Cavitation Modeling and the Hysteretic Behavior Investigation on Twin-Tube Hydraulic Adjustable Damper

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Abstract. As a key component of automobile suspension, damper plays a decisive role in the performance of suspension. In order to improve the comfort and stability of vehicle, it is especially important to conduct further study on the performance of the damper. In this paper, the hysteretic behavior of twin-tube hydraulic adjustable damper (twin-tube HAD) widely used in the market is deeply studied. The modeling of the fluid cavitation mechanism and its effect on the damping output characteristics of the twin-tube HAD are analyzed. The process of cavitation in the twin-tube HAD is studied by studying the compressibility of the mixture and the structure of valve port. The results show that the generation of cavitation bubbles mainly come from complex valve system, the more complicated the structure of the valve port, the greater the possibility of cavitation. The volume of cavitation bubbles increases over time during the operation of the twin-tube HAD.

Keywords: twin-tube HAD; hysteresis; cavitation; compressibility; valve port; compression stroke; rebound stroke.

1. Introduction

The design of the suspension system play an important role in the handling and comfort of the vehicle. In order to improve the performance of the vehicle, it is necessary to carry out detailed design for each part of the suspension[1, 2]. Twin-tube HAD is widely used in automobile suspensions and its performance directly affects the ride comfort, safety and steering stability of the vehicle. However, Twin-tube HAD generates a large amount of bubbles during the operation process due to high frequency vibration. The generation and existence of cavitation bubbles will cause the damping output hysteresis of the twin-tube HAD, which has not negligible effect on the performance of the twin-tube HAD. Therefore, before studying damping output hysteresis mechanism of the twin-tube HAD, it is very necessary to study the formation mechanism of cavitation bubbles in the damper. After clarifying the formation mechanism of the cavitation bubbles in the twin-tube HAD, the relationship between the existence of cavitation bubbles and the mechanism of the damping output hysteresis of the twin-tube HAD is studied by establishing the twin-tube HAD model. The presence of cavitation bubbles complicate the coupling relationship between the oil and the valve system and increasing the difficulty of establishing a precise mathematical model. Few studies have established a mathematical model to explain the relationship between the existence of cavitation bubbles and the damping output hysteresis mechanism of the twin-tube HAD[3-8].

There have been many studies on different aspects of the characteristics and performance of hydraulic dampers[9-12]. Guan et al[13] investigated the dynamic performance of twin-tube shock absorber by experiment and simulation. The virtual prototyping technology is proposed to further investigate dynamic properties of shock absorber. Lang[14] was the first to establish a bubble based on evaporation, known as cavitation, to study the damping output hysteresis of the hydraulic damper. Lee [15] studied the analytical model of monotube hydraulic dampers. Duym et al.[16] worked on a analytical model of the hysteretic behavior in twin-tube dampers.

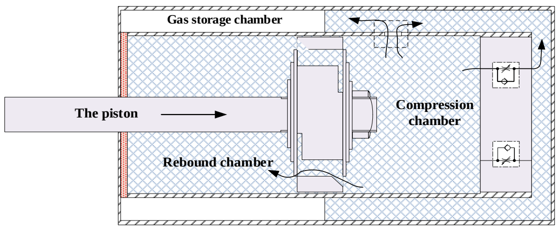
This article will simplify the combination of non-parametric methods and parametric methods for complex valve systems. By considering Solid-liquid coupling, seal friction, valve opening, effective piston force area, bubble volume fraction and cavitation mechanism of the valve port, a nonlinear stiffness and damping characteristic model of the twin-tube is established. The formation mechanism of valve outlet cavitation is analyzed, the nonlinear stiffness and damping characteristic model of twin-tube HAD is established.

2. Working principle of twin-tube HAD

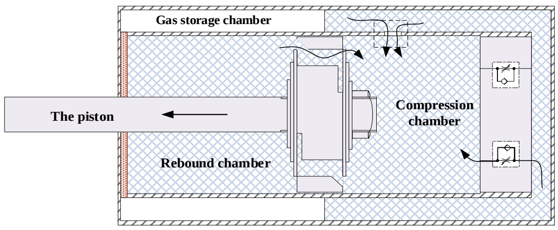
Twin-tube HAD has been widely applied in vehicle suspension system. The piston of the absorber moves up and down in the working cylinder with a high frequency when the relative displacement occur between the sprung mass and the unsprung mass. The motion of piston will cause the transfer of the hydraulic oil from the high pressure chamber to the low pressure chamber (ie. In the compression stroke, the piston assembly moves downward and the hydraulic oil in the lower chamber get through the piston assembly to the upper chamber). Meanwhile, the majority of damping force was generated because of the friction between oil molecules and the valve assembly. Thus, the structure of valve assembly is the key to generate damping force.

