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Abstract

With the rapid development of the automotive industry, improving the performance and safety of braking systems has increasingly become a focus of scientific research. The anti-lock braking system (ABS), as a crucial safety regulation mechanism for preventing tire lock-up during emergency braking, relies directly on the operating performance of its core component—the ball valve—which determines the working efficiency and reliability of ABS. At present, no reliable numerical model has been established for the service process of the ball valve to analyze its service performance, and experimental research conducted without model guidance is relatively inefficient. These factors will greatly affect the development of high-quality ABS anti-lock braking systems. In view of this, this study adopts fluid-structure interaction technology to conduct an in-depth and comprehensive comparative analysis of the stress distribution, deformation characteristics, and velocity response of ball valves under various operating conditions. The results show that during the braking process of an automotive anti-lock braking system, the deformation, velocity response, and stress borne by the ball valve all exhibit sinusoidal variation patterns. The ball valve made of structural steel has the smallest deformation amplitude, the cast iron ball valve exhibits a rapid velocity response, and the pure copper ball valve bears relatively low stress, indicating that material properties significantly affect ball valve performance. The results provide a key theoretical basis and data support for the optimal design of multi-material valve cores for ball valves in automotive ABS systems.

Full Text

Modeling and Simulation of Fluid-Structure Interaction Dynamics in Ball Valves for Automotive Anti-Lock Braking Systems

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Abstract: With the rapid development of the automobile industry, the improvement of braking-system performance and safety has increasingly become a focus in scientific research. As a crucial safety regulation mechanism for preventing tire lock during emergency braking in the course of vehicle driving, the anti-lock braking system (ABS) is of vital importance. The operating performance of its core component—the ball valve—is directly related to the working efficiency and reliability of the ABS. At present, no reliable numerical model has yet been established for the service process of the ball valve to analyze its service performance, and experimental studies carried out without model guidance are relatively inefficient. The above factors will greatly affect the development of high-quality ABS anti-lock braking systems. In view of this, this study adopts fluid–structure interaction technology to conduct an in-depth and comprehensive comparative analysis of the stress distribution, deformation characteristics, and velocity response of ball valves under multiple operating conditions. The research results show that, during the braking process of an automotive anti-lock braking system, the deformation, velocity response, and stress borne by the ball valve all exhibit sinusoidal variation. Ball valves made of structural steel have the smallest deformation amplitude; cast-iron ball valves have sensitive velocity responses; and ball valves made of pure steel bear relatively small stress, indicating that material properties significantly affect ball-valve performance. The research results provide key theoretical basis and data support for the optimized design of multi-material valve cores in ball valves for automotive ABS systems.

Keywords: anti-lock braking system; ball valve; fluid–structure interaction simulation; multi-material valve core

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Modeling and simulation of fluid-structure interaction dynamics in ball valves for automotive anti-lock braking systems

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Abstract: With the rapid development of the automobile industry, the improvement of the braking system performance and safety has increasingly become the focus of the scientific research field. The anti-lock braking system (ABS) is a crucial safety adjustment mechanism to prevent tire lock during emergency braking process of automobile driving. The operating performance of its core component—the ball valve is

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directly related to the working efficiency and reliability of ABS. At present, no reliable numerical model has been formed for the service process of the ball valve to analyze the service performance of the ball valve, and experimental research without model guidance is inefficient. The above factors will greatly affect the research and development of high-quality ABS anti-lock systems. In view of this, the stress distribution, deformation characteristics, and velocity response of the ball valve were investigated. The results show the deformation of the ball valve, the velocity response, and the stress of the vehicle. In this case, the ball valve made of structural steel exhibits the lowest deformation amplitude, the cast-iron ball valve shows excellent agility in velocity response, and the pure-copper ball valve bears relatively small stress, which clearly reveals the significant influence of material characteristics on stress distribution. The results will provide a key theoretical basis and data support for the optimal design of multi-material spools for automotive ABS systems.

