Radial-piston pump for drive of test machines

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Abstract. The article reviews the development of radial-piston pump with phase control and alternating-flow mode for seismic-testing platforms and other test machines. The prospects for use of the developed device are proved. It is noted that the method of frequency modulation with the detection of the natural frequencies is easily realized by using the radial-piston pump. The prospects of further research are given proof.

1. Introduction

The destructive effect of vibration on various technical systems is due to the occurrence of resonance phenomena in the devices elements as well as dynamic loads which lead to mechanical failure and faults of the objects [1–4] during a standard operation. As a rule, several elements of the system simultaneously resonate resulting a synergetic effect. There are many methods and means of testing for vibration and vibration resistance, for example [5, 6]. Hydrostatic vibro-exciters are referred as a special type of test facilities which are capable to excite spectrally saturated vibrations at very high carrying capacity. Also they are distinguished by the ability to control the vibration mode in a wide range [7–10]. During the seismic resistance tests the large-scale mock-ups were performed by loading the fragments of buildings and structures which give the adequate to real seismic effects [3, 4]. In the result there were worked out several approaches to seismic resistance. This requires the installation of test platforms of much higher carrying capacity. These tests platforms must be capable to simulate the true conditions for the test of dynamic load occurring during earthquakes. Test platforms equipped with a hydrostatic vibratory drive are the most suitable for such purposes as they feature a high specific power and control capability inherent in volumetric hydraulic drives [1, 2].

Due to the impact of seismic vibrations on construction objects the irreversible deformations of elements and components of their structures occur in the result of resonance phenomena. It is experimentally proven that any structure is characterized by a spectrum of natural frequencies, which, as a rule, is in the range of 0.5...15 Hz [3]. As seismic oscillations have a continuous spectrum with the largest harmonic levels in the interval of 0.1...10 Hz, there is always a correspondence between the excitation frequencies and the natural frequencies, which leads to the appearance of resonances.

Another factor of seismic resistance is the duration of such an impact. Short-term load of 4...5 even at a 10-point of earth shock is not dangerous, as the resonances do not have time to develop, and a small-amplitude earthquake which is lasting for several tens of seconds leads to serious destruction [3, 11–16].

The method of a time sweep frequencies is based on those factors which include the preliminary scanning and follow-up tests at resonance frequencies. As the oscillation spectrum is simulated sequentially, the test conditions are inadequate to real seismic impacts when the resonances of the elements and their construction parts do not occur simultaneously.

If we select the amplitude levels from the spectrum of random ground vibrations and average them to the third-octave ranges, then the spectrum can be represented as an imitating line spectrum which ratio of the harmonic levels is close to the spectrum of amplitude-modulated (AM) oscillations. This result is not accidental, as the actual ground vibrations during an earthquake are the natural modulation process [3] (Figure 1), although it is not described by mathematic harmony. Thus, the process of amplitude or amplitude-frequency modulation is the most adequate oscillation process simulating seismic oscillations during test. The envelopes of AM oscillations can be defined by different functions, that allows to simulate the oscillation processes which are different in harmonic composition.
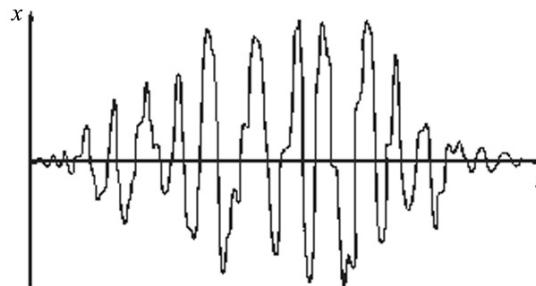

Figure 1. The ground vibrations during an earthquake.

2. Design and operation of a radial piston pump

Figures 2 and 3 show a radial piston pump comprising a stator *1*, a rotor *2* and a phase regulator *3* with an eccentric *4* and an eccentric ring *5* mounted coaxially in the body. The shafts of the phase regulator and the rotor are located in the bearings *6*, *8* and *9*. The pistons *11* are located in the rotor cylinders *10*, which are linked by the ends with the eccentric *4*, and the transverse slits a with the eccentric ring *5*. The channels *12* and *13* (Figure 3) with a width smaller than the width of the rotor are built in the pump body. There are pressure clamps *15* with springs *16* located in the ducts *14*. The cavities above the clamps are communicated through valves *23* and *24* with hydraulic lines *A* and *B* (Figure 3), which make tight contact of the jumpers with the rotor and provide high tightness of the channels *12* and *13*.

