Structural parameter effect of a railway hydraulic damper on its dynamic damping characteristics

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Abstract. A parametric dynamic damping characteristics model, which includes the dynamic force equilibrium equation, the flow continuity equation, the flow losses model, the comprehensive stiffness model and the valve dynamics, is established and validated by experiments. Numerical simulation of structural parameter effect on dynamic damping characteristics of the hydraulic damper is performed. The analyses show that increase of inner tube height would cause drop of dynamic stiffness of the damper, however, increase of piston diameter would lead to obvious increase of dynamic stiffness and dynamic damping coefficient, therefore, the biggest piston diameter under constraint is usually used in engineering; in addition, fluid leakage would apparently decrease damping capability of the damper, increase of leakage coefficient would lead to significant drop of dynamic stiffness and dynamic damping coefficient, and also remarkable damping force lag. The obtained full parametric model and analysis result in this work would be instructive and meaningful in further railway vehicle dynamics research and design procedures.

1. Introduction
Hydraulic dampers [1-2] are widely used in modern railway vehicle systems to control running stability and ride comfort, at high operation speeds, the influence of damper parameters [3] on vehicle system dynamics would become significant and cannot be omitted.

In previous studies, Zhou et al [4] introduced the theoretical calculation approach on dynamic damping characteristics of railway hydraulic damper, Yuan et al [5] carried out research on dynamic damping characteristics of damper on high-speed train dynamics, but both of the research have used the macro level damper model introduced in the textbook [1] or the standard [2], which is more suitable for vehicle system dynamics simulation and does not contain concrete physical parameters of the damper, so it is not ideal in predicting the influence of damper parameters on vehicle system dynamics.

However, Mellado et al [6] and Alonso et al [7] have built simple parameter models in predicting the remarkable effects of damper parameter on dynamic damping characteristics of the damper and dynamic stability of the vehicle system, Huang et al [8] and Wang et al [9] have built complex parameter damper models in describing dynamic behaviour of damper and also damper performance on vehicle dynamics, but the parameters involved are limited and next step research works should be carried out.
In this study, mathematical modelling of the dynamic damping characteristics of a railway hydraulic damper is conducted, in modelling the full parameter damper model, the dynamic force equilibrium equation, the flow continuity equation, the flow losses model, the comprehensive stiffness model and the valve dynamics are all considered. Both numerical simulation and bench test of the damper are performed to validate the established full parametric model. Further parameter sensitivity analyses are also conducted to find the structural parameter effect on dynamic damping characteristics of the damper. Therefore, the obtained full parametric model and analysis result of the railway hydraulic damper would be instructive in further rail vehicle dynamics research and design procedures.

2. Modelling the dynamic damping characteristics

Figure 1 shows the Force-displacement diagram and Force equilibrium vector diagram of dynamic damping characteristics of a hydraulic damper under harmonic excitations, therefore, the dynamic stiffness and dynamic damping coefficient of the damper can be readily formulated by

\[ K_{dyn} = \frac{F_{\text{max}}}{A} \sqrt{1 + \tan^2 \phi} \tag{1} \]

and

\[ C_{dyn} = \frac{K_{dyn}}{2\pi f \tan \phi} \tag{2} \]

where \( F_{\text{max}} \) is the maximum damping force, \( A, f \) are respectively the amplitude and frequency of the excitation signal, \( \phi \) is the phase angle of the damping force.

For Equations (1) and (2) do not include concrete structural parameters, a full parametric damper model has to be built. In modelling the full parameter damper model [10] of a high-speed train hydraulic damper, the dynamic force equilibrium equation, the flow continuity equation, the flow losses model, the comprehensive stiffness model and the valve dynamics are all considered.

The total flow loss of the damper \( Q_1 \) can be expressed as

\[ Q_1 = k_1 (p - p_b) \tag{3} \]

where \( p, p_b \) are respectively the working pressure and back pressure of the damper, \( k_1 \) is the leakage coefficient and it can be formulated by

\[ k_1 = \frac{\pi}{6\mu} \left[ \frac{D\Delta_1^3}{2l_2} + \frac{d\Delta_2^3}{2l_1} + \frac{\Delta_3^3}{\ln\left(\frac{r_2}{r_1}\right)} \right] \tag{4} \]

for the extension stroke, and
for the compression stroke, where Δ₁, Δ₂ and Δ₃ are clearances of the piston, rod and inner tube, respectively, \( r₁, r₂ \) are respectively inner and outer radii of the inner tube, \( l₁, l₂ \) are respectively seal widths of the rod and piston, \( \mu \) is the dynamic viscosity of the oil.

In Equation (3), the back pressure \( p_b \) is given by

\[
p_b = \left[ \frac{0.9L}{0.9L - x₂} \right]^{1.4} p_{b₀}
\]

where \( L \) is the travel of the damper, \( x₂ \) is the actual displacement input of the damper, \( p_{b₀} \) is the back pressure when the damper piston is in the neutral position.

The complete valve system dynamics was modelled in detail by literature [10], however, dynamics of the check valve for the piston or foot valve, as shown in Figure 2, has to be described.

The dynamics equation of the check valve shim can be described by

\[
F_{i₃} - k_i x_i - m_i g = m_i \ddot{x}_i
\]

where \( F_{i₃} \) is the fluid pressure force acting on the shim, \( m_i \) and \( x_i \) are respectively mass and displacement of the shim, \( k_i \) is spring stiffness of the check valve.

