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COMPRESSORS, PUMPS, AND PIPELINE FITTINGS

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COMPREHENSIVE ASSESSMENT OF PULSATION PHENOMENA AND DYNAMIC LOADS IN THE WORKING ELEMENTS OF A HYDRAULIC DRIVE

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The operation of the hydraulic drive system is accompanied by pulsations of the flow rate and pressure of the working fluid, which reduce the energy efficiency of the hydraulic drive due to the increase in noise characteristics and additional loads. Based on an analysis, the primary factors affecting the pulsation phenomena in the hydraulic drive were identified. Our results revealed that the pulsation of liquid pressure and probability of hydraulic shock occurrence were primarily responsible for the increased dynamic loads in the working elements of the hydraulic drive.

Keywords: hydraulic drive, pressure pulsation, hydraulic machine, irregularity of supply.

Various movements of fluids in hydraulic systems are implemented under the influence of excess pressure, varying over a wide range.

Pressurized fluids can be used to perform mechanical work in control systems and hydraulic power drives.

Hydraulic drives are used in various industries such as oil and gas production and transportation, aircraft manufacturing, and shipbuilding for independent hydraulic systems, where the necessary excess fluid pressure is created by positive displacement pumps.

The design aspects and operating principle of positive displacement pumps cause fluid flow pulsations, which lead to an increase in the noise characteristics of the hydraulic drive, the occurrence of additional loads, and a reduction in the hydraulic drive energy efficiency.

Thus, to ensure optimal performance of the hydraulic drive, considering the pulsation phenomena and dynamic loads in the hydraulic drive system is crucial. Herein, we examined the primary factors influencing the fluid pulsations and dynamic loads in hydraulic systems.

Analysis of Factors Influencing Pulsation (Fluid Flow Pulsations) in a Hydraulic Drive

Let us review the functional groups of elements constituting the hydraulic drive:

– *energy supply elements*: positive displacement pumps and hydraulic accumulators;

– *actuating elements*: hydraulic motors, hydraulic cylinders, and rotary hydraulic motors;

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– *guiding elements*: hydraulic directional valves, hydraulic locks, and check valves;

– *flow regulating elements*: throttles, flow rate regulators, and flow diverting valves;

– *pressure-regulating valves*: pressure and pressure-reducing valves;

– *additional equipment*: hydraulic tanks, hydraulic lines, filters, and heat exchangers.

Owing to their operation principle and the frequency of processes (suction and discharge), positive displacement pumps (used in hydraulic drives as energy-supplying elements) are characterized by uneven performance, which is estimated by the theoretical coefficient of supply unevenness:

$$\Delta = (Q_{\max} - Q_{\min})/Q_{\text{avg}}, \tag{1}$$

where

$Q_{\max}$, $Q_{\min}$, and Q_{avg} are the maximum, minimum, and average feeding values, respectively.

Notably, different types of pumps and pump designs correspond to different values of supply unevenness coefficients. However, analyzing pumps based on the criterion of theoretical unevenness of supply revealed that in practice, pumps with an odd $(Z = 5, 7, 9)$ number of displacers, namely, pistons (in axial piston and radial piston pumps) or plates (in guided-vane pumps) are mainly used. Such pumps are characterized by relatively low values of Δ, namely with the number of displacers $Z = 5, 7$, and 9, the coefficient of supply unevenness $\Delta = 4.4\%, 2.0\%$, and 1.6%, respectively.

Gear pumps, in comparison with other rotary pumps, are characterized by higher (several times) values of Δ of 40%–10%; higher values of Δ correspond to pumps with a few teeth, while lower values of Δ (i.e., reduction of uneven flow) correspond to pumps with a large number of teeth.

The actual pulsation of the fluid flow created by the pump is determined not only by the theoretical coefficient of supply unevenness but also (to a large extent) by the imperfection of the phase distribution of the working fluid.

Notably, the actual unevenness of the supply may considerably exceed the theoretical value due to the working fluid compression during the transition from the suction process to the discharge process. In addition, when connecting the working chamber of the pump to the discharge line, the pressure in the chamber cavity is often considerably lower than that in the discharge line. The pressure difference leads to a reverse flow of the liquid, resulting in an overpressure accompanied by flow fluctuations.

