Dynamic behavior analysis of radial hydraulically damped bushing based on FSI FEA method

Lin Li¹,⁴, Xiangkun Zeng² and Xiaolin Feng³

¹Department of Automotive, Guangdong Industry Technical College, Guangzhou 510300
²School of Automobile and Transportation Engineering, Guangdong Polytechnic Normal University, Guangzhou 510645
³Lenze Drive System (Shanghai) Co., Ltd, Research and Development Center, Shanghai 200000
⁴E-mail: lilin_11_05@163.com

Abstract. Nonlinear dynamic performances of hydraulically damped bushings (HDBs) can be characterized with two terms, dynamic stiffness and loss angle. In this paper, dynamic characteristics of a RHDB are estimated based on FSI FEA methods. Dynamic performances of the RHDB by FSI FEA method are precise. Obviously, FSI FEA method proposed in this paper can be effectively used to investigate and optimize dynamic characteristics of a RHDB, and also further to solve FSI problems of other component with hydraulic damping properties in the design stage.

1. Introduction
Nonlinear dynamic performances of hydraulically damped bushings (HDBs) can be characterized with two terms, dynamic stiffness and loss angle, which are defined as amplitude ratio and phase difference between load and displacement response in frequency domain, respectively [1-4]. The basic idea of HDBs is to use hyper-elastic rubber for providing stiffness combined with a hydraulic component such as inertia track for generating large damping at a prescribed frequency [5]. Therefore, some researchers have conducted experimental study and model formulation to investigate dynamic characteristics of HDBs.

Two-way fluid-structure interaction (FSI) nonlinear finite element analysis (FEA) technique is a powerful method for evaluating frequency-dependency dynamic behaviors of HDBs. Technical difficulty of FSI FEA method focuses on establishing boundary conditions between large deformations of rubber structure and pressure exerted by fluid in it. In recent years, with the development of Arbitrary Lagrangian-Eulerian (ALE) approach, simulation of large deformations for FSI boundary has been made great progress [6-13]. Numerous research works are contributed to explore damping characteristics of hydraulic mounts (HM) by using FEA method. In the works of Reference [14], which carries out analysis of partial lumped-parameters of a HM by a symmetric FEA model, but fluid model is not considered. In order to remedy linear models, a FSI model used to evaluate chamber’s volumetric stiffness of a HM combining with computational fluid dynamics methods is proposed in Reference [15]. Furthermore, a systematic experiment and numerical study of a HM’s dynamic characteristics are provided in Reference [16], where a finite element model with a floating decoupler is adopted to predict static and dynamic characteristics of an HM and rubber spring, and lumped-
parameters optimization of the HM is conducted by using FEA method. However, few researches are presented to use two-way FSI FEA method for extraction of lumped-parameters of RHDB’s LP model.

One of the contributions in this paper includes establishing a fully coupled FSI FEA model of a RHDB with one inertia track, where interaction between hyper elasticity of rubber material and large deformation of rubber-fluid is considered. Then, estimated dynamic performances of a RHDB are calculated by FEA method, which are compared favorably with experimental data. Furthermore, estimated dynamic characteristics of a RHDB using lumped-parameters identified by FSI FEA method are more accurately than that by the least-squares method. It verifies the proposed approach of FSI FEA method, which can be effectively used to decrease number of prototypes and tests, and to save considerable time in the designing stage.

2. Analysis of dynamic behaviors of a RHDB with FSI FEA method

Configuration and LP model of a typical RHDB with one inertial track are shown in Figure 1. In this section, a FSI FEA model used for analysis of a RHDB’s dynamic characteristics is proposed. Then, estimated dynamic performances of a RHDB obtained by FSI FEA method are compared with experimental data. Furthermore, dynamic behaviors of chamber’s fluid are investigated by FSI FEA method, which can not be obtained by experiment or RHDB’s LP model.

![](image1.png)

Figure 1. Construction and LP model of a RHDB with one inertial track.

2.1. FSI FEA model of a RHDB

Structure undergoes deformations under fluid pressure while structure deformations change fluid boundary conditions, which is the basic principle of two-way coupled FSI. Dynamic behaviors of elastic solid response can be modeled using the standard Lagrangian formulation, which governing field equation can be expressed as

\[ \tau_{ij,j} + f^B_i = \rho_s u^s_i \]  

where \( \tau_{ij} \) is the \( ij \)th component of Cauchy stress tensor for \((i,j=1,2,3)\), \( u_i \) is material particle acceleration in the coordinate \( i \) direction, \( \rho_s \) is mass density of the solid, \( f^B_i \) is a component of the body force [10].

