Propagation Characteristics of Pressure Pulsation in Hydraulic Hose

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Abstract. Most modern aircraft hydraulic systems use variable plunger pumps. The pulsating flow output is its inherent characteristic. The resulting pressure pulsation often causes serious damage to the energy pipeline system and endangers the lives of the occupants. This paper studies the propagation law of hydraulic oil in hydraulic hoses, fully considers the coupling vibration of hydraulic oil high-pressure fluid and flexible solids of the hose, establishes a fluid-solid coupling vibration model of hydraulic hoses, and uses ANSYS for numerical simulation to study different frequencies and pipe bending. Using ANSYS for numerical simulation to study the influence of different frequencies and pipe bending radii on the amplitude of fluid pressure pulsation, after comparative analysis, the law of fluid pressure pulsation propagation in hydraulic hoses is obtained.

Keywords: Hydraulic hose; Fluid-solid coupling; Fluid pressure pulsation propagation.

1. Introduction
Hydraulic hose is a connection and compensation device for pipelines. It has many excellent properties such as reliable sealing, pressure resistance, high and low temperature resistance, corrosion resistance, flexibility and fatigue resistance. It is generally believed that the hose in the hydraulic pipeline can absorb the vibration in the pipeline and play a role in reducing pressure pulsation. However, if the hydraulic hose parameters do not match the system, not only will it not be able to absorb vibration, but the pressure pulsation after the hose may even be greater than the pressure pulsation before the hose. Due to the mutual influence of pulsation and vibration between the fluid and the pipeline, the fluid in the pipeline will excite the solids in the pipeline, and the vibration of the pipeline will also affect the instability of the fluid and the pulsation of the fluid. Therefore, fluid-solid coupling occurs between the pipe solid and the internal fluid.

In recent research on hydraulic hoses, Petter Krus focus on simplified models for hydraulic transmission lines and hoses, efficient approximate models for flexible hoses are presented[1]. Ramkarn Patne consider plane Couette flows coupled by a DS, demonstrate that, as a consequence of the coupling and irrespective of the thickness of the DS, a viscous instability exists, which can lead to absolute instability at sufficiently high dimensionless speed of the lower plate[2]. Sandip Patil, Rutuja Bagade and Javedkhan Tamboli investigates the effect of thermostatic subzero (-650F) and high ambient temperature (+2750F) on the hose performance, it was observed that the flexing mechanism of hose when combined with thermostatic subzero and high ambient temperature[3]. In order to expand Electro-hydrostatic actuators(EHAs) potential to be used for robots, Kenta Tsuda investigates the effect of the rigidity of hydraulic hoses by applying different type of hoses in an EHA[4]. Jakubauskas
consider the additional mass of the fluid, an accurate calculation formula for the natural frequency of the hose is proposed[5]. Morishita used the Timoshenko beam model to prove that to accurately determine the natural frequency of the hose's lateral vibration, the influence of its moment of inertia needs to be considered[6]. Jakubauskas and Weaver[7] verified the conclusions of Morishita et al. and gave a method to calculate the natural frequency of the lateral vibration of the hose in consideration of the additional mass of the fluid. Researchers such as Sarkar regard fluid and structure as a single simpler power system unit, and combined with the theory of embedded boundary method, the vibration characteristics of the structural fluid-solid coupling produced by the solid structure installed on the elastic foundation are studied[8][9]. Tijsseling considers the coupling relationship between the fluid in the pipe and the pipe wall, and derives the mathematical model that can accurately describe the characteristics of the liquid-filled pipe and the fluid-solid coupling vibration equation on the structure based on the classic water hammer and beam theory[10][11]. Researchers such as Lee [12][13], based on Paidoussis and Wiggert's mathematical models of pipe vibration response, deduced and calculated the nonlinear dynamics mathematical model that exists when the fluid and the pipe are coupled with each other.

This paper mainly conducts finite element simulation analysis on the propagation characteristics of pressure pulsation in hydraulic hoses, uses finite element knowledge, combined with ANSYS software to simulate, establishes a hydraulic hose pressure pulsation model, and studies the two-way fluid-solid coupling under conditions of different frequencies and pipe bending radii. Simulation, analysis of the pressure pulsation propagation characteristics and laws of hydraulic hoses, to provide references for designing hydraulic hoses that meet the requirements of engineering use.