Key words: anti-lock braking system; ball valve; fluid-structure interaction simulation; multi-material spool

The automotive anti-lock braking system (anti-lock braking system, ABS) [1] plays a crucial role in the field of modern automotive safety. ABS has the characteristics of a small flow-resistance coefficient, good sealing performance, convenient operation, and light weight. It can effectively prevent the wheels from locking during braking, thereby ensuring that the vehicle still has good controllability and stability when braking, and reducing the probability of traffic accidents [2-3]. In an ABS system, the ball valve is one of the core control components, and the selection of its spool material may cause compatibility problems under different working environments. If the material is not selected properly, the ball valve may deform and wear more severely, thereby affecting its performance and service life [4]. Therefore, it is particularly important to conduct in-depth study of the flow-field characteristics inside the ball valve and the mechanical response mechanism of the spool under fluid action.

Relevant scholars have already carried out certain research on the performance of ball valves. Jia Wanli et al. [5] conducted an in-depth investigation of the effect of ball-valve opening and inlet velocity in a solid-liquid two-phase flow field. The results showed that, as the valve opening increased, the streamlines on the axial section tended to become straight, and the pressure gradient, velocity gradient, and flow-resistance coefficient decreased accordingly. Zu Jie [6] carried out a detailed fluid-structure coupling simulation of ball valves under different inlet-pressure conditions. The results revealed that, as inlet pressure increased, the internal flow velocity of the ball valve increased accordingly; in the region of the valve body near the wall, the flow velocity showed a slight decreasing trend compared with other regions. Lei Yongqiang [7] conducted an in-depth study on the influence of different spool openings of a ball valve on the medium flow velocity. The results showed that, as spool opening gradually increased, both the wear rate on the ball-valve wall and the flow velocity of the internal medium exhibited a slowing trend. Ma Guangfei et al. [8] started from whether or not a ball-valve gap exists, performed simulation calculations, and found that the fluid-flow condition of the model with a gap was more complex. In addition, Ma Bianji et al. [9] analyzed in depth the relationship between pressure-load variation and performance in ball valves, and proposed corresponding measures to extend the service life of ball valves.

Existing studies have already explored ball valves in considerable depth from multiple dimensions, but comparative research on spools made of different materials for anti-lock braking systems under multiple operating conditions remains relatively scarce. Research on multi-material spools will provide a new path for optimizing ball-valve performance. Different materials have different mechanical properties, densities, thermal-expansion coefficients, and other characteristics, and these characteristics have a significant influence on the deformation, stress distribution, and interaction with the fluid of the ball valve.

In view of the above considerations, this study uses an advanced numerical simulation method [10-11], constructs a fluid-solid coupling model [12], and conducts an in-depth investigation and analysis of the performance of the ball valve in an automotive anti-lock braking system under different conditions [13]. It also carefully examines the deformation, stress distribution, and velocity response of the spool under multiple material configurations, aiming to provide a rigorous scientific basis for material selection and structural optimization of the ball-valve spool in automotive anti-lock braking systems, so as to further promote the improvement of automotive braking-system performance and provide theoretical support for the further development of automotive safety technology.

1 Ball-Valve Modeling and Mesh Generation

1.1 Geometric Modeling

Existing studies that use two-dimensional models can describe only the situation within a plane. This study adopts the three-dimensional model shown in Fig. 1. This model can comprehensively present the flow behavior of the fluid in the ball-valve space. The fluid passages inside the ball valve are mostly intricate three-dimensional structures, and a three-dimensional model can accurately capture subtle changes in velocity, pressure, and other physical parameters of the fluid in multiple directions. Therefore, this study does not use a conventional two-dimensional cross-sectional model of a ball valve, but instead applies more advanced three-dimensional simulation technology.

Fig. 1 Ball valve model

Figure 1: Fig. 1 Ball valve model

(a) Ball-valve structural model

(b) Ball-valve simulation model

Fig. 1 Ball valve model

The ball valve is mainly composed of core components such as the valve body, valve seat, ball, and spring. Among them, the valve body is the outer shell of the ball valve and provides a flow passage for the medium; the valve-core ball undertakes the core function of controlling medium flow in the entire valve system, and the design of its internal passage enables the movement of the ball to accurately realize the opening and closing of the valve; the spring provides an appropriate preload for the ball in the ball valve, thereby ensuring that the ball and the valve seat always remain in close contact.