Substantial pressure differences between the discharge and suction lines lead to higher actual supply unevenness (compared to the calculated supply unevenness).

When using hydraulic accumulators, in contrast, the amplitude of the oscillatory processes generated by the hydraulic system pumps is reduced and the flow of the working fluid is considerably smoother, but the flow pulsation is not eliminated.

Hydraulic motors (related to the actuating elements) and pumps are sources of the working fluid vibrations, which are associated with the same operation principles of the hydraulic machines.

The operation of the remaining elements constituting the hydraulic drive under steady-state operating conditions does not affect the oscillatory phenomena in the system (compared to the constant generation of oscillations of operating pumps). However, during the transient operating modes of a hydraulic drive (for example, when stopping or changing the direction of motion of a hydraulic cylinder or a hydraulic turner), oscillatory processes also occur in the hydraulic drive due to the fluid inertia.

When operating high-speed hydraulic devices (hydraulic distributors, hydraulic locks, check valves), oscillations can also occur because of the inertia of fluid movement.

Notably, self-oscillations can occur in a real hydraulic drive, which is unacceptable as the oscillations can damage the hydraulic drive elements and reduce the accuracy of controlling the object. Self-oscillations in the hydraulic drive system can result from various factors such as dry friction in a spool-type hydraulic distributor, hysteresis in the magnetic system of electromechanical converters, mixed friction in hydraulic motors, formation of a nonlinear dependence of fluid flow through the hydraulic distributor on the pressure differential, and gaps in the connection of the output link with the regulating body of the object controlled. However, these factors in the formation of self-oscillating phenomena relate to the hydraulic drive operation in the event of system malfunctions, while the analysis identifies the factors influencing the pulsation phenomena during proper hydraulic drive operation.

The analysis results established that the primary factors of pulsation phenomena generation (fluid flow pulsations) in a fault-free hydraulic drive are as follows:

- the presence of a positive displacement pump (a source that forms an uneven flow of working fluid) in the system;
- compressibility of the working fluid (when the working chamber of the pump transfers from the line with suction pressure to the line with discharge pressure);
- inertia of fluid movement (which leads to pressure fluctuations in the system during transient operating modes of the hydraulic drive).

Analysis of Dynamic Loads in the Working Elements of a Hydraulic Drive

Various dynamic loads accompany the working processes of hydraulic drives. A characteristic type of hydrodynamic load is pressure pulsations caused by the operation principle of a positive displacement pump.

Flow fluctuations during pump operation induce discharge pressure pulsations (due to the hydraulic resistance of the discharge line, inertia, and elasticity of the working fluid), while the amplitude values of the pressure pulsations are substantially higher than those of the flow fluctuations.

When pressure pulsates in the hydraulic drive system, fatigue damage to hydraulic lines and disruption of the operation of valves and other distribution devices is possible; therefore, factors influencing the increase in pressure pulsations in hydraulic systems must be considered to minimize dynamic loads.

Notably, pressure pulsations in a hydraulic drive have a complex nonharmonic nature, which differs between different-type and same-type pumps. The nature of pressure pulsations (their amplitude and frequency) is influenced by the operating mode design of the pump and the physical properties of the liquid, as well as the geometric parameters of the hydraulic lines, the set of local resistances in the hydraulic drive, and other factors. According to the literature, the presence in the pulsating pressure (created by the pump) of oscillation components with high amplitude and frequency (several times exceeding the periodicity of the pump plungers) is due precisely to the influence of other factors, for example, wave phenomena in the discharge line.

To identify the main factors influencing the intensity of dynamic loads (pressure fluctuations) in hydraulic systems, we will consider data from current literature sources on this subject.

In experimental studies of high-speed plunger pumps, high-pressure pulsation amplitudes were established on the suction line (0.30–0.75 MPa) and the discharge line (0.3–2.0 MPa) [1], and when switching to resonant operating modes of the pump, the pulsation values exceeded the specified values. Analysis of spectrograms [1] revealed the main plunger harmonic in the spectrum of pressure pulsations on the discharge line, the frequency of which is determined by the following equation:

$$f = \omega z/(2\pi), \quad (2)$$

where

ω is the angular velocity of the pump drive shaft,

and

z is the number of plungers.