Fluid response is modeled using the full N-S equations assuming incompressible flow. In Arbitrary Lagrangian-Eulerian (ALE) form, the N–S equations are given in Reference [12],

Continuity:

\[ u_{i,i} = 0 \]  

Momentum:
\[
\rho \frac{\partial u_i}{\partial t} + \rho (u_j - u_m) \frac{\partial u_i}{\partial x_j} = \frac{\partial \tau_{ij}}{\partial x_j} + f_i
\]  

(3)

where \( \rho \) is constant mass density of fluid, \( u_i \) is a component of velocity, \( u_m \) is the velocity of moving mesh which can be arbitrarily specified \( u_m \) in the fluid domain. \( f_i \) is a component of the body force vector, and \( \tau_{ij} \) is the \( ij \)th component of the stress tensor defined as

\[
\tau_{ij} = -p \delta_{ij} + \mu (u_{i,j} + u_{j,i})
\]

(4)

where \( p \) is the fluid pressure, \( \delta_{ij} \) is the Kronecker delta, and \( \mu \) is the coefficient of viscosity.

Boundary conditions applied to FSI FEA model are

\[
d_f = d_s, n \cdot \tau_f = n \cdot \tau_s
\]

(5)

where \( d_f \) and \( d_s \) are displacements of fluid and solid, respectively, \( \tau_f \) and \( \tau_s \) are stresses of fluid and solid, respectively. Underlining denotes that the values are defined on the fluid-structure interfaces only. \( n \) is the normal direction on the coupling boundary.

After finite element spatial discretization of the solid Equation (1) and ALE N-S Equations (2)-(4), and application of the boundary conditions Equation (5) to the discrete finite element equations of the fluid and the structure, the coupled FSI system equation can be obtained and expressed as [16]

\[
F(X) = \begin{bmatrix} F_f & F_s(X_f) \\ F_s(X_f) & F_s(X_s) \end{bmatrix} = 0
\]

(6)

where \( X = (X_f, X_s) \) are the solution vectors of the coupled system, \( X_f \) and \( X_s \) are vectors of the fluid and solid defined at the fluid and solid nodes, respectively, \( F_f \) and \( F_s \) are the finite element equations corresponding to the fluid and structure model, respectively.

The two-way coupled FSI equation of a RHDB is nonlinear. Therefore, a moment solution is obtained by iterative method based on ALE, and iteration-convergence numerical results can be checked according to criteria of stress and displacement,

\[
r_\tau = \frac{\| \tau_f^k - \tau_f^{k-1} \|}{\max \| \tau_f^k \|, \varepsilon_\tau} \leq \varepsilon_\tau
\]

\[
r_d = \frac{\| d_s^k - d_s^{k-1} \|}{\max \| d_s^k \|, \varepsilon_0} \leq \varepsilon_d
\]

(7)

where \( r_\tau \) and \( r_d \) are criterions of the stress and displacement, respectively, \( \varepsilon_\tau \) and \( \varepsilon_d \) are allowance errors of the stress- and displacement-convergence, respectively. \( \varepsilon_0 \) is a constant given in advance \((= 10^{-8})\).

Equation (6) is solved incrementally in time using the finite element method with all non-linearities included, and commercially available FEA system ADINA is used in this study. FEA models of rubber spring and fluid of a RHDB with the maximum element size of 5 mm, which include 18917 tetrahedral elements and 4621 nodes, and 2490 tetrahedral elements and 635 nodes, respectively, as shown in Figure 2.

Dynamics-implicit algorithm is used for the analysis type of solid model. FSI interface is the area of solid model contacting to fluid model, as seen the dark area in Figure 2(b). Fluid model is defined as transient analysis model. Outer area of the fluid model is defined as wall without slip, while influences of temperature on viscosity and density of the fluid are ignored during calculation process.
Constraints are applied to the nodes which are located at the outer radial surfaces of rubber spring and fluid, and are with zero degrees of freedom, as shown in Figure 3. Excitation displacement are located at the inner surface of rubber spring and contacted to the outer surface of inner sleeve. It is noted that the direction of excitation displacement is radial and perpendicular to the symmetry plane of two chambers. Excitation of sinusoidal displacement can be expressed by

$$x(t) = A \sin(2\pi f t)$$

(8)

where $A$ and $f$ are excitation amplitude and frequency of dynamic displacement, respectively.

Figure 2. Geometry and FEA models of a RHDB.

Furthermore, several assumptions are made to establish the FEA model: (i) fluid in chambers is incompressible; (ii) fluid pressure inside each chamber is uniform; (iii) dynamic viscosity and density properties of the liquid are constant.

Figure 3. Constraints of FEA models of rubber spring and fluid.