During the opening stage, when the pressure of the hydraulic oil gradually rises to the preset peak value, the oil pressure applies a positive acting force to the ball. This acting force causes the spring to undergo compressive deformation and at the same time drives the ball to produce a corresponding displacement, thereby realizing the opening action of the ball valve and allowing the hydraulic oil to flow smoothly into the valve chamber.

During the closing process, as the hydraulic-oil pressure gradually decreases, the restoring force of the spring gradually exceeds the force generated by the oil pressure. Driven by this dynamic change in force, the spring produces a reverse displacement, which in turn drives the ball to move synchronously, causing the ball and the valve seat to come into tight contact again and bringing the valve into the closed state.

1.2 Mesh Division

As a core preprocessing step in numerical simulation, mesh division directly affects the accuracy, convergence performance, and computational-resource requirements of subsequent fluid-solid coupling simulation calculations. Appropriate mesh division can accurately discretize the geometric model of the ball valve and lay a solid foundation for precise simulation of the interaction between fluid flow and the solid structure.

Fig. 2(a) presents the meshing effect of the fluid part. The meshed region mainly involves the fluid medium and the fluid-solid coupling region, especially the narrow gap between the ball-coupling part and the valve seat.

Fig. 2(b) presents the meshing result of the structural part. The ball valve is mainly composed of components such as the valve seat, valve-core spring, and valve-core ball. In view of the relatively small influence of the valve seat on

Fig. 2 Meshing results

Figure 2: Fig. 2 Meshing results

the performance of the ball valve, it is regarded as a rigid body in this study and is not included in the computational domain. For the complex geometric structure of the ball valve, this study adopts a hybrid meshing strategy to improve computational accuracy. For the regular ball-body part, a hexahedral structured mesh is used, effectively reducing numerical discretization error and improving computational efficiency; for irregularly shaped parts such as the valve-core spring, a tetrahedral unstructured mesh is used, which better fits the geometric boundaries and ensures both mesh quality and computational accuracy.

(a) Fluid structural mesh

(b) Structural mesh

Fig. 2 Meshing results

Fig. 3 is a schematic diagram of the structural principle of the ABS actuator system

. One-way ball valve 1: this component is responsible for ensuring the one-way transmission of brake fluid in the braking system from the brake master cylinder to the brake wheel cylinder. During conventional braking, when the brake master cylinder generates pressure and pushes the brake fluid to flow, one-way ball valve 1 ensures that the fluid flows smoothly to the brake wheel cylinder to complete the braking operation. When the wheel is about to lock and the system performs pressure regulation, one-way ball valve 1 effectively prevents the brake fluid from flowing backward to the brake master cylinder, thereby maintaining the stability of brake pressure and ensuring the reliability of braking performance. One-way ball valve 2: this valve mainly plays a role when the ABS system performs pressure-reduction operation. When the system detects the need to reduce the pressure of the brake wheel cylinder—for example, when the wheel shows a tendency to lock—the brake fluid flows through one-way ball valve 2 to the reservoir. In this process, one-way ball valve 2 plays a key role in preventing the brake fluid in the reservoir from flowing back to the brake wheel cylinder, ensuring that the brake pressure can be effectively regulated and preventing the wheel from locking due to excessive braking. One-way ball valve 3: under specific operating conditions, such as when the system performs pressure regulation, this valve works in coordination with other components to accurately control the flow direction of the brake fluid. The ball valve ensures that the brake fluid flows among different components according to system commands, thereby assisting the ABS system in achieving precise regulation of brake pressure and further improving the safety and stability of the vehicle during braking.

