussion. Analysis of Research Results

Analyzing the results of the acceleration measurements, it is possible to notice several harmonic components that appear in each spectrum. The pulsation frequency of the pump performance coincides with the acceleration amplitudes oscillating at 175 Hz (the first component of the spectrum in Fig. 4). In addition, harmonic components with frequencies many times higher than the vibration caused by the pump (350 Hz and 525 Hz) are the next components present in the amplitude spectrum. Pulsations of 50 Hz, equivalent to the frequency of the mains voltage in Poland, are also visible. Although their values are so small that they were mostly ignored in the test, their presence is noticeable in every measurement. It can be concluded that these pulsations are caused by interference from the electrical network to which the signal conditioner was connected. The detail analysis of changes in the axial force and vibration acceleration spectra of the composite microhose is presented in Table 1.

Table 1. Analysis of changes in the axial force and vibration acceleration spectra of the composite microhose

Physical size	Change in the amplitude of the first component f1_50/f1_100	Change in the amplitude of the second component f1_50/f1_100	Change in the amplitude of the third component f1_50/f1_100
X-axis acceleration	0.64	0.61	0.43
Y-axis acceleration	0.74	3.66	0.44
Z-axis acceleration	1.99	0.39	2.40
Axial force	0.90	0.52	0.69

The hydraulic line shows a predisposition to natural vibrations in each of its axes, which further contributes to an increase in the amplitude of the vibrations with the increasing system pressure. Spectral analysis revealed that the sources of vibration are mainly the pulsations of the piston pump, which reduces the culture of the hydraulic line. It can be noticed that for higher values of the average pressure (sample No. 2), the amplitudes of the presented spectral components increased significantly. An increase in pressure values from 50 bar to 100 bar (a 100% increase) resulted in an increasing the amplitude of the first harmonic component of the presented spectra for the x and y directions. For the x direction, the third component of the vibration spectrum is dominant.

5 Conclusions

The article presents a universal test stand for studying hydrodynamic processes in hydraulic lines. The stand was equipped with a multi-channel measurement track. As a test object, it was decided to use a composite micropipe, which was forced by pulsating flow generated by a positive displacement pump. From the posted results, for the direction of vibration X, as the mean pressure increases, the values of the amplitudes of the components of the spectrum - the first three harmonics presented - increase. A 100% increase in the value of the average pressure from 5 MPa to 10 MPa results in an increasing the values of the amplitudes of the first two harmonics by almost 50%. An even greater increase in the amplitude of vibration acceleration is observed for the third component. In addition, for all three directions, the increase in the amplitude of acceleration for the z axis is at the similar level - more than 100%. The relatively smallest increases in the amplitudes of hose vibrations with an increasing in the value of the average pressure are observed for the first component of the spectrum. On the other hand, the value of the axial force changes slightly with a 100% increase in the average pressure inside the hose for the first component of the spectrum.

The presented exemplary test results demonstrate the nonlinear characteristics of the composite microhose. It is important to notice that the tests were carried out at one fixed temperature of the working fluid and the tested microhose. The design of the stand allows to make the temperature value a variable parameter, stabilized in time. The results of the tests will allow the evaluation of the dynamic properties of the hydraulic line and will form the basis for further research and analysis. The obtained measurement results will be used to develop a mathematical model of the hose's vibrations. An important research challenge is the problem of reliably measuring the radial deformation of the microhose - the constant component resulting from the average pressure and the variable component resulting from the pressure pulsation.

From the results presented, it can be seen that the amplitude and frequency of flexural vibrations of the composite microhose are influenced, among other things, by the value of the mean pressure. Limitation of the vibration amplitude in practical cases is achieved by using additional supports for the hose, restraining it to the ground. In addition, the cable's ferrules are a critical point in a vibrating microhose. Prolonged vibration can lead to the formation and development of fatigue cracks in these areas and, in critical cases, to a loss of integrity and rupture of the hose.

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