An analysis [1] established that pressure pulsation at the discharge is a polyharmonic process with a predominance of high-frequency harmonics. A similar pattern is typical for the suction process of a multiplunger pump, with the amplitude of the suction pressure pulsation increasing with the discharge pressure.

A study of the nature of pressure pulsations in the discharge line of a hydraulic drive system (from the power pump to the hydraulic cylinder) has been presented [2]. Note that the pressure pulsations created by the pump are pronounced throughout the hydraulic line (from the power pump to the cylinders) based on the analysis of the spectrum of vibration accelerations of the wall of the pressure hydraulic line with pronounced harmonics. The complication of the fluid flow from the pump to the hydraulic cylinder (and, accordingly, the nature of pressure pulsations in the system) is also due to vibrations created by many hydraulic elements (spools, valves, etc.).

In addition to experimental studies, theoretical studies of pressure pulsations in hydraulic systems were also performed. For example, a method for calculating the design of an axial piston pump distributor has been proposed — based on which a theory for modeling pressure pulsations of a multipiston pump is developed by summing the feed rates of each pump piston [3].

Theoretical studies [4] established that leaks in the elements of an axial piston pump have a small influence on pressure pulsations in the hydraulic system.

Using computational fluid dynamics methods, pressure pulsations of an axial piston pump were studied [5] and the influence of the damping cavity of a multipiston pump was assessed [6]. In addition, studies were performed on the influence of the working volume and rotation speed of an axial piston pump on the pressure pulsation and modeling of an adjustable axial piston pump [7], as well as the modeling of work processes, which was performed considering the pump drive mechanism kinematics [8] and considering or neglecting the pulsation damper [9].

Numerical studies [10] on the mutual influence of the hydraulic system and the axial piston pump on pressure pulsation amplitude established that the pipeline length considerably influences pressure pulsations. The amplitudes of pressure pulsations due to wave phenomena are sometimes several times larger than the amplitudes of pulsations caused by axial piston pump kinematics; therefore, when designing a hydraulic drive, the pipeline influence on pressure pulsations must be considered. Thus, theoretical and empirical data on the study of pressure pulsations in the hydraulic drive system created by the *pump–hydraulic line* combination are well correlated.

Owing to the fluid inertia, the operation of pipeline fittings (guide, control, and safety) also leads to pressure pulsations in the hydraulic drive system. Notably, sudden actuation of fittings is characterized by highly turbulent flows, which can lead to a decrease in pressure (up to cavitation) and an increase in pressure. Ultimately, a rapid change in the open flow areas of pipeline fittings can lead to hydraulic impact and depressurization of the hydraulic system and damage to hydraulic machines, hydraulic equipment, and control-measuring instruments.

Many researchers have confirmed the relevance of research on hydraulic impact in hydraulic systems.

N. E. Zhukovsky was the first to study the physical processes influencing hydraulic impact. Subsequently, many researchers studied transient processes in the hydraulic systems during hydraulic impact, considering the influence of the fluid friction, compressibility, and viscosity.

With the development of computer technology and the possibility to analyze unsteady flows using numerical methods, research is underway to create mathematical models for calculating transient processes in pipelines of hydraulic systems [11].

In one of the works [12], focused on the formation of pressure oscillations and hydraulic impact in hydraulic systems, physical and mathematical models of the generation of pulse vibration of fittings are proposed to determine the dynamic forces depending on the fittings installation location, pressure differential, law of motion of the shut-off element, and time of operation. They reported that the pulse vibration and dynamic force increase with decreasing fitting response time. An increased pressure differential also leads to increasing vibration and dynamic force. The law of motion of the shut-off element also substantially influences the dynamic force.

Conclusions based on the results of the analysis of dynamic loads in the working elements of the hydraulic drive:

– dynamic loads in the hydraulic drive increase due to the pressure fluctuations and hydraulic impact in the system;

– pressure fluctuations in the system arise due to the following factors: uneven supply of the pump, increase with increasing length of the discharge line, and an increase in the number of local resistances along the working fluid movement;

– hydraulic shocks in the hydraulic drive system can occur because of rapid changes in the open flow areas of pipeline fittings.

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