Fig. 3 A schematic diagram of the ABS structure

Figure 3: Fig. 3 A schematic diagram of the ABS structure

Through continuous cyclic pressure-regulation processes, the ABS system

$$15-16$$

can keep the wheel in a rolling state during braking and avoid wheel lock-up, thereby improving the vehicle’ s controllability and stability during braking

$$17-19$$

.

Fig. 3 A schematic diagram of the ABS structure

2 Establishment of the Numerical Model

2.1 Governing Equations

Based on the fundamental theories of fluid mechanics and solid mechanics, in an automotive ABS ball-valve system, the flow of brake fluid exerts fluid forces on the valve core, causing deformation of the valve core; in turn, the deformation of the valve core changes the flow-field distribution of the brake fluid. This interaction persists cyclically and mutually affects the braking process[^20]. Its mathematical model involves the Navier–Stokes equations for the fluid and the mechanical equilibrium equations for the solid, etc.; through a specific coupling algorithm, data exchange and iterative solution between the fluid domain and the solid domain are realized. The Navier–Stokes equation describes the conservation of momentum of the fluid[^21-22]. For an incompressible Newtonian fluid, its vector form is

$$\rho \frac{\mathrm{D}v}{\mathrm{D}t} = -\nabla p + \mu \nabla^2 v + f \qquad (1)$$

where: ρ is the fluid density; $\frac{\mathrm{D}}{\mathrm{D}t}$ is the material derivative, expressed as $\frac{\mathrm{D}}{\mathrm{D}t} = \frac{\partial}{\partial t} + (v \cdot \nabla)$; p is the fluid pressure; μ is the dynamic viscosity; ∇^2 is the Laplace operator; and f is the body force per unit volume acting on the fluid, such as gravity.

According to the mathematical equation of continuity[^23], the mass of the fluid entering and leaving the ball valve must be equal, ensuring conservation of fluid mass. Its mathematical expression is

$$\nabla \cdot v = 0 \qquad (2)$$

where v is the fluid velocity vector. In the Cartesian coordinate system[^24], it can be expanded as $v = (u, v, w)$, and thus the component form of the continuity equation is

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0.$$

In the fluid domain of the automotive ABS ball valve, regardless of how the brake fluid flows, its mass is neither created from nor disappears into the void. This is the basic premise for subsequent flow-field analysis.

At the fluid–solid coupling interface, the displacements of the fluid and the solid are continuous. In the ball valve, this means that at the location where the ball-core surface contacts the fluid, the displacement of the fluid is the same as the displacement of the ball-core surface, satisfying the displacement continuity equation, namely

$$u_\mathrm{f} = u_\mathrm{s} \qquad (3)$$

where u_f denotes the displacement of the fluid, and u_s denotes the displacement of the ball-valve surface. The stresses of the solid and the fluid at the interface are also in equilibrium, satisfying the stress equilibrium equation, namely

$$\sigma_\mathrm{s} \cdot n = \sigma_\mathrm{f} \cdot n \qquad (4)$$

where n is the normal vector of the interface; σ_s and σ_f are, respectively, the fluid stress and the stress on the contact surface between the valve core and the fluid. For the ball valve, at the surface where the ball core contacts the fluid, the force exerted by the fluid on the ball core and the stress inside the ball core are balanced in the normal direction of the interface. This ensures that the transmission of force at the interface is reasonable and can accurately describe the interaction between the fluid and the solid.

The above numerical model describes the dynamic equilibrium of the solid under external forces, including fluid forces, and is the basis for studying deformation and stress during the fluid–solid coupling process. In the automotive ABS ball valve, the valve core acts as a solid component; when subjected to the pressure and viscous forces of the brake fluid, the distribution of its internal stress and the change in displacement will be described by these numerical models.

2.2 Theoretical Equations of the Flow Field

Because the fluid is turbulent, the k-epsilon (k-ε) turbulence model must be used[^25]. In fluid mechanics, the (k-) model is a commonly used turbulence model. Based on the Boussinesq assumption, turbulent flow is described by solving the transport equations for the turbulent kinetic energy k and the turbulent kinetic energy dissipation rate ε.

