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Rail vehicle dynamic response to a nonlinear physical 'in-service' model of its secondary suspension hydraulic dampers

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ABSTRACT

A full nonlinear physical 'in-service' model was built for a rail vehicle secondary suspension hydraulic damper with shim-pack-type valves. In the modelling process, a shim pack deflection theory with an equivalent-pressure correction factor was proposed, and a Finite Element Analysis (FEA) approach was applied. Bench test results validated the damper model over its full velocity range and thus also proved that the proposed shim pack deflection theory and the FEA-based parameter identification approach are effective. The validated full damper model was subsequently incorporated into a detailed vehicle dynamics simulation to study how its key in-service parameter variations influence the secondary-suspension-related vehicle system dynamics. The obtained nonlinear physical in-service damper model and the vehicle dynamic response characteristics in this study could be used in the product design optimization and nonlinear optimal specifications of high-speed rail hydraulic dampers.

1. Introduction

The secondary suspension of a passenger rail vehicle commonly includes several vertical and several lateral hydraulic dampers, which play important roles in car body stabilization, vibration reduction, ride comfort improvement and curve negotiation. In practice, hydraulic dampers are highly nonlinear devices (see Mellado et al. [1] and Wang et al. [2]), with characteristics that are sensitive to in-service conditions and could have unpredictable and significant influences on the vehicle system dynamics (see Wang et al. [3]). As speeds and loads increase in modern rail vehicles, these effects become more significant, and it is thus important to include an exact representation of realistic damper parameters in studies of vehicle system dynamics.

In related works, Kasteel et al. [4] and Farjoud et al. [5] built detailed nonlinear physical models for hydraulic dampers with shim stacks and orifices. Simms and Crolla [6] and Calvo et al. [7] performed simulations on the effects of damper characteristics on road vehicle dynamics, the macro damper models used include symmetric or asymmetric models, and simple linear or piecewise linear or linear with hysteresis performance models. Worden et al. [8] conducted both time and

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Nomenclature

A_a	pressure acting area on a shim or shim pack (m^2)
A_i	acceleration amplitude of vehicle body vibration at No. i frequency (g)
$B_1 \sim B_5$	constant coefficients
C	damping coefficient (N s/m)
C_{d1}, C_{d2}	discharge coefficients
C_e	equivalent-pressure correction factor
C_w	deflection coefficient of a shim or shim pack (m^6/N)
$C_1 \sim C_5$	constant coefficients
E	elastic modulus (Pa)
F, F_b, F_r	damping force, bending force, damper saturation force (N)
$F(f_i)$	frequency-dependent correction coefficient at No. i frequency
K_e, K_{rubber}, K_w	effective stiffness, rubber attachment stiffness, bending stiffness (N/m)
M_b	bending torque (N m)
P, P_b, P_e	working pressure, reservoir back-pressure, equivalent pressure (Pa)
Q_{valve}	flow through the valve system (m^3/s)
R (m)	railway curve radius (m)
RMS_A_y	root mean square centrifugal acceleration of the car body (m/s^2)
RMS_D_c	root mean square derailment coefficient
RMS_F_y	root mean square wheelset-rail lateral shift force (N)
RMS_W_n	root mean square total wear number (N)
T	oil temperature (°C)
V, V_r	vehicle speed (km/h), damper saturation speed (m/s)
W_z, W_{zy}, W_{zz}	ride index, lateral and vertical ride indices
d_c	diameter of the constant orifice (m)
f_i	no. i frequency (Hz)
h, h_e	shim thickness, equivalent thickness of a shim pack (m)
$p_1 \sim p_n$	pressures acting on the shims of a shim pack (Pa)
r, r_n, r_w	radius, clamping radius and free radius of a shim (m)
s	damper displacement (m)
t	time (s)
v	damper velocity (m/s)
$w(r)$	disk deflection in terms of the radius (m)
$x_r(t)$	actual instantaneous displacement of the damper (m)
$2a$	small clearance between a damper and its two fixing seats (m)
ε_0	entrained air ratio of oil (%)
ν	Poisson's ratio
ρ	instantaneous density of oil (kg/m^3)

frequency-domain analyses in the nonlinear identification of automotive dampers, the frequency-dependent damping characteristics were addressed. Park et al. [9] performed a sensitivity analysis of suspension parameters on high-speed train dynamics using the commercial Multibody System (MBS) dynamics simulation software Vampire and a Design of Experiments (DoE) approach. However, the applied hydraulic damper model is a simple linear model that contains only one parameter, i.e., the damping coefficient.

In recent years, studies of active stability system (see Pearson et al. [10]) and active lateral secondary suspension system (see Orvnas et al. [11] and Zhou et al. [12]) were also conducted for high-speed rail applications in pursuing better stability and ride comfort, and magnetorheological damper prototype (see Wang and Liao [13]) was also developed for the semi-active suspension control of rail vehicles.

In rail vehicle design studies, Shieh et al. [14] and He and Mcphee [15] also used the simple linear hydraulic damper model for suspension optimization, but Hao et al. [16] used the linear Maxwell damper model, i.e., a linear damping coefficient in series with a linear stiffness (see [17]) in a multi-objective optimization search and obtained better results. Wang et al. [18] proposed a full nonlinear damper model concept that includes most of the in-service parameters, and a detailed physical model was built. The nonlinear in-service damper model was successfully used in the optimal specifications of a locomotive axle-box hydraulic damper for vibration reduction and track-friendliness (see Wang et al. [19]).

In this work, a detailed nonlinear physical in-service model was built for a secondary suspension vertical hydraulic damper with shim-pack-type valves. In the modelling process, a shim pack deflection theory with an equivalent-pressure correction factor was proposed, and the Finite Element Analysis (FEA) approach was applied for parameter identification. The