The flow discharged from the check valve \( Q_i \) can be formulated by

\[
Q_i = 2\pi C_d h_i n_i d_i^2 \sqrt{\frac{2S_{i₂}}{\rho \left( \pi n_i^2d_i^4 + 64S_{i₂}h_i^2 \right)}} \Delta p_i
\]

where \( C_d \) is the discharge coefficient, \( h_i \) is the opening height of the shim, \( d_i \) and \( n_i \) are respectively diameter and number of the orifice in the piston or in the foot valve, \( \rho \) is the oil density, \( S_{i₂} \) is the area of the shim and \( \Delta p_i \) the pressure difference on both sides of the shim.

Finally, the dynamic force equilibrium equation, the flow continuity equation, the flow loss model, the complete valve system dynamic model, the comprehensive stiffness model and the check valve model are coupled to obtain a full parametric model. Numerical simulation on the dynamic damping characteristics is performed in MATALB environment by using the established full parametric model, bench test of the dynamic damping characteristics is also carried out by using a MTS test stand, therefore the established full parametric model of the hydraulic damper is validated [10], it is accurate and can be used in damper parameter sensitivity analysis.
3. Structural parameter effect analysis

3.1 Effect of pressure chamber parameter on dynamic damping characteristics

Numerical simulation of parameter effects on dynamic damping characteristics of the hydraulic damper is performed in MATLAB environment by using the validated model. Figure 3 demonstrates the effect of pressure chamber parameter on main indices of the dynamic damping characteristics.

![Figure 3](image)

Figure 3. Effect of pressure chamber parameter on main indices of dynamic damping characteristics of the damper: (a) Force-displacement characteristics of the damper when with different inner tube height, (b) Dynamic Stiffness vs. inner tube height, (c) Dynamic Stiffness vs. piston diameter and (d) Dynamic damping coefficient vs. piston diameter.

Table 1. The effect of piston diameter on main dynamic damping characteristics indices and its rate of change of the hydraulic damper.

| Damping Performance Indices | Excitation amplitude (mm) | 55 mm | 60 mm | The Rate of Change (%) |
|-----------------------------|---------------------------|-------|-------|------------------------|
| Dynamic Stiffness (kN/mm)   | 0.5                       | 46.31 | 52.76 | ↑13.9                  |
|                             | 1                         | 24.88 | 29.85 | ↑20.0                  |
| Dynamic Damping Coefficient (kNs/mm) | 0.5       | 1.11  | 1.19  | ↑7.2                   |
|                             | 1                         | 0.52  | 0.59  | ↑13.5                  |
Table 1 continues to prove that with the increase of piston diameter, almost all the main dynamic damping indices would increase, for instance, when with an excitation amplitude of 1 mm, and when piston diameter increases from 55 mm to 60 mm, the dynamic stiffness would have a remarkable increase of 20%, the dynamic damping coefficient would have an increase of 13.5%, and the phase angle would have an increase of 7.5%.

3.2 Effect of leakage coefficient on dynamic damping characteristics

Table 2. The effect of leakage coefficient on main dynamic damping characteristics indices and its rate of change of the hydraulic damper.

| Damping Performance Indices | Excitation amplitude (mm) | 1e-5 | 2e-5 | The Rate of Change (%) |
|-----------------------------|---------------------------|------|------|------------------------|
| **Dynamic Stiffness (kN/mm)** | 0.5 | 57.89 | 44.62 | ↓22.9 |

Figure 4. (a) Force-displacement characteristics of the damper when with different leakage coefficient, (b) Dynamic Stiffness vs. leakage coefficient, (c) Dynamic damping coefficient vs. leakage coefficient and (d) Phase angle vs. leakage coefficient.

Figure 4(a) similarly shows that change of leakage coefficient would also cause apparent change of Force-displacement characteristics, Figure 4(b), (c) and (d) combine to illustrate that with the increase of leakage coefficient, the dynamic stiffness and dynamic damping coefficient would drop significantly, and the phase angle would increase significantly. Therefore, it implies that fluid leakage would apparently decrease damping capability of the damper.
Table 2 continues to prove that dynamic damping characteristics indices are sensitive to fluid leakage. Increase of leakage coefficient would lead to significant drop of damping capability. For instance, when with an excitation amplitude of 1 mm, and when leakage coefficient increases from $1e^{-5}$ to $2e^{-5}$, the dynamic stiffness would have a remarkable drop of 35.5%, the dynamic damping coefficient would have a decrease of 37.8%, and the phase angle would have an increase (which means more damping force lag) of 34%.

4. Conclusions

(1) A parametric dynamic damping characteristics model, which includes the dynamic force equilibrium equation, the flow continuity equation, the flow losses model, the comprehensive stiffness model and the valve dynamics, is established and validated by experiments. Numerical simulation of structural parameter effect on dynamic damping characteristics of the hydraulic damper is performed.

(2) Increase of inner tube height would cause drop of dynamic stiffness of the damper, however, increase of piston diameter would lead to obvious increase of dynamic stiffness and dynamic damping coefficient, the dynamic stiffness would have a significant increase of 20% when the piston diameter increases from 55 mm to 60 mm.

(3) Fluid leakage would apparently decrease damping capability of the damper, increase of leakage coefficient would lead to significant drop of dynamic stiffness and dynamic damping coefficient, and also remarkable damping force lag. The dynamic stiffness would have a remarkable drop of 35.5% if the leakage coefficient increases from $1e^{-5}$ to $2e^{-5}$.

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