The turbulent kinetic energy equation[^26] is

$$\frac{\partial(\rho k)}{\partial t} + \nabla \cdot (\rho v k) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + G_k - \rho\varepsilon \qquad (5)$$

where: t is time; σ_k is the Prandtl number for turbulent kinetic energy k; G_k is the production term of turbulent kinetic energy due to the mean velocity gradient; and ε is the turbulent kinetic energy dissipation rate. The equation for the turbulent kinetic energy dissipation rate[^27] is translated as follows:

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \nabla \cdot (\rho v \varepsilon) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + C_{1\varepsilon} \frac{\varepsilon}{k} G_k - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \qquad (6)$$

where: σ_ε is the Prandtl number for the turbulent kinetic energy dissipation rate, usually taken as 1.3; $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are empirical constants, usually taken as $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$.

2.3 Theoretical Equation for Ball-Valve Deformation

Under the assumptions of small deformation and linear elasticity, the deformation of the valve core can be described by the basic equations of elasticity [28]. The basic equations of three-dimensional elasticity include the equilibrium equation, geometric equation, and physical equation. The equilibrium equation [29] is

$$\sigma_{ij,j} + f_i = 0 \qquad (7)$$

where: σ_{ij} is the stress tensor; f_i is the body-force vector; the subscript after the comma denotes differentiation with respect to the coordinate. This equilibrium equation represents the balance relationship between the stress components and body forces at any point inside the ball valve [30]. The geometric equation is

$$\varepsilon_{ij} = \frac{1}{2}(s_{i,j} + s_{j,i}) \qquad (8)$$

where: ε_{ij} is the strain tensor; s_i is the displacement vector. This equation describes the geometric relationship between displacement deformation and strain in the ball valve, namely that strain is a linear combination of the first derivatives of displacement [31]. The physical equation is

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl} \qquad (9)$$

where C_{ijkl} is the elastic-constant tensor. This physical equation establishes the constitutive relationship between stress and strain. For isotropic materials, the elastic-constant tensor can be simplified into two independent elastic constants, namely the Lamé constants λ and β. At this time the physical equation [32] is

$$\sigma_{ij} = \lambda \varepsilon_{kk} \delta_{ij} + 2\beta \varepsilon_{ij} \qquad (10)$$

where δ_{ij} is the Kronecker symbol.

The deformation of the spring satisfies Hooke' s law [33], namely

$$F = kx \qquad (11)$$

where: F is the external force applied to the spring; k is the stiffness coefficient of the spring; x is the deformation of the spring, that is, the length by which the spring is stretched or compressed.

2.4 Theoretical Equation for Ball-Valve Velocity

Based on Newton' s second law [34],

$$m \frac{\mathrm{d}v_f}{\mathrm{d}t} = F_{\text{fluid}} + F_{\text{spring}} + F_{\text{other}} \qquad (12)$$

where: m is the mass of the valve core; v_f is the velocity of the valve core in the working direction; F_{fluid} is the force exerted by the fluid on the valve core; F_{spring} is the force exerted by the spring on the valve core; F_{other} represents other possible external forces acting on the valve core, such as friction and gravity. Solving this differential equation gives the time-varying relationship of the valve-core velocity.

2.5 Theoretical Equation for Ball-Valve Stress

Based on the stress formulas of elasticity [35], the stresses borne by the ball valve are mainly normal stress and shear stress. The principal stresses are

$$\begin{cases} \sigma_{xx} = \dfrac{E}{(1+a)(1-2a)} \left[(1-a) \dfrac{\partial u_x}{\partial x} + \mu \left(\dfrac{\partial v_x}{\partial y} + \dfrac{\partial w_z}{\partial z} \right) \right] \\ \sigma_{yy} = \dfrac{E}{(1+a)(1-2a)} \left[(1-a) \dfrac{\partial v_x}{\partial y} + \mu \left(\dfrac{\partial u_x}{\partial x} + \dfrac{\partial w_z}{\partial z} \right) \right] \\ \sigma_{zz} = \dfrac{E}{(1+a)(1-2a)} \left[(1-a) \dfrac{\partial w_x}{\partial z} + a \left(\dfrac{\partial u_x}{\partial x} + \dfrac{\partial v_y}{\partial y} \right) \right] \end{cases} \qquad (13)$$

