

Transient Response of Hydraulic Bushing with Inertia Track and Orifice-Like Elements

Tan Chai, Jason T. Dreyer and Rajendra Singh
 The Ohio State University

ABSTRACT

Hydraulic bushings are widely used in vehicle applications, such as suspension and sub-frame systems, for motion control and noise and vibration isolation. To study the dynamic properties of such devices, a controlled laboratory bushing prototype is designed and fabricated. This device has the capability of varying different combinations of long and short flow passages and flow restriction elements. Transient experiments with step-up and step-down excitations are conducted on the prototype, and the transmitted force responses are measured. The transient properties of several commonly seen hydraulic bushing designs are experimentally studied. Analytical models for bushings with different design features are developed based on the linear system theory. System parameters are then estimated for step responses based on theory and measurements. Finally, the linear models are utilized to analyze the step force measurements, from which some nonlinearities of the bushing system are identified.

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INTRODUCTION

Suspension bushings are often expected to provide a high viscous damping coefficient (c) and stiffness (k) for large amplitude excitations at lower frequencies [1,2,3,4,5]. Further, lower k and c values are needed for controlling structure-borne noise at moderate to higher frequencies [1,2,7]. Since elastomeric bushings cannot satisfy such conflicting requirements, many fluid-filled bushing designs have been developed and utilized in vehicles [1-2], as evident from some articles [7,8,9,10] and patents [11,12,13,14,15,16,17,18,19,20]. Even though many patents [11,12,13,14,15,16,17,18,19,20] claim performance features, they provide no analytical justifications or even measured dynamic properties. Further, very few scholarly articles have addressed hydraulic bushing characterization and modeling issues [7,8,9,10]. Moreover, prior articles [1,7,8,9,10] have only examined the frequency domain properties, and most designs [1,7,8,9,10,11,12,13,14,15,16,17,18,19,20] are based on spectral characteristics. Therefore, this article aims to propose new or improved models based on the linear time invariant system theory and study the time domain characteristics of hydraulic bushings.

The schematic of a typical fluid-filled bushing is shown in Figure 1. Such a device consists of two almost identical elastomeric chambers between inner and outer metal sleeves. These chambers are filled with the anti-freeze mixture, and

they communicate fluid via a long passage (inertia track), and/or a short passage (or a controlled leakage orifice [1]). The relative deflection of the inner and outer metal causes chamber pressures to vary, and thus fluid flows back and forth through the inertia track and orifice-like passages, which provides effective damping at the desired frequency range.

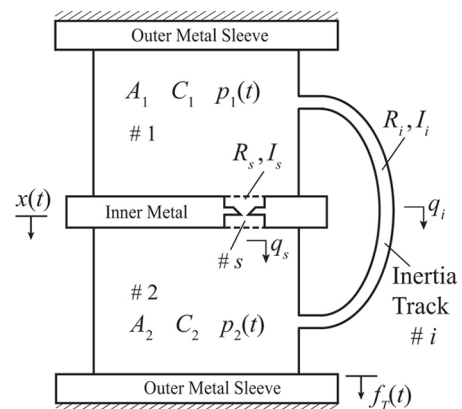


Figure 1. Fluid model I of the hydraulic path with a long flow passage (inertia track, #i) and a short flow passage with restriction (#s).

Although fluid-filled bushings exhibit frequency-dependent and amplitude-sensitive properties [7], a linear time-invariant model must be developed first to gain physical insight into the bushing system and systematically examine its dynamic properties. Only radial damping is considered because the relative displacement between the inner and outer metal parts is assumed to be only in the radial direction. Accordingly, specific objectives for this article are as follows: (a) Design a laboratory device with controlled internal configurations and conduct experiments on this prototype under transient excitations with step-up and step-down displacement excitations; (b) Develop lumped parameter linear models of fluid-filled bushings and analogous mechanical models; (c) Analyze the measured transient responses by utilizing the linear system theory.