2. Hydraulic Hose-fluid Coupling Vibration Model

2.1. Hose Vibration Equation

The deformation of hydraulic hoses under working conditions is an extremely complex nonlinear behavior. Under small loads, the stress-strain relationship of the hose material is linear, but when it is subjected to high pressure or large compensation displacement loads, the thin-walled structure may be at a high stress level, the local areas of the wave crests and troughs may have been plastically deformed, the material fibers have great translation and rotation, and the material will no longer be in a linear state. Therefore, the operating state of the hydraulic hose can be regarded as a geometrically nonlinear state. The geometric nonlinearity of hydraulic hoses can be expressed by Lagrangian equation:

$$\left( K_t + K_o + K_s - K_d \right) \Delta q = K q = F + T - P$$

(1)

$K_t$ is the tangent stiffness matrix, which represents the relationship between load increment and displacement increment, $K_o$ is the elastic stiffness matrix, that is, the stiffness matrix in the conventional finite element method. $K_s$ is the initial stress or geometric stiffness matrix, which indicates the effect of initial stress on the stiffness of the structure in the case of large deformation, $K_i$ is the initial displacement stiffness matrix or the large displacement stiffness matrix, which is the structural stiffness change caused by the large displacement, $\Delta q$ is the nodal displacement increment, $F$ is the body load, $T$ is the surface load, $P$ is the structural reaction force.

2.2. Basic Equations of Fluid Flow

Continuity equation[14]:

$$\frac{\partial \rho_f}{\partial t} + \frac{\partial (\rho_f v_f)}{\partial x} + \frac{\partial (\rho_f v_f)}{\partial y} + \frac{\partial (\rho_f v_f)}{\partial z} = 0$$

(2)

$v_x$, $v_y$, $v_z$ is the velocity vector in the $p_f$ direction, $t$ is a time variable.

Momentum equation:
\[
\frac{\partial \rho_j v_x}{\partial t} + \frac{\partial (\rho_j v_x v_x)}{\partial x} + \frac{\partial (\rho_j v_x v_y)}{\partial y} + \frac{\partial (\rho_j v_x v_z)}{\partial z} = \rho_j g_x - \frac{\partial P}{\partial x} + \frac{\partial}{\partial x} (\mu_e \frac{\partial v_x}{\partial x}) + \frac{\partial}{\partial y} (\mu_e \frac{\partial v_x}{\partial y}) + \frac{\partial}{\partial z} (\mu_e \frac{\partial v_x}{\partial z}) + T_x
\]

(3)

\[
\frac{\partial \rho_j v_y}{\partial t} + \frac{\partial (\rho_j v_y v_x)}{\partial x} + \frac{\partial (\rho_j v_y v_y)}{\partial y} + \frac{\partial (\rho_j v_y v_z)}{\partial z} = \rho_j g_y - \frac{\partial P}{\partial y} + \frac{\partial}{\partial x} (\mu_e \frac{\partial v_y}{\partial x}) + \frac{\partial}{\partial y} (\mu_e \frac{\partial v_y}{\partial y}) + \frac{\partial}{\partial z} (\mu_e \frac{\partial v_y}{\partial z}) + T_y
\]

(4)

\[
\frac{\partial \rho_j v_z}{\partial t} + \frac{\partial (\rho_j v_z v_x)}{\partial x} + \frac{\partial (\rho_j v_z v_y)}{\partial y} + \frac{\partial (\rho_j v_z v_z)}{\partial z} = \rho_j g_z - \frac{\partial P}{\partial z} + \frac{\partial}{\partial x} (\mu_e \frac{\partial v_z}{\partial x}) + \frac{\partial}{\partial y} (\mu_e \frac{\partial v_z}{\partial y}) + \frac{\partial}{\partial z} (\mu_e \frac{\partial v_z}{\partial z}) + T_z
\]

(5)

g_x, g_y, g_z is the gravitational acceleration value in the direction. \(P\) is the fluid pressure. \(\mu_e\) is the effective viscosity coefficient of the fluid. \(T_x, T_y, T_z\) is the viscosity loss term in the \(x, y, z\) direction.