There are bypass valves *17* with springs 18 (Figure 4) in the pressure clamps. Holes *19* link them with the cylinders *10*, when the latter are under the jumpers. The above-valves spaces are connected to the channels *13* and *12* through the holes *20* and *21*. The fixed sealing discs *25* and *26* with seals *27* are installed on both sides of the rotor (Figure 2). Due to annular ducts *28* which are in the body and connected to the hydraulic lines *A* and *B* through the return valves *29* and *30*, the discs *25* and *26* are pressed to the ends of the rotor providing high hermeticity of the channels *12* and *13* (Figure 3).

One of the drawbacks of radial piston pumps and rotary hydro-pulsators [1, 5] is the precision of a complex sequence of couplings that closes on the spool valve. The sequence includes the rotor bore, its mounting surfaces for bearings, their base mounting bushings and the collector The gaps in the hydro-mechanical couplings sequence such as the «spool – rotor» and «spool-collector» are designed within 0.02...0.03 mm in order to ensure the sufficient tightness. Therefore the other couplings must be within the tolerances of 0.005...0.05 mm [1].

The flow distribution system in the pump eliminates gaps and provides a higher hermeticity due to the float position of the jumpers and end disks. When the fixed phase regulator (phase angle $\varphi=0$) is at the position of the eccentric 4 (Figure 3), then the hydraulic unit operates as a radial-piston pump with a constant and maximum flow (m^3/s):

$$Q = 2ezs_{\mathrm{p}}f_{\mathrm{r}} = \frac{ezs_{\mathrm{p}}\omega_{\mathrm{r}}}{\pi},$$

where e – the eccentricity of the phase regulator, m, z – the number of pistons, s_p – the area of the piston, m^2, f_r – the rotor speed, Rev/s, and ω_r – the angular velocity of rotor rotation, rad/s.
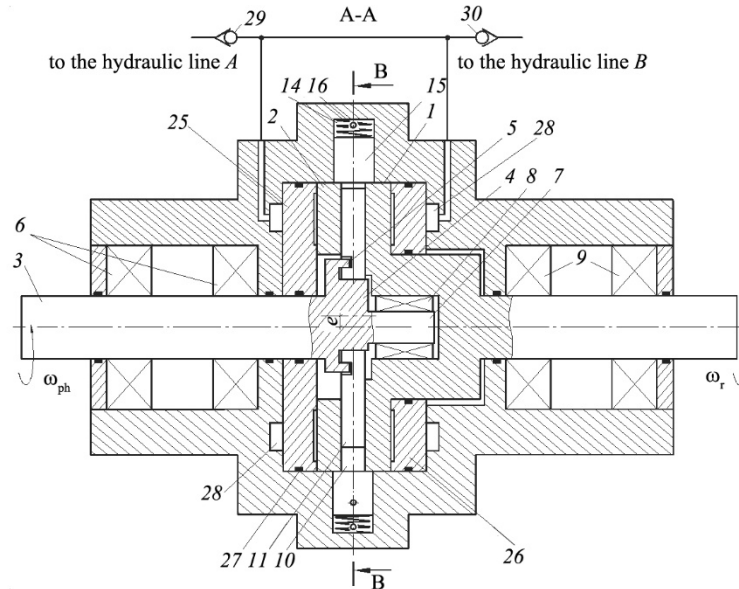

Figure 2. The radial piston unit.