EXPERIMENTAL STUDIES

Fluid passages in production hydraulic bushings usually have irregular geometry and are constructed with alternate material from elastomers to metals. Moreover, experimentation with many bushing samples from different manufacturers would pose a difficult task. Thus, a laboratory device which can provide insights into various aspects is designed and fabricated for dynamic characterization and scientific examination. This device is able to provide different combinations of long fluid passage (inertia track) and short passage with adjustable flow restriction. Experiments are conducted on five configurations (designated B1 to B5, as listed in Figure 2 and Table 1) of this prototype using the MTS elastomer test machine [21]. Additionally, two limiting cases (B0 with all fluid passages closed and BR with the drained bushing) are also evaluated in the experiment.

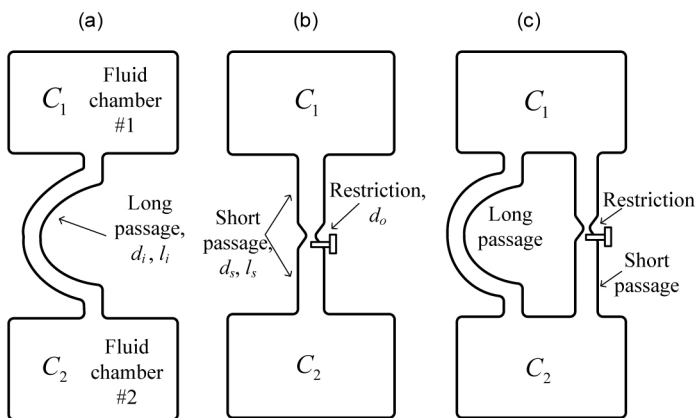


Figure 2. Multiple configurations of the hydraulic bushing constructed for controlled laboratory studies. (a) Configuration B1 with long fluid passage of diameter d_l ; (b) Configuration B2 with short flow passage with restriction of diameter d_o and configuration B3 of diameter $d_o/3$; (c) Configuration B4 with parallel long and short flow passages with d_o and B5 with $d_o/3$.

Table 1. Configurations of the hydraulic bushing prototype

Configuration	Description (Also see Fig. 2)
B1	One long flow passage of diameter d_l
B2	One short fluid passage with a restriction of diameter d_o
B3	One short fluid passage with a restriction of diameter $d_o/3$
B4	One long passage and one short passage with a restriction of diameter d_o in parallel
B5	One long passage and one short passage with a restriction of diameter $d_o/3$ in parallel
B0	All fluid passages closed
BR	Drained bushing

In the transient experiment, a step-up and step-down excitation is applied to the prototype device, and the transmitted force is measured. As shown in Figure 3 (a), first a compressive mean load f_m corresponding to displacement $x_M(t) = A_o$ is applied, and then the step-up process increases the load to reach $x_M(t) = A_o + A_x$ and holds it for $\Delta t = t_2 - t_1$; then $x_M(t)$ is released to $A_o - A_x$ via the step-down process and is held for another $\Delta t = t_3 - t_2$. Finally, the load is increased back to around f_m such that now $x_M(t) \approx A_o$. However, an ideal step function as shown in Figure 3(a) is extremely difficult to generate given the practical limitations of the actuator. Thus, only step-like functions such as smoothened step events are realized as shown in Figure 3(b). Note that the step-down excitation has twice the step height A_e of the step-up, and their initial loading levels are different. Thus, this measurement will investigate the effect of A_e and the mean load on transient responses. Experimental results will be discussed in detail along with analytical analysis in the later sections.

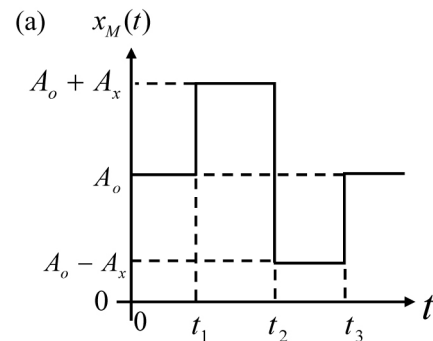


Fig. 3. Excitation profiles for the transient experiment. (a) Ideal step-up and step-down pulse; (b) Smoothened step-up excitation. Key:....., measured step excitation; —, analytical approximation; - - -, ideal step function.