The working stroke of twin-tube HAD consists of compression stroke and rebound stroke. In the compression stroke, the damping force generated when the downward movement of the piston cause the hydraulic oil in the lower chamber getting through the compression valve to the upper chamber and reservoir chamber. In the rebound stroke, the damping force generated when the upward movement of the piston cause the hydraulic oil in the upper chamber and reservoir chamber getting through the rebound valve to the lower chamber. As shown in Fig. 1.

In the compression stroke, hydraulic oil via the lower chamber to the upper chamber. At the same time the spacer in the compression valve was deformed by the pressure which is generated by the hydraulic oil. (Fig. 1(a) shows the details of the flowing condition). In this moment, strong couple happened between spacer of compression valve and hydraulic oil when the oil get through the throttle. Meanwhile, with the deformation of the spacer, the throttle aperture appeared and caused a part of the hydraulic oil via the lower chamber to the upper chamber. On the other hand, the rest of fluid in the lower chamber get through the relief valve to the reservoir chamber. In this moment, strong couple happened between spacer of relief valve and hydraulic oil when the oil get through the throttle. Meanwhile, because of the deformation of the spacer, the throttle aperture appeared and caused the rest of fluid via the lower chamber to the reservoir chamber. In addition, the piston gap and the adjustable valve are also the way which lead the hydraulic oil to the upper chamber and reservoir chamber. Fig 1.(a) show the flow condition of the oil from the lower chamber to the reservoir chamber. As same flowing principle as the hydraulic oil in compression stroke, the flow condition of hydraulic oil in the rebound stroke are also exhibited in Fig. 1(b).



a. Compression stroke



b. Rebound stroke

Fig. 1 Compression stroke and rebound stroke of fluid flow

3. Hysteresis behavior for twin-tube HAD

3.1. Definition of hysteresis for twin-tube HAD

Hysteresis is a condition of system that not only dependent on current inputs but have different results depending on past inputs. A system operating through an input cannot return to its original state even if the same input value is changed back to its original state.

In term of damper, the phenomenon of hysteresis mainly shown as the lag of damping force. As shown in Fig. 2, the increasing and decreasing of damping force would follow the same routine if piston velocity change in a symmetric manner. However, the increasing and decreasing of damping force would not follow the same routine for realistic model. Hence, with the consideration of hysteresis, the output of damping force not only depend on the transient velocity of piston, but also was influenced by past strokes.

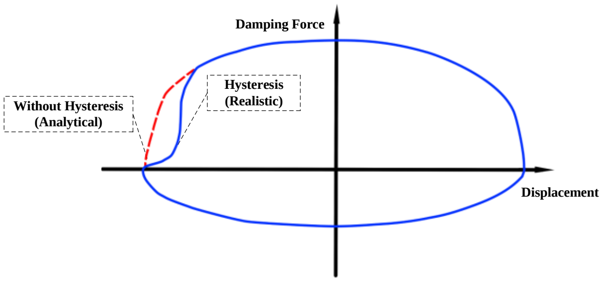


Fig. 2 Schematic diagram of hysteresis mechanism for twin-tube HAD

3.2. Dynamic characteristics of oil

According to the cavitation mechanism, cavitation bubbles are firstly produced in the low pressure chamber. The following will analyze the liquid flow state of the oil from the high pressure chamber to the low pressure chamber. The oil is divided into a number of oil micelles and each oil micelle is represented by a hexahedral unit. As shown in Fig. 3. From the perspective of oil micelle movement, the flow of oil from the high pressure chamber to the low pressure chamber is closely related to the force state of the oil micelle at the valve port. Cylindrical coordinate system(r φ z) is created. r, φ, z are radial direction, torsional direction, motion of direction of piston, respectively. Take oil micelle on the outer edge of the valve plate to be the research object, the fluid velocity and pressure can be expressed as:

$$\begin{aligned} \vec{v} &= (v_r, v_\theta, v_z) \\ P &= (p_r, p_\theta, p_z) \end{aligned} \tag{1}$$