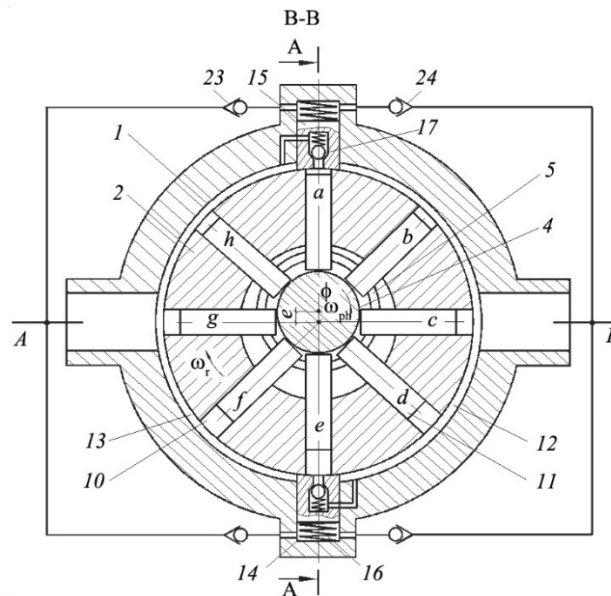**Figure 3.** The radial piston unit (the zero phase the regulator φ=0).

When the rotor rotates clockwise, the pistons are retracted by the eccentric ring *5* (Figure 2). Then pistons pass from position *a* through stages *b, c* and *d* to position *e*, sucking liquid through channel *12* from hydroline *B*. The remaining pistons contact with channel 13, go over their positions *e*, through stages *f, g* and *h*, to position *a* and push the liquid into hydroline *A*. When the cylinder passes under the jumper *15* (Figure 4), the piston moves from position I (indicated by dash) into the position II of the «dead point» and completes the displacement of the liquid into channel *13* until the point *i* on the edge of the cylinder is aligned with point *j* on the edge of the jumper. When the cylinder is cut off from the channel *13*, a liquid compression arises in the over-piston cavity and if it exceeds the working pressure of the pump, the valve *17* will transfer the trapped liquid into the channel *13* through the apertures *20* and *21*. In the first phase the regulator (φ=π/2) is positioned anti-clockwise (Figure 5), the pistons return from position *c* through the stage *d* to position *e*, and suck liquid from channel *12*. The

other pistons pass from position *e* through stage *f* to position *g* and force liquid into channel *12*. The volumes of the sucked and displaced liquid are compensated, there is no supply. The mutual compensation of the volume occurs the same way: when the pistons move from position *a*, through stage *b* to position *c* and then move from the position *g* through stage *h* to position *a*. Thus, the first phase position corresponds to the time of reversed flow in the hydrolines *A* and *B*.
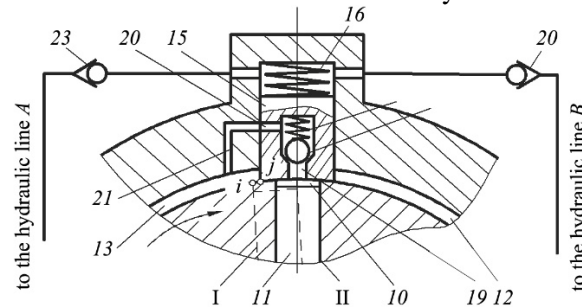

Figure 4. The design of jumper and bypass valve.

When the cylinders pass under the lower jumper *15* (Figure 4) the piston (Figure 5) moves from position I to position II at maximum speed. And when point *i* is aligned with point *j*, the piston will displace the larger volume of the trapped liquid through valve *17* and its compression will also be eliminated.
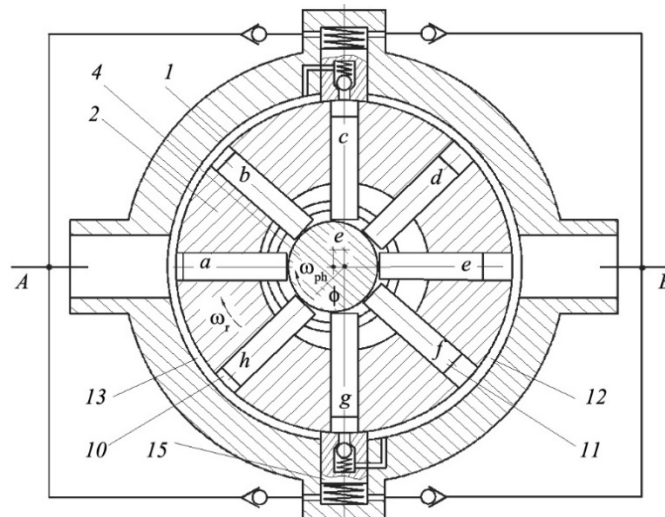

Figure 5. The radial piston unit (the first phase the regulator φ=π/2).