where: E is the elastic modulus; a is Poisson' s ratio; u_x, v_y, and w_z are respectively the displacement components of the valve core in the x, y, and z directions. The shear stresses borne by the ball valve are

$$\begin{cases} \tau_{xy} = \dfrac{E}{2(1+a)}\left(\dfrac{\partial u_x}{\partial y} + \dfrac{\partial v_y}{\partial x}\right) \\ \tau_{yz} = \dfrac{E}{2(1+a)}\left(\dfrac{\partial v_x}{\partial z} + \dfrac{\partial w_z}{\partial y}\right) \\ \tau_{zx} = \dfrac{E}{2(1+a)}\left(\dfrac{\partial w_z}{\partial x} + \dfrac{\partial u_y}{\partial z}\right) \end{cases} \quad (14)$$

3 Operating-Condition Design

This study adopts a comparative-simulation experimental method to conduct a detailed and in-depth analysis of the fluid–solid coupling effect of the ball-valve core. To comprehensively reveal the characteristics and behavioral laws under different operating conditions, the three representative valve-core materials listed in Table 1 were selected, and analyses were carried out under three different liquid-pressure environments, establishing the nine research operating conditions shown in Table 2. The fluid type used was turbulent flow, with a turbulence intensity of 5%, a turbulent viscosity ratio of 10, a material density of 889 kg/m^3, and a viscosity of 1.06 $kg/(m \cdot s)$.

In the automotive anti-lock braking system, under normal braking, the inlet oil pressure of the hydraulic oil can reach $10 \sim 12$ MPa. Under extreme operating conditions such as specific emergency braking, the oil pressure is dynamically adjusted according to the system' s determination of the wheel lock-up state and its control strategy. In view of this, this study selected three different groups of inlet pressures as variables, with the aim of deeply exploring the performance differences of the ball-valve core under different material conditions when facing different inlet-pressure forced-braking conditions.

Table 1 Material parameters

Tab. 1 Material parameters

Material name	Material strength/MPa	Young' s modulus/MPa	Poisson' s ratio	Density/($kg \cdot mm^{-3}$)
Structural steel	625	2×10^5	0.300	7.85×10^{-6}
Pure copper	530	1.26×10^5	0.345	8.942×10^{-6}
Cast iron	480	89 440	0.260	6.999×10^{-6}

Table 2 Research conditions

Fig. 4 Flow field contour diagram

Figure 4: Fig. 4 Flow field contour diagram

Tab. 2 Research conditions

Condition	Valve-core material	Inlet oil pressure/MPa
1	Structural steel	5
2	Structural steel	10
3	Structural steel	15
4	Pure copper	5
5	Pure copper	10
6	Pure copper	15
7	Cast iron	5
8	Cast iron	10
9	Cast iron	15

4 Flow-field settings

Using simulation methods, the pressure distribution and velocity distribution of the flow field under three different inlet pressure conditions were investigated. The flow-field contour plots are shown in Fig. 4.

(a) Inlet pressure 5 MPa

(b) Inlet pressure 10 MPa

(c) Inlet pressure 15 MPa

Fig. 4 Flow field contour diagram

As can be seen from the corresponding contour analysis in Fig. 4, there is a significant positive correlation between the pressure and velocity in the flow field and the pressure intensity at the inlet. During the starting and braking stage of the ball valve, the fluid pressure and flow velocity at the inlet gradually increase; when the inlet pressure increases to a certain threshold, after the force acting on the ball valve due to pressure becomes greater than the preload of the spring, the spring begins to be compressed, thereby causing the valve core to open, and the fluid then flows into the interior of the ball valve and is transmitted toward the outlet end.

