On Cavitation in the Hydraulic Drives of Mobile Machines

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Abstract: The paper considers the processes and conditions for the occurrence of cavitation in the hydraulic drive of the work equipment hoisting mechanism and closed-loop pulse hydraulic systems. A dynamic system of an oscillatory scrapper of compacted snow and ice is developed; a mathematical model and a numerical solution are provided. The inertia mass haul diagrams and amplitude-frequency curves are obtained. The effect of the fluid pulse frequency on the vibrating mass motion was experimentally studied, and the occurrence of cavitation in resonant modes was established.

1. Introduction

Most of the process operations associated with excavating and moving soils and rocks are performed by earthmoving machines. These machines are mobile units consisting of a base chassis, work equipment, and a control system. The position of work equipment relative to the medium being processed determines the process stage: cutting, moving the soil, unloading, and lowering the work equipment. In modern mobile machines, a hydraulic drive is widely used to change the position of work equipment.

General issues of the theory and calculation of the volumetric hydraulic drive are comprehensively and deeply studied by T.M. Bashta [4, 5, 6], V.N. Prokofiev [14], and K.V. Frolov [12].

In the monograph by A.I. Voshchinin and I.F. Savin [8], the operation principles, the design of hydraulic units, and methods for choosing the parameters of hydraulic systems of construction and road machines are outlined.

Specifics of work and techniques for calculating construction and road machines have been proposed by T.V. Alekseeva [1, 2, 3] and her students V.F. Amelchenko, V.Ya. Sokolov, N.S. Galdin, and others. Hydraulic cylinders designed for hoisting and lowering the work equipment are installed with an upper or lower rod. Most earthmoving machines have lower hydraulic cylinder rods: bulldozers, motor graders, scrapers, etc. Lowering the work equipment was first studied by T.V. Alekseeva [1], and a new phenomenon of the pressure fluid flow discontinuity in the upper cavity of the hydraulic cylinder to hoist the work equipment of a bulldozer was established.

The consequence of this phenomenon was the emergence of a vacuum and the release of the gas phase from the pressure fluid, which was called cavitation. Cavitation is more often observed at the suction of pumps at a high driveshaft speed or operation on viscous oil. Cavitation causes sharp pressure fluctuations that cause noise, shock loads on bearings, and erosion of casing walls, gears, and plungers. All this leads to accelerated wear of the parts of pumps and other hydraulic equipment: valves, distributors, and flow and pressure regulators. Erosive destruction is facilitated by local defects.
in the metal and mainly the poor quality of the part surface processing. The erosion resistance of parts grows with an increase in the hardness of the steel surfaces.

Cavitation occurs in pipelines and hydraulic valves of axial piston hydraulic machines at a sharp change in the pressure fluid flow rate (throttling devices, hydraulic valve channels, etc.). At the cavitation in pipelines and hydraulic pumps, air bubbles reaching the high-pressure area of the injection lines sharply decrease in size, and the pressure fluid bursts into the center of the bubbles, which collapse and hit the surfaces of the parts. The motion law of the rod and piston of the hydraulic cylinder for hoisting - lowering the work equipment was established by T.V. Alekseeva and V.Ya. Sokolov for rational temperature regimes [2].

The construction and mining equipment operating practice shows that the development of natural minerals in the Far North is performed in more severe operating modes due to negative temperatures and significant overloads, which deteriorate the reliability and durability of hydraulic systems.

When choosing the hydraulic drive parameters, the possibility of filling the hydraulic cylinder cavities during the work equipment lowering should be checked. Lowering the work equipment occurs when the hydraulic valve spool is switched to the position, in which the upper cavity of the hydraulic cylinder is connected to the hydraulic pump and the lower one to the tank. As experimental studies by T.V. Alekseeva show, when lowering the work equipment of a bulldozer, a vacuum emerges in the upper cavity of the hydraulic cylinder, the value of which reaches 0.04 ... 0.07 MPa. The rapid fall of the work equipment leads to the pressure fluid flow discontinuity in the upper cavity of the hydraulic cylinder due to an increase in the released volume compared to that of the pressure fluid discharged by the hydraulic pump.

The pressure fluid flow discontinuity causes cavitation and air release and disruption of the continuous flow. Studies of the tensile strength of mineral oils performed by V.A. Khokhlov have shown that reducing the pressure to 0.015 ... 0.06 MPa at +45 ... + 50 °C leads to the pressure fluid flow discontinuity with the release of vapors and gases dissolved in it [15].

To eliminate cavitation in the hydraulic systems of mobile machines, various braking devices are used in the form of brake valves or speed limiters.

M.E. Goyo also studied lowering the work equipment of a bulldozer, obtained the dependences of the rod motion speed change, and proposed a differential scheme for installing hydraulic cylinders [9, 10, 11].

As a result of the studies performed, the criteria for the non-cavitation operation of the hydraulic drive of mobile machines have been obtained, which are ensured by the equality of the volume of the pressure fluid entering the hydraulic cylinders and that released when lowering the work equipment.

For a long time, Pacific University has been working on creating closed-loop pulse hydraulic devices to improve the efficiency of the destruction of snow and ice bodies on highways [15].