When the regulator is transferred to the second phase position (φ=π), the feed reaches maximum again, but the liquid is displaced into channel *12* and the hydroline B, and is sucked from channel *13* and hydroline A. The third phase position (φ=3π/2) fully corresponds to the first – there is no feed.

Oscillation mode of the phase regulator can be used for hydraulic drives of the machines which are used to test structures for alternating loads. Oscillation mode is to be set between zero and the second phase positions in the range of φ=0...180°. The angular oscillations frequency determines the frequency of load of the test structure. The level of structure deformation determines the holding time *t* of the regulator in the extreme phase positions and, accordingly, the stroke of the hydraulic cylinder, (*m*):

$$h = \frac{ezs_p\omega_r}{\pi} \cdot \frac{t}{F},$$

where *F* – the effective area of the piston of the two-rod hydraulic cylinder, m^2, which is connected to the pump.

When the phase regulator rotates with a constant angular velocity ω_{ph}, for example, towards the rotor rotation (Figure 3) its phase position changes continuously:

$$\varphi = \omega_{ph} \cdot t,$$

and reversed feed occurs in one revolution. The pump goes into rotary pulsator mode, when a cyclic, sign-variable fluid motion is created in the hydrolines A and B.

3. Test platform operation
Figure 6 shows the schematic diagram of the platform hydraulic drive for seismic testing of the objects based on the radial piston hydraulic unit *1*. The unit creates oscillatory fluid flows in pipelines *2* and *3* with an angular frequency ω_{ph} given by the phase regulator. The hydraulic cylinder *4* excites the oscillations x of the platform *10* at a frequency of Hz:
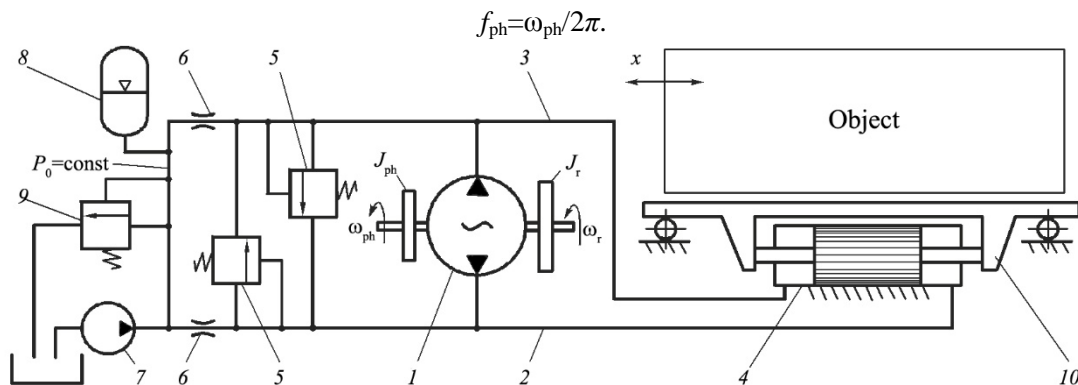
$$f_{ph} = \omega_{ph}/2\pi.$$

Figure 6. The platform hydraulic drive based on the radial piston hydraulic unit.

The drive operates at the initial pressure P_0 in the system supported by make-up pump *7*, the accumulator 8 together with the throttle *6*. Valve *9* provides adjustment P_0, and valves *5* eliminate overload of the hydraulic system. In this case, the rotor shafts and the phase regulator are equipped with flywheels with inertia moments J_r and J_{ph}, which smooth out the pulsation of their torque moments.

One of the seismic test methods is a smooth sweep frequency of the excitation and the preliminary scanning of the test object in the 0.5 to 15 Hz range (sometimes more). The method also allows to detect natural frequencies and subsequent tests in the local resonance mode. When scanning the test object, the rotor preset the constant angular speed ω_r, and the phase regulator drive – variable $\omega_{ph}(t)$, with constant acceleration $d\omega_{ph}/dt$=const, and provides a slow sweep frequency of the excitation f_{ph} in the interval of $\omega_{ph(min)}-\omega_{ph(max)}$ (Figure 7).