5 Analysis of simulation results

5.1 Simulation deformation results

The ball valve mainly achieves sealing through tight contact between the ball and the valve seat. When the ball or the valve seat deforms under load, gaps appear

Ball valve deformation cloud diagrams. Panels show deformation (mm) under inlet pressures of 5 MPa, 10 MPa, and 15 MPa for (a) structural steel, (b) pure copper, and (c) cast iron.

Figure 5: Ball valve deformation cloud diagrams. Panels show deformation (mm) under inlet pressures of 5 MPa, 10 MPa, and 15 MPa for (a) structural steel, (b) pure copper, and (c) cast iron.

on the sealing surfaces that were originally in close contact. The contact of the sealing surfaces after deformation is nonuniform, which leads to an increase in local stress during operation of the ball.

The deformation contour plots of the ball valve at $t = 0.2$ s, obtained through simulation analysis under different materials and operating conditions, are shown in Fig. 5. The observed results show that the maximum deformation of structural steel is 0.324 10 mm, the maximum deformation of pure copper is 0.736 33 mm, and the maximum deformation of cast iron is 0.305 13 mm. Further analysis of the deformation contour plots clearly shows that the deformation of the ball valve is mainly concentrated in the ball portion; therefore, as the key component bearing the oil pressure, the ball bears the main acting force. The spring portion of the ball valve and its contact area with the front end of the ball also have relatively large total deformation due to the influence of the force transmitted by the ball. As the spring is compressed, the opening of the ball valve gradually increases, and at this time the valve-core brake fluid begins to flow toward the outlet end.

A comparative analysis of the deformation curves of the ball valve shown in Fig. 6 indicates that, as the inlet oil pressure increases, the total deformation of the ball valve continuously rises. When the oil pressure rises to 15 MPa, the peak total deformations of the structural-steel, pure-copper, and cast-iron ball valves reach 0.50, 0.93, and 1.27 mm, respectively. During the working cycle of the three experimental materials, the total deformation exhibited by structural steel is the smallest, whereas the total deformation occurring in the cast-iron ball valve is relatively significant, with an amplitude approximately 2.4 times that of structural steel. Further analysis of the deformation curves shows that the total deformation of the ball valve follows an evident sinusoidal distribution pattern.

(a) Structural steel (b) Pure copper (c) Cast iron

Fig. 5 Ball valve deformation cloud diagram

(a) Inlet pressure 5 MPa (b) Inlet pressure 10 MPa (c) Inlet pressure 15 MPa

Fig. 6 Deformation curves of a ball valve

Deformation curves of a ball valve. Curves compare structural steel, pure copper, and cast iron under inlet pressures of 5 MPa, 10 MPa, and 15 MPa.

Figure 6: Deformation curves of a ball valve. Curves compare structural steel, pure copper, and cast iron under inlet pressures of 5 MPa, 10 MPa, and 15 MPa.

Fig. 7 Ball valve velocity curves

Figure 7: Fig. 7 Ball valve velocity curves

5.2 Velocity response simulation results

During emergency braking, the velocity response of the ball valve in the anti-lock braking system is particularly critical. If the response of the ball valve lags, then when the wheel is on the verge of locking, the brake-fluid pressure cannot be adjusted in time. In addition, the rapid response of the ball valve is also vitally important for ensuring vehicle stability during braking. Road conditions during driving are complex and variable; when sudden situations require emergency braking, a rapidly responding ball valve can ensure that the ABS system controls the braking pressure of each wheel promptly and accurately, thereby ensuring that the vehicle can, as expected by the driver, decelerate steadily along the intended trajectory.

According to the ball-valve velocity curves in Fig. 7, after the ball valve is subjected to the pressure transmitted to it by the valve core, it undergoes reciprocating motion; that is, the ball valve controls the operation of the anti-lock braking system through continuous opening and closing. Under different hydraulic pressures, the fastest responses of the structural-steel, pure-copper, and cast-iron ball valves are 225, 283, and 317 mm/s, respectively. The velocity response of the cast-iron valve core is superior to that of the other two materials, while the velocity response of structural steel is the poorest. Under the action of hydraulic pressure, the velocity response of the ball valve during braking also clearly follows a sinusoidal distribution.