Where v is velocity vector of fluid. According to the Navier-Stokes equations:

$$\rho \frac{D\vec{v}}{Dt} = -\nabla P + \mu \Delta \vec{v} \tag{2}$$

The component form is:

$$\begin{cases} \rho \dfrac{Dv_r}{Dt} = -(\dfrac{\partial p_{rr}}{\partial r} e_r + \dfrac{1}{r}\dfrac{\partial p_{\varphi r}}{\partial \varphi} e_\varphi + \dfrac{\partial p_{zr}}{\partial z} e_z) \\ +\mu(\nabla^2 v_r - \dfrac{v_r}{r^2} - \dfrac{2}{r^2}\dfrac{\partial v_\varphi}{\partial \varphi}) e_r \\ \rho \dfrac{Dv_\varphi}{Dt} = -(\dfrac{\partial p_{r\varphi}}{\partial r} e_r + \dfrac{1}{r}\dfrac{\partial p_{\varphi\varphi}}{\partial \varphi} e_\varphi + \dfrac{\partial p_{z\varphi}}{\partial z} e_z) \\ +\mu(\nabla^2 v_\varphi - \dfrac{v_\varphi}{r^2} + \dfrac{2}{r^2}\dfrac{\partial v_r}{\partial \varphi}) e_\varphi \\ \rho \dfrac{Dv_z}{Dt} = -(\dfrac{\partial p_{rz}}{\partial r} e_r + \dfrac{1}{r}\dfrac{\partial p_{\varphi z}}{\partial \varphi} e_\varphi + \dfrac{\partial p_{zz}}{\partial z} e_z) \\ +\mu \nabla^2 v_z e_z \end{cases} \tag{3}$$

Where ρ is density of fluid. e_i is error modification coefficient.

The annular exit of the outer edge for the valve is axisymmetric structure. The pressure at the equal radius is consistent and the oil flows in the radial direction, the following boundary conditions are:

$$\begin{cases} \vec{v} = (v_r, 0, 0) \\ \nabla v_r = e_r \dfrac{\partial v_{rr}}{\partial r} + e_\varphi \dfrac{1}{r}\dfrac{\partial v_{\varphi r}}{\partial \varphi} + e_z \dfrac{\partial v_{zr}}{\partial z} = e_r \dfrac{\partial v_{rr}}{\partial r} + e_z \dfrac{\partial v_{zr}}{\partial z} \\ \nabla p_r = e_r \dfrac{\partial p_{rr}}{\partial r} + e_\varphi \dfrac{1}{r}\dfrac{\partial p_{\varphi r}}{\partial \varphi} + e_z \dfrac{\partial p_{zr}}{\partial z} = e_r \dfrac{\partial p_{rr}}{\partial r} \end{cases} \tag{4}$$

For the annular slit formed by the deformation of the piston valve, the opening degree gradually increases in the radial direction.

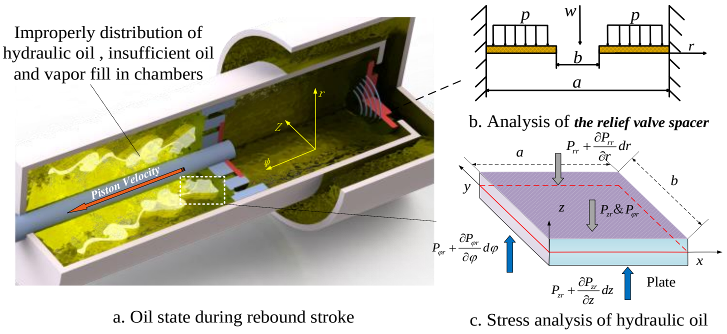


Fig. 3 Schematic diagram of hysteresis mechanism for twin-tube HAD

However, the deformation of the valve in the z direction is not more than 0.1 mm due to the existence of the stopper. Thus, the flow of the annular slit can be approximated as parallel plane flow. According to the principle of fluid continuity:

$$\begin{cases} \nabla^2 v_r = \dfrac{\partial^2 v_r}{\partial z^2} \\ \rho \dfrac{Dv_r}{Dt} = -\dfrac{\partial p_{rr}}{\partial r} e_r + \mu\left(\dfrac{\partial^2 v_r}{\partial z^2} - \dfrac{v_r}{r^2}\right) e_r \end{cases} \tag{5}$$

The valve opening of the piston valve is not more than 0.45 mm, the high-viscosity oil passes through the gap of the valve in a high-speed jet state. The shear force is mush larger than the inertial force, so the inertial force can be ignored and the equation is simplified:

$$\frac{\partial p_{rr}}{\partial r} = \mu\left(\frac{\partial^2 v_r}{\partial z^2} - \frac{v_r}{r^2}\right) \tag{6}$$