In contrast to rotary hydro-pulsators with a controlled valve [1], here the liquid supply to pipelines *2* and *3* (Figure 6) is determined taking into account the angular velocity of phase regulator rotation:

$$Q = Q_{amp} \cdot \cos \omega_{ph} \cdot t,$$

where Q_{amp} – feed amplitude, m^3/s:

$$Q_{amp} = \frac{ezs_p}{\pi} \cdot \left(\omega_r - \omega_{ph} \right), \tag{1}$$

the vibration law and vibration velocity for the test platform are described by the follow equations:

$$x = \frac{ezs_p}{\pi F} \cdot \left(\frac{\omega_r}{\omega_{ph}} - 1 \right) \cdot \sin \omega_{ph} t, \tag{2}$$

$$v = \frac{ezs_p}{\pi F} \cdot \left(\omega_r - \omega_{ph} \right) \cdot \cos \omega_{ph} \cdot t. \tag{3}$$

The spectral characteristic of the test stand, deployed in a two-decadal range $\omega_{ph(min)} \ldots \omega_{ph(max)}$ (Figure 7). The lower graph corresponds to the unidirectional rotation of the regulator and the rotor $\omega_{ph}-\omega_r$, the upper one to multy-directed rotation $\omega_{ph}+\omega_r$. Frequency-modulated oscillations form a continuous spectrum. The «lifetime» of the continuous spectrum harmonics depends on the change rate of the modulating function $\omega_{ph}(t)$. The oscillation spectrum is sequential and the mobility of the process does not create the right conditions for the object excitation, as the corresponding reactions

cannot be established in it. Therefore, the frequency sweep speed should be low. However, the intensity of the related levels, for example, of the vibration velocities taken in the third-octave ranges of the frequency axis in the interval $\Delta\omega = \omega_2 - \omega_1$, will have a final value and a real physical result will be sufficient to excite the resonances of the structural elements of the object. The spectral characteristic (Figure 7) is applied within working range which corresponds to local resonances (0.8…16 Hz) of the most building structures. We aim to exclude the influence of the resonance of the platform-object system. Therefore the stiffness c of the oscillatory system is determined mainly by the liquid volumes enclosed in the hydraulic cylinder chambers and determined by the expression:

$$c = 2F^2 \frac{E_0}{W_0},$$

where E_0 – the modulus of fluid elasticity, n/m^2, W_0 – the fluid volume in the hydraulic cylinder chambers, m^3.
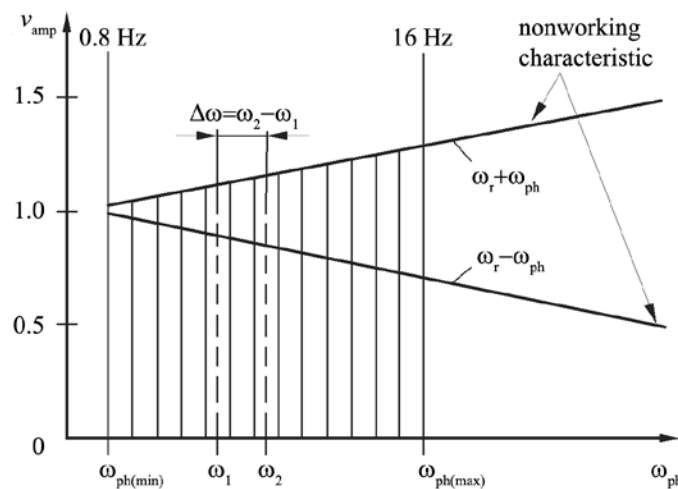

Figure 7. The spectral characteristic of the seismic-testing platforms.

The stiffness should be maximum. The operating volume of the hydraulic unit 1 and other elements of the hydraulic drive circuit in Figure 6 are small, compared to W_0, however, the length of the pipelines should be minimized, and all hydraulic equipment is assembled into a single hydroblock. Taking into account attached mass of test object the natural oscillation frequency of the platform f_0, must not be less than an order of magnitude higher than the upper limit of the frequency range $f_{ph(max)}$ (16 Hz):

$$f_0 = \frac{1}{2\pi} \sqrt{\left(\frac{1}{(m_{pl} + \kappa m_{to})} \right) \cdot \left(c_{eq} + \frac{2F^2 E_0}{W_0} \right)} > 10 f_{ph(max)},$$

where m_{pl} – the platform mass, kg; m_{to} – the mass of the test object, kg; k – the coefficient that takes into account the fraction of the attached object mass; c_{eq} – the equivalent stiffness of the «hydraulic springs» of the hydrolysines and hydraulic devices, reduced to the piston of the loading hydraulic cylinder.