(a) Inlet pressure 5 MPa (b) Inlet pressure 10 MPa (c) Inlet pressure 15 MPa

Figure 7 Ball valve velocity curves

Fig. 7 Ball valve velocity curves

5.3 Stress simulation results

Figures 8–9 show the stress distribution of the ball valve core at $t = 0.2$ s. The analysis results indicate that, under different materials and operating conditions, the maximum stress in the ball portion of the ball valve core is mainly concentrated at the upper and lower ends of the ball; at the same time, the stress distribution in the valve-core spring portion is relatively uniform.

Fig. 8 Stress cloud diagram of a ball valve

Figure 8: Fig. 8 Stress cloud diagram of a ball valve

Fig. 9 Ball valve spring stress cloud diagram

Figure 9: Fig. 9 Ball valve spring stress cloud diagram

(a) Structural steel (b) Pure copper (c) Cast iron

Figure 8 Stress cloud diagram of a ball valve

Fig. 8 Stress cloud diagram of a ball valve

According to the analysis of the ball-valve stress curves shown in Figure 10, it can be clearly observed that the stress borne by the ball valve is positively correlated with the oil pressure, and its distribution pattern follows a sinusoidal fluctuation law. Under different hydraulic pressure values, the maximum stresses of the structural-steel, pure-copper, and cast-iron ball valves are 419, 409, and 427 MPa, respectively. When the ball valve is subjected to a relatively large stress, it will first face severe deformation of the spring; if this deformation exceeds the elastic limit, it may lead to spring damage. At the same time, the ball will also be adversely affected. An excessively high stress level will cause deformation of the ball, thereby affecting the fit with the valve seat and weakening the sealing performance. Under high stress, the fatigue-damage process of the components of the ball valve will accelerate. Key components such as the valve body, ball, and spring are prone to fatigue cracks when repeatedly subjected to excessive stress. As the switching operation is repeated many times, these cracks will continue to propagate and ultimately trigger component failure. In comparison, the stress borne by the pure-copper ball valve is slightly smaller.

(a) Structural steel (b) Pure copper (c) Cast iron

Fig. 9 Ball valve spring stress cloud diagram

(a) Inlet pressure 5 MPa (b) Inlet pressure 10 MPa (c) Inlet pressure 10 MPa

Fig. 10 Ball valve stress curves

6 Conclusion

In this study, a detailed dynamics model was established, and a simulation experiment of fluid–solid coupling was carried out. Through in-depth analysis and comparison of various simulation data, the following conclusions were obtained.

Fig. 10 Ball valve stress curves

Figure 10: Fig. 10 Ball valve stress curves

1) For the ball valve in an automotive anti-lock braking system, its deformation, velocity response, and the stress it bears during the braking process all exhibit obvious sinusoidal-function characteristics.
2) The deformation of the ball valve is mainly concentrated in the valve-core sphere and at the connection between the spring and the sphere. Through comparative analysis of different experimental materials, it is found that the total deformation of the structural-steel ball valve is relatively the lowest, whereas the deformation of the cast-iron ball valve is relatively the most significant. Therefore, when selecting materials, deformation should be taken as an important basis, and structural steel should be given priority.
3) The spherical part of the ball-valve core compresses the spring under the action of hydraulic pressure, thereby producing deformation, and the opening and closing function is realized through the reciprocating motion of the spring. By comparing the simulation results, it can be seen that the cast-iron ball valve shows the most sensitive velocity response.
4) Regarding the stress distribution of the spherical part of the ball-valve core, under different materials and operating conditions, the maximum stress is mainly concentrated on the upper and lower sides of the sphere, followed by the stress at the inlet end and at the contact area with the spring; the stress distribution in the valve-core spring is relatively uniform. In the stress comparison under different operating conditions, the stress borne by the ball valve made of pure copper is smaller than that of the other two materials.

The above conclusions provide a strong theoretical basis for the optimization design of automotive anti-lock braking systems.

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