Energy conservation equation:

\[
\frac{\partial (\rho C_p T)}{\partial t} + \frac{\partial (\rho v_j C_p T)}{\partial x} + \frac{\partial (\rho v_j C_p T)}{\partial y} + \frac{\partial (\rho v_j C_p T)}{\partial z} = \frac{\partial}{\partial x} (K \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (K \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z} (K \frac{\partial T}{\partial z}) + Q_v
\]

(6)

\(C_p\) is the specific heat capacity at constant pressure. \(T\) is the fluid temperature value. \(K\) is the fluid thermal conductivity. \(Q\) is the volumetric heat source.

3. Simulation Analysis

Based on the ANSYS Workbench platform, the pipeline is analyzed for fluid-structure coupling[15]. In order to study the inlet pressure and outlet pressure of the hose, a piece of hard pipe with a length of 1m was externally connected to the inlet and outlet of the hose. The straight line distance between the inlet and outlet ends of the hose is 0.5m. Pipe inner diameter 25.4mm, outer diameter 38.1mm.Material properties are shown in Table 1.The boundary condition is fixed at both ends.

| Material          | Density (kg m\(^{-3}\)) | Young’s Modulus (Pa) | Poisson’s Ratio | Viscosity(Pa s ) |
|-------------------|--------------------------|----------------------|-----------------|-----------------|
| hose              | 8030                     | 1.93E+10             | 0.29            |                 |
| steel pipe        | 7850                     | 2E+11                | 0.3             |                 |
| hydraulic oil     | 880                      |                      |                 | 0.04048         |

3.1. The Influence of Hose Bending Radius on Fluid Pressure Characteristics

Set fluid pressure to: \(600000 + 12000\sin(400\pi t)\) Pa, the outlet static pressure is 0 Pa. Taking the inlet section and outlet section of the hose as the research object, when the hose is straightened, the corresponding pressure pulsation curve is shown in Figure 1.
According to the simulation results in Figure 1, there is a significant pressure drop after the fluid passes through the hose, but the pulsation amplitude varies slightly. When the hose bending radius is 0mm, 5762.5mm, 2885mm, 1927.5mm, 1450mm, 1164.5mm, 975mm, 840.357mm, 740mm, the pressure pulsation amplitude and pressure drop are shown in Figure 2.

According to the simulation results in Figure 2, when the hydraulic hose is stretched to the bending stage, the ability of the hydraulic hose to attenuate the amplitude of the fluid pressure pulsation is weakened. When the bending radius is from 2885mm to 1164.5mm, the pressure pulsation amplitude and pressure drop gradually increase, indicating the hydraulic hose in this range the ability to attenuate the amplitude of fluid pressure pulsation is gradually enhanced, and the hydraulic hose with a bending radius of 1164.5mm has the strongest ability to attenuate the amplitude of fluid pressure pulsation.

### 3.2. The Influence of Frequency on Fluid Pressure Characteristics

When the bending radius of the hose is 1927.5mm, the frequency is 20Hz, 50Hz, 100Hz, 150Hz, 200Hz, 300Hz, and the inlet pressure of the pipe is set as: $600000 + 12000 \sin(\omega t) \ Pa$, the outlet static pressure is 0 Pa. Taking the inlet section and outlet section of the hose as the research object, the pressure signals are obtained respectively. After processing, the fluid frequency characteristic curve is shown in Figure 3, and the fluid pressure fluctuation amplitude variation curve is shown in Figure 4.

According to the simulation results in Figure 3, when the fluid excitation frequency is less than 100Hz, the pressure of the fluid in the pipeline does not change with the frequency. When the fluid excitation frequency is greater than 100Hz, the greater the excitation frequency, the greater the fluid pressure in the pipeline.