4. Results
The angular velocity of the phase regulator ω_{ph} is successively set to the corresponding resonances and maintained for a regulated time in the seismic test mode at the detected natural frequencies of the object. The angular velocity of the rotor ω_r is changed by means of an adjustable drive if it is necessary to adjust the platform-object system, for example, to the required vibration amplitudenor vibration speed (2, 3).

5. Summary
The method of frequency modulation with the detection of the natural frequencies of the test object is the simplest and easily realized by means of the considered pump. But the potential of the method is

limited, as there is no simultaneous occurrence of resonances and the synergetic effect mentioned above is absent. To expand the functionality of the radial piston hydraulic machine and implement amplitude-frequency modulation during testing, in addition to the phase adjustment, it is necessary to provide volumetric regulation, which requires further improvement of the hydrounit.

The development of hydrostatic random oscillations generators which are capable of exciting narrow-band vibration with a high level of spectral density of vibration acceleration [1, 5] is the further development of the concept of volumetric hydraulic machines for the initiation of test dynamic systems. Such hydraulic units have already been created, they can be used not only in the seismic testing technique, but also in the testing of various instruments and equipment for vibration and vibration resistance and will be considered in future publications of the authors.

References

[1]   Kljuev V 1982 *Test engineering: reference book 1,2* (Moscow: Mashinostroeniye)
[2]   Plotnikova I V, Efremova O N, Tchaikovskaya O N 2017 J. Ponte **73** 158–162 doi: 10.21506/j.ponte.2017.4.45
[3]   Zhunusov T 1972 *Vibrations of buildings and ground during the explosions and earthquakes* (Alma-Ata: Nauka)
[4]   Leonov A P, Red'ko V V, Red'ko L A et al. 2015 IOP Conference Series: Materials Science and Engineering **81** doi:10.1088/1757-899X/81/1/012094
[5]   Kljuev V 2010 *Devices and systems for measuring vibration, noise and shock. Reference book. Book 2* (Moscow: Mashinostroeniye)
[6]   Gavrilin A, Moyzes B, Cherkasov A *et al* 2016 *MATEC Web of Conferences* **79** 01078 doi: 10.1051/matecconf/20167901078
[7]   Gavrilin A, Krauin'sh P, Perestoronin P 1990 *Vibration diagnostics of machines and mechanisms* 64–65 (in Russian)
[8]   Nizhegorodov A, Gavrilin A, Moyzes B 2015 *Key Engineering Materials* **685** 320–325 doi: 10.4028/www.scientific.net/KEM.685.320
[9]   Nizhegorodov A, Gavrilin A, Moyzes B et al 2016 *Journal of Vibroengineering* **18** 3734–3742 doi: 10.21595/jve.2016.16994
[10]   Nizhegorodov A I, Gavrilin A N, Moyzes B B *Journal of Physics: Conf. Ser*. **671** 012037 doi: 10.1088/1742-6596/671/1/012037
[11]   Redko V V, Starikova N S, Redko L A, Vavilova G W 2015 *IOP Conference Series: Materials Science and Engineering* **81** 012083 doi: 10.1088/1757-899X/81/1/012083
[12]   Goldshtein A E, Vavilova G V, Mazikov S V 2016 *MATEC Web of Conferences* **79** 01009 doi: 10.1051/matecconf/20167901009
[13]   Gomboeva S.G, Shishkin I F, Hamhanova D N, Vasendina E A, Plotnikova I V and Efremova O N 2016 *Key Engineering Materials* **685** 463–466 doi: 10.4028/www.scientific.net/KEM.685.463
[14]   Kalinichenko N P, Kalinichenko A N, Lobanova I S, Borisov S S 2013 *Russian Journal of Nondestructive Testing* **49** 668–672 doi: 10.1134/S1061830913110041
[15]   Fedorov E M, Bortnikov I D 2015 *Technical Physics* **60** 1689–1692 doi: 10.1134/S1063784215110110
[16]   Fedorov E, Koba A 2016 *MATEC Web of Conferences* **79** 01082 doi: 10.1051/matecconf/20167901082