The flow rate through the piston valve is correlated with $\partial P_{rr}/\partial r$, $\partial P_{rr}/\partial r$ is the difference between the oil pressure passing through the valve plate and the pressure at the outer edge of the valve plate. According to the theoretical analysis of the literature [7], the pressure of the upper chamber oil on the outer edge of the valve plate should be higher than the upper chamber pressure and less than the oil pressure passed through the valve plate. Therefore, the relationship of the pressures and the flow can be described as:

$$\begin{cases} P_{up} \le P_{up\_local} \le P_{low} - P_{comv} \\ \dfrac{\partial P_{rr}}{\partial r} = (P_{low} - P_{comv}) - P_{up\_local} \\ Q_{comv} \propto -P_{up} \end{cases} \tag{7}$$

Therefore, it is necessary to analyze the pressure change of the chambers to obtain accurate flow rate for the chambers. The upper chamber belongs to the low pressure chamber under the compression stroke. When $\dot{V_{up}} \ge Q_{comv}$, the pressure of the upper chamber can be expressed as:

$$P_{up} = P_0 - \frac{\beta_E \Delta V}{V} (P_V \le P_{up} \le P_0) \tag{8}$$

Where P_0 is the initial pressure of the upper chamber, P_V is the saturated vapor pressure of the oil, β_E is the effective elastic modulus of the oil, and ΔV and V are the change of chamber volume and the volume of chamber, respectively.

For the storage chamber, the flow rate of the storage chamber is restricted by the pressure of the storage chamber during the compression stroke. The storage chamber is composed of two components for oil and nitrogen. The nitrogen in the liquid storage chamber is regarded as an ideal gas. Under the compression stroke, the oil enters the storage chamber while nitrogen is compressed. The pressure of the storage chamber is derived from the initial state of the nitrogen.

4. Results and discussions

The essential requirement for performing the simulation in computational fluid dynamics (CFD) programming displayed in this section. The CFD codes are compiled around the statistical algorithms that can handle cavity generation issues. The correctness of the derivation of cavitation in the above theoretical model is verified. So as to simplify the calculation process and improve the computing power of the computer, the structure of twin-tube HAD be simplified. The current section represents the regulated system to attain the issue result by CFD strategy.

4.1. Mesh generation and mesh quality

It is necessary to model the problem in proe 3D before simulation of the twin-tube HAD. The process of simulation has been done with the help of ANSYS WORKBENCH software. Mesh generation is performed by ICEM-CFD software. For ICEM-CFD software, tri, quad in 2D and tetra, prism, hex in 3D can be given by different grid generation techniques. In the current study, blocking technology was used to create the tetra element in the computational domain. The tetra element domain achieves the best quality calculations with a large reduction in the number of elements. The computation domain is allocated as one block. Subsequently, the allocated blocks are spited, and its shape is similar to the computational domain.

After blocking, the outer edge of the block is associated with the geometric curve, and the vertex of the block is associated with the geometric point to divide them into smaller elements. Then with the using of the blocking tools, the mesh generation is done, as shown in Fig. 4. After obtaining better quality hexahedral mesh, the domain proceeds to furnish the boundary conditions in CFD software. The common solver based on WBPJ design is only suitable for unstructured organization work. In order to obtain this arrangement, it is very important to select FLUENT solver from different solvers in ICEM-CFD programming database.

Fig. 4 Meshing of model

4.2. Rebound stroke

CFD Results for Rebound stroke: Segment left piston is rebound piston side. While rebound stroke in operation of hydraulic powered damper, the fluid passes through the small valve port, and the gas core in the oil gradually grows into bubbles. as shown in Fig. 5. As the pressure in the left chamber increases, the number of bubbles that appear at the valve port increases. CFD results show that the location of bubbles is consistent with the theoretical analysis and the volume of cavitation bubbles increases over time in the simplified twin-tube HAD.