According to the simulation results in Figure 4, when the fluid excitation frequency is less than 100Hz, the fluid pressure fluctuation amplitude in the pipeline changes little. When the fluid excitation
frequency is 150 Hz, the fluid pressure pulsation amplitude is the smallest, and according to the simulation result of this frequency in Figure 3, it shows that the hose has the greatest suppression effect on the fluid pressure pulsation amplitude at this frequency. When the fluid excitation frequency is greater than 150 Hz, the greater the fluid excitation frequency, the greater the amplitude of the fluid pressure pulsation in the pipeline.

4. Conclusion
The smaller the bending radius of the hydraulic hose, the stronger the ability of the hydraulic hose to suppress the amplitude of fluid pressure pulsation. The amplitude of fluid pressure pulsation, like resistance, will also show frequency characteristics. When the fluid excitation frequency is less than 100 Hz, the fluid pressure fluctuation amplitude in the pipeline changes little. When the fluid excitation frequency is greater than 150 Hz, the greater the fluid excitation frequency, the greater the amplitude of the fluid pressure pulsation in the pipeline.

References
[1] Krus, P.. (2017). Dynamic Models for Transmission Lines and Hoses. DINAME 2017. XVII International Symposium on Dynamics Problems in Mechanics.
[2] Patne, R., & Ramon, G. Z.. (2020). Stability of fluid flows coupled by a deformable solid layer. Journal of Fluid Mechanics, 905.
[3] Patil, S., Bagade, R., & Tamboli, J.. (2020). The effect of thermostatic test environment on the flexural fatigue performance of hydraulic hose assemblies. IOP Conference Series: Materials Science and Engineering, 804(1), 012001 (7pp).
[4] Tsuda, K., Umeda, K., Kota, I., Sakaino, S., & Tsuji, T.. (2017). Analysis on rigidity of hydraulic hoses for electro-hydrostatic actuators. IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society. IEEE.
[5] V.F. Jakubauskas. Added fluid mass for bellows expansion joints in axial vibrations[J]. Trans ASME, J. Press. Vess. Technol., 1999(121):216 – 219.
[6] Morishita, M., Ikahata, N., & Kitamura, S.. (1989). Dynamic analysis methods of bellows including fluid-structure interaction.
[7] V. F. Jakubauskas and D.S.Weaver. Transverse vibrations of fluid filled bellows expansion joints[C]. Symposium on Fluid Structure Interaction, Aeroelasticity, Fluid-Induced Vibration and Noise. 1997, ASME AD-Vol.53-2, Vol. 2, pp. 463 – 471.
[8] M.P.Sarkar. A cantilever conveying fluid: coherent modes versus beam modes[J]. International Journal of Non-Linear Mechanics, 2004,39: 467-481.
[9] M. P. Sarkar and Li. GX. Pipes conveying fluid: a model dynamical problems[J].Journal of Fluids and Structures, 1993,7:137-204.
[10] Tijsse ling A.S., Vardy A.E., Fan D. Fluid-structure interaction and cavitation in a single-elbow pipe system. Journal of Fluids and Structures 1996,10 (4):395-420P
[11] U. Lee, C.H. Pak and S.C. Hong. The dynamics of a piping system with internal unsteady flow[J]. Journal of Sound and Vibration, 1995, 180 (2): 297-311.
[12] V.Lee. The Dynamic of a Piping System with Internal Unsteady Flow[J].Journal of Sound and Vibration, 1995, 180 (2):297-311.
[13] Tijsse ling A.S., Vaugrante P..FSI in L-shaped and T-shaped pipe systems. Proceedings of the 10thInternational Meeting of the IAHR Work Group on the Behavior of Hydraulic Machinery under Steady Oscillatory Conditions, Trondheim, Norway, June 2001,Paper C3.
[14] R.Temam. Navier-Stokes equations: theory and numerical analysis[M]. Amer Mathematical Society, 2001.
[15] Yang, Z., Li, J., Zhou, L., & Cai, Y.. (2018). Influence of axial vibration on pressure fluctuation at outlet of hydraulic hose. Huazhong Keji Daxue Xuebao (Ziran Kexue Ban)/Journal of Huazhong University of Science and Technology (Natural Science Edition), 46(11), 53-58.