Figure 4 shows dynamic performances of a RHDB with single-peak amplitude of 0.1 mm based on the proposed LP model are calculated. It is found that the estimated dynamic characteristics of the RHDB using lumped-parameters identified by FSI FEA method are more consistent with experiment data compared with that using the least-squares method. It verifies the proposed FSI FEA method which is an effectively method can be used for accurately identifying lumped-parameters of a RHDB LP model.
2.2. Analysis of dynamic behaviors of chamber’s fluid

Pressure versus time curves of fluid in two chambers of a RHDB is shown in Figure 5, where radial excitation amplitude and frequency are equal to 0.1 mm and 60 Hz, respectively. It is found that pressures of two chambers change alternately and absolute pressure values of two chambers are almost the same, but which vector directions are opposite. Pressure distributions of two chambers with different excitation frequencies of 5 Hz, 20 Hz and 40 Hz and single-peak amplitude of 0.1 mm are presented in Figure 6. Velocity responses of fluid flow with excitation frequency of 40 Hz are shown in Figure 7. It is found that dynamic behaviors of fluid in the RHDB can be intuitively simulated using FSI FEA method, which can not be obtained by experiment or LP model.

---

**Figure 4.** Dynamic characteristics of a RHDB with different method ($A=0.1$ mm).

**Figure 5.** Pressure-time curve of fluid in two chambers ($A=0.1$ mm, $f=60$ Hz).
Figure 6. Pressure distributions of two chambers ($A=0.1$ mm).

Figure 7. Velocity responses of fluid flow ($A=0.1$ mm, $f=40$ Hz).

3. Conclusions
In this work, dynamic characteristics of the RHDB are estimated based on the LP model using two kinds of lumped-parameters identified by the two methods, which are compared favorably with the experimental data. However, it shows that dynamic performances of the RHDB estimated using lumped-parameters identified by FSI FEA method are more precise than that by the least-squares method. FSI FEA method proposed in this paper can be effectively used for investigating and optimizing dynamic characteristics of a RHDB, and further for other components with hydraulic damping properties in design stage.
References
[1] Den Hartog 1956 Mechanical Vibrations[M]. New York: McGraw-Hill 426-536
[2] Jazar R N 2008 Vehicle Dynamics: Theory and Application[M]. Springer 426-536
[3] Chai T, Dreyer J T and Singh R 2014 Time domain responses of hydraulic bushing with two flow passages[J]. Journal of Sound and Vibration 333(3) 693-710
[4] Chai T, Dreyer J T and Singh R 2015 Nonlinear dynamic properties of hydraulic suspension bushing with emphasis on the flow passage characteristics[J]. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering 229(10) 1327-1344
[5] Heißing Bernd and Ersoy Metin 2011 Chassis Handbook[M]. Springer
[6] Christopherson J and Jazar R 2006 Dynamic behavior comparison of passive hydraulic engine mounts Part 1: Mathematical analysis[J]. Journal of Sound and Vibration 290 1040-1070
[7] Christopherson J and Jazar R 2006 Dynamic behavior comparison of passive hydraulic engine mounts Part 2: Finite element analysis[J]. Journal of Sound and Vibration 290 1071-1090
[8] Yoon J Y and Singh T 2010 Indirect measurement of dynamic force transmitted by a nonlinear hydraulic mount under sinusoidal excitation with focus on super-harmonics[J]. Journal of Sound and Vibration 329 5249-5272
[9] Tarrago M J, Kari L, Vinolas J and Gil-Negrete N 2007 Frequency and amplitude dependence of the axial and radial stiffness of carbon-black filled rubber bushings[J]. Polymer Testing 26 629-638
[10] Wang L R., Lu Z H and I Hagiwara 2010 Integration of experiment and hydrostatic fluid-structure finite element analysis into dynamic characteristic prediction of a hydraulically damped rubber mount[J]. International Journal of Automotive Technology 11(2) 245-255
[11] Chen Zhiyong, Wu Guangming and Shi Wenku 2011 Finite Element Analysis of Light Vehicle Cab’s Hydraulic Mount Based on Fluid-Structure Interaction Method[C]. SAE Technical Paper Series 2011-01-1604
[12] Adina R and D Adina 2010 Theory and Modeling Guide-ADINA-A and-F
[13] Hormoz Marzbani, Reza N Jazar and M Fard 2013 Hydraulic engine mounts:a survey[J]. Journal of Vibration and Control 12(38) 1-25
[14] Mahnken B and Borgerson M 2006 Application of NVH countermeasures for cabin boom isolation using hydraulic bushing and silicone tuned mass absorber[R]. SAE Technical Paper Series 2006-01-1681
[15] Wang L R, Lu Z H and Hagiwara I 2010 Analytical analysis approach to nonlinear dynamic characteristics of hydraulically damped rubber mount for vehicle engine[J]. Nonlinear Dynamics 61(1-2) 251-264
[16] Nomura T and Hughes T J R 1992 An arbitrary Langangian-Eulerian finite element method for interaction of fluid and a rigid body[J]. Computer Methods in Applied Mechanics and Engineering 95(1) 115-38