Mechanical Systems and Signal Processing 62-63 (2015) 517–533

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

In-service parametric modelling a rail vehicle's axle-box hydraulic damper for high-speed transit problems

W.L. Wang [a,b,c,*], D.S. Yu [a], Z. Zhou [a]

[a] College of Mechanical and Vehicle Engineering, Hunan University, Changsha 410082, Hunan Province, PR China
[b] The State Key Laboratory of Fluid Power Transmission and Control, Zhejiang University, Hangzhou 310027, Zhejiang Province, PR China
[c] Institute of Railway Research, School of Computing and Engineering, University of Huddersfield, Queensgate, Huddersfield HD1 3DH, UK

ARTICLE INFO

Article history:
Received 23 February 2014
Received in revised form
5 March 2015
Accepted 13 March 2015
Available online 2 April 2015

Keywords:
In-service parametric modelling
Axle-box hydraulic damper
Damping characteristics
Relief-valve system
Parameter effect
High-speed rail vehicle

ABSTRACT

Due to the high-speed operation of modern rail vehicles and severe in-service environment of their hydraulic dampers, it has become important to establish more practical and accurate damper models and apply those models in high-speed transit problem studies. An improved full parametric model with actual in-service parameters, such as variable viscous damping, comprehensive stiffness and small mounting clearance was established for a rail vehicle's axle-box hydraulic damper. A subtle variable oil property model was built and coupled to the modelling process, which included modelling of the dynamic flow losses and the relief-valve system dynamics. The experiments validated the accuracy and robustness of the established full in-service parametric model and simulation which captured the damping characteristics over an extremely wide range of excitation speeds. Further simulations were performed using the model to uncover the effects of key in-service parameter variations on the nominal damping characteristics of the damper. The obtained in-service parametric model coupled all of the main factors that had significant impacts on the damping characteristics, so that the model could be useful in more extensive parameter effects analysis, optimal specification and product design optimisation of hydraulic dampers for track-friendliness, ride comfort and other high-speed transit problems.

1. Introduction

Modern railway vehicles are equipped with multiple hydraulic dampers, whose damping characteristics must guarantee both passenger ride comfort and vehicle safety. An axle-box hydraulic damper, as shown in Fig. 1, is one of the key primary suspension components in the bogie, dissipating the energy from harsh shocks and vibrations from the wheel-set and resisting the energy transferred from the wheel-set to the bogie frame and carbody. Therefore, an axle-box hydraulic damper serves to reduce vibrations in the sprung mass and soften wheel–rail dynamic interaction forces. In normal cases, each bogie is equipped with two axle-box hydraulic dampers for its front wheel-set and another two for its rear wheel-set.

* Corresponding author at: College of Mechanical and Vehicle Engineering, Hunan University, Changsha 410082, Hunan Province, PR China. Tel.: +86 731 88822330.
E-mail address: pianowwl@163.com (W.L. Wang).

http://dx.doi.org/10.1016/j.ymssp.2015.03.015
0888-3270/

Nomenclature

A_{act}	piston or rod-side area (m^2)
B	viscous friction coefficient of kinematic pairs in the damper (N s/m)
C	damping coefficient (N s/m)
C_d	discharge coefficient
D	piston diameter (m)
F	damping force at a typical speed (N)
$F(t)$, $F_r(t)$	nominal and actual instantaneous damping forces (N)
H, H_g, H_p	heights of inner tube, guide seat and piston (m)
K_e	damper comprehensive stiffness (N/m)
K_{leak}	pressure leakage coefficient ($m^3\ Pa^{-1}\ s^{-1}$)
K_{oil}, K_{rubber}, K_{seat}	stiffnesses of oil spring, rubber attachment and steel mounting seat (N/m)
L	piston seal width (m)
L_{gap}	accumulated clearance at damper ends (m)
L_t	piston sweep distance (m)
L_v	rectangular relief valve port length (m)
P, P_0	instantaneous working pressure and atmospheric pressure (Pa)
P_b, P_{b0}	instantaneous back pressure in the reservoir and that when piston is in neutral position (Pa)
P_t	set pressure of a relief valve (Pa)
Q	instantaneous flow (m^3/s)
Q_{leak}, Q_{loss}, Q_{valve}	instantaneous flows of pressure leakage, total flow loss and that displaced through the relief-valve system (m^3/s)
T, T_0	instantaneous and reference oil temperatures (°C)
V_{oil}	instantaneous oil volume of the pressure chamber (m^3)
d	rod diameter (m)
d_c, d_f, d_x	constant orifice diameters of piston compression relief valve, relief valve in foot valve assembly and piston extension relief valve (m)
d_v	outer diameter of the relief valve spool (m)
f_c	sliding friction force of the outer tube assembly (N)
h_c, h_f, h_x	instantaneous spool displacements of piston compression relief valve, relief valve in foot valve assembly and piston extension relief valve (m)
h_{c0}, h_{f0}, h_{x0}	initial spring length reductions of piston compression relief valve, relief valve in foot valve assembly and piston extension relief valve (m)
i, j	index numbers
k_c, k_f, k_x	spring stiffnesses of piston compression relief valve, relief valve in foot valve assembly and piston extension relief valve (N/m)
l, l_v	seal width of rod and that between spool and sleeve in a relief valve (m)
m	mass of the outer tube assembly (kg)
r_1, r_2	inner and outer radii of the inner tube port restriction (m)
v	typical speed (m/s)
$x(t)$, $x_r(t)$	nominal and actual instantaneous displacements (m)
α_P	oil viscosity–pressure coefficient (Pa^{-1})
α_T	oil volumetric thermal expansion coefficient ($°C^{-1}$)
β	instantaneous oil compressibility coefficient (Pa^{-1})
β_e, β_{e0}	instantaneous bulk modulus of oil and that of pure oil at P_0 and T_0 (Pa)
δ	seal or port restriction clearance (m)
ε, ε_0	instantaneous entrained air ratio of oil and that at P_0 and T_0
λ	oil viscosity–temperature coefficient ($°C^{-1}$)
μ, μ_0	instantaneous oil dynamic viscosity and that at P_0 and T_0 (Pa s)
ρ, ρ_0	instantaneous oil density and that at P_0 and T_0 (kg/m^3)
σ	radial clearance between kinematic pairs in the damper (m)

The modelling and identification of hydraulic dampers (or shock absorbers) in the context of vehicle system dynamics and hydraulic damper product design has been studied and reported since 1977 [1], and there are currently four categories of hydraulic damper models.

(1) Physical parametric models [1–9] are established based on the hydraulic dampers' physical mechanisms or first principles, and usually include structural, fluid, thermal and frictional parameters. Physical parametric models are fully tunable, so they are essential to the product design of hydraulic dampers and effects analysis of damper parameter variations on vehicle system dynamics.
(2) Simplified parametric models [10–13] neglect most of the damper parameters and use well-known basic mechanical elements, such as springs, dashpots and friction, to depict damping characteristics. The basic mechanical elements can be linear or nonlinear, in series or in parallel. Thus, simplified parametric models are semi-physical and partially tunable and are frequently used in vehicle system dynamics simulations with high efficiency and allowable accuracy.
(3) Non-parametric models [14–17], also called black-box models, abandon the concrete damper parameters completely and are built using test data of hydraulic dampers. Approaches involving the restoration force state mapping [14], spline function fitting [15] and neural network training [16,17] are commonly used to process the test data and describe the damping characteristics. Because the test data are usually obtained under unique test conditions, non-parametric