The hydraulic oscillatory scrapper of compacted snow has a dynamic system comprising two vibro-masses connected by elastic elements and a hydraulic pusher, which is the exciter of vibro-masses. The lower vibrating mass is equipped with curvilinear elastic working tools. As a result of vertical oscillations of the lower vibrating mass, the blades of curvilinear elastic working tools penetrate the compacted snow layer with simultaneous rotation and horizontal motion. The resulting stress state in the blade and medium contact zone is characterized by biaxial compression and tangential shear stresses on the surface 'compacted snow layer - road coating'.

The pulses of the pressure transmitted to the hydraulic pusher are formed by the hydraulic pulsator capable to change the pulse frequency.

To study the hydraulic oscillatory scrapper operation, its dynamic model has been built (Fig. 1), the parameters of which are the upper and lower vibro-masses oscillation amplitude, their masses $m_1$ and $m_2$, and the stiffnesses of elastic working tools $C_1$ and $C_2$. The exciter of oscillations is a hydraulic cylinder, the upper wall of which is rigidly connected to the mass $m_1$. The hydraulic cylinder rod rests freely on the mass $m_1$. 

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Figure 1. Design Scheme for Determining the Main Parameters of a Two-Mass Oscillatory Scraper.

A system of differential equations describing the motion of vibro-masses has been built, which is supplemented by an equation considering the hydraulic pusher area, the motion of vibro-masses, the hydraulic system elasticity, and the volume of the pressure fluid fed by the hydraulic pulsator.

\[
\begin{align*}
    m_1 \Delta y_1'' + k (\Delta y_1' + \Delta y_1') + C_1 \Delta y_1 + C_2 (\Delta y_1 + \Delta y_2) &= p F \\
    m_2 \Delta y_2'' + k (\Delta y_2' + \Delta y_2') + C_2 (\Delta y_1 + \Delta y_2) &= p F \\
    F (\Delta y_1 + \Delta y_2) + \frac{V_0}{E} p &= q (1 - \cos \omega t)
\end{align*}
\]

where \( q \) is the specific discharge of the hydraulic pulsator; \( V_0 \) is the hydraulic system volume; \( E \) is the pressure fluid elasticity modulus; \( p \) is the hydraulic system pressure; \( \omega \) is the frequency of pressure change in the hydraulic system; \( k \) is the coefficient of viscous friction of the piston against the hydraulic cylinder wall; \( F \) is the hydraulic pusher area.

After transformations, we get a system of two differential equations:

\[
\begin{align*}
    m_1 \Delta y_1'' + k \Delta y_1' + \gamma_1 \Delta y_1 + \gamma_2 \Delta y_2 &= a - a \cos \omega t \\
    m_2 \Delta y_2'' + k \Delta y_2' + \gamma_1 \Delta y_1 + \gamma_2 \Delta y_2 &= a - a \cos \omega t
\end{align*}
\]

where the following denotations are introduced:

\[
\gamma_1 = C_1 + C_2 + \frac{EF^2}{V_0}; \quad \gamma_2 = C_2 + \frac{EF^2}{V_0}; \quad a = \frac{qEF}{V_0}.
\]

The solution to the generalized system of equations is the dependence of the vibration amplitude of vibro-masses (Fig. 2) and pressure on the hydraulic pulsator forced oscillation frequency.
The main idea of the new equipment is installing a spring-loaded vibro-mass with a high-frequency resonance frequency on an inertial mass in the form of a force plate with low resonant frequencies, oscillating relative to the force plate. This design allows simulating the road surface unevenness.

An increase in the $m_1/m_0$ ratio leads to a decrease in the oscillation amplitude $y_2$ and an improved efficiency of the destruction of a compacted snow layer due to an increase in the oscillation amplitude $y_1$ of the working body blade.

An analysis of the vibro-mass motion amplitude-frequency curve has shown that there are two resonance frequencies $\omega_1$ and $\omega_2$ according to the number of masses (Fig. 3). At the first resonant frequency, the released volume exceeds the maximum value of the supplied pressure fluid, and the discharge line pressure falls below the critical value for cavitation. Experimental studies have shown oscillations dying-away due to the release of air from a closed volume: the manifestation of cavitation at a slow increase in the pulsation frequency of the pressure fluid supplied to the hydraulic pushers. To eliminate this phenomenon, pipelines should be dismantled, the air removed, and the hydraulic system re-assembled.

Based on the amplitude-frequency curve, the optimal operating pressure pulsation frequency in the hydraulic system has been determined. The criterion for choosing this frequency is eliminating cavitation in the hydraulic system at the steady oscillations of vibro-masses. We adopt the optimal frequency $\omega = 0.8\omega_r$ or $\omega = 235\text{ rad/c}$, where $\omega_r$ is the resonant frequency. When choosing the values of the $m_1$ and $m_2$ masses and $C_1$ and $C_2$ stiffnesses, the mass oscillation amplitude should be within 2-3 cm and the $m_2$ mass amplitude as small as possible. It was found that these conditions are met at the
ratios $m_2/m_1 = 5$ and $C_2/C_1 = 0.7$. Based on this, the parameters have been determined for the system studied.

In prototypes at significant frequencies, a quick pass of the first resonance frequency occurs, and cavitation is not observed.

2. Conclusion
In closed-loop pulse hydraulic systems, the occurrence of cavitation at frequencies close to resonance has been established. To exclude cavitation, when designing pulse hydraulic drives, the recommended ratios of masses and elastic elements should be considered and the oscillation frequency set within the range excluding resonances.

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