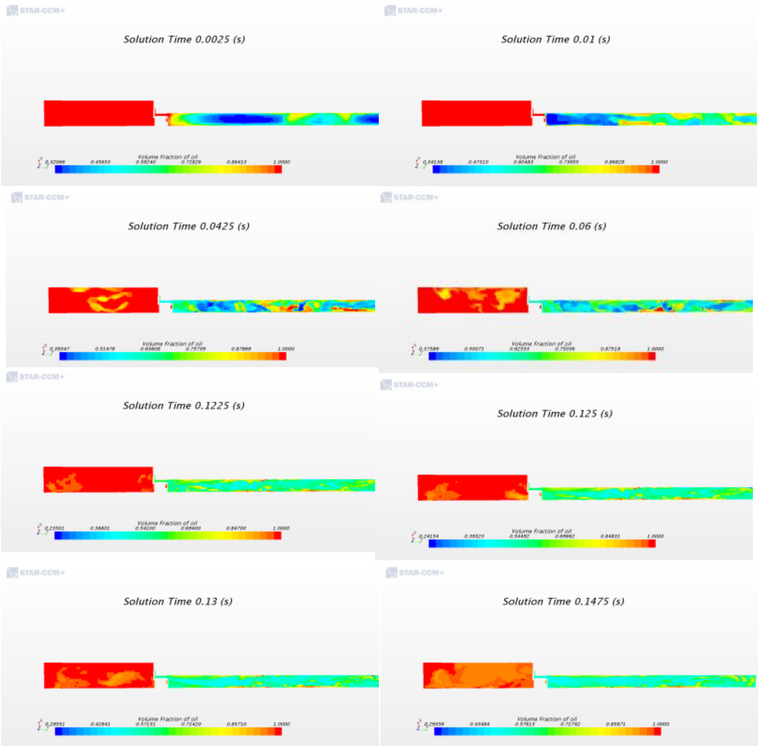


Fig. 5 Volume fraction of bubble in rebound stroke

4.3. Compression stroke

CFD Results for Compression stroke: Partition left piston is compression piston side. While compression stroke in operation of twin-tube damper, the fluid flows from the high-pressure compression chamber to the low pressure rebound chamber. The fluid passes through the small valve port, and the gas core in the oil gradually grows into bubbles. The CFD results show that the content of bubbles in the compression stroke in the sealed container is significantly smaller than that in the rebound process. The content of bubbles in the compression process increases first and then decreases during one cycle as shown in Fig. 6. Comparing the analysis of Fig. 5 and Fig. 6, it is found that the increasing trend of the total amount of cavitation bubbles is consistent with the theoretical analysis when the increase of the working time.

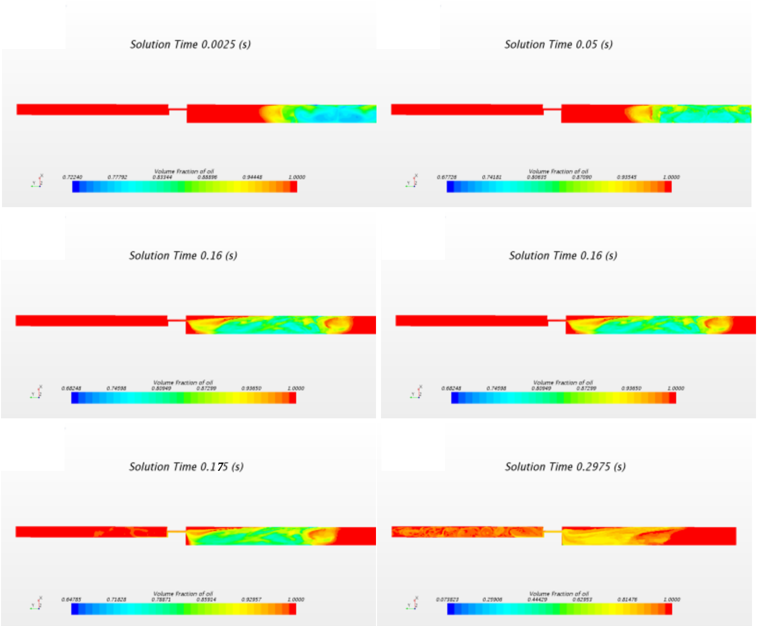


Fig. 6 Volume fraction of bubble in compression stroke

5. Summary and Conclusions

The focus of this study is on the modeling of the fluid cavitation mechanism and its effect on the damping output characteristics of the damper. The process of cavitation in the valve structure in twin-tube HAD is studied by theoretical analysis and CFD experiment.The FLUENT solver is used to encode and verify the correctness of the theory. The above research results show that:

(1) The generation of cavitation bubbles is main reason for the damping output hysteresis in twin-tube HAD.

(2) The location of bubbles is consistent with the theoretical analysis and the volume of cavitation bubbles increases over time in the simplified twin-tube HAD.

(3) The increasing trend of the total amount of cavitation bubbles is consistent with the theoretical analysis when the increase of the working time.

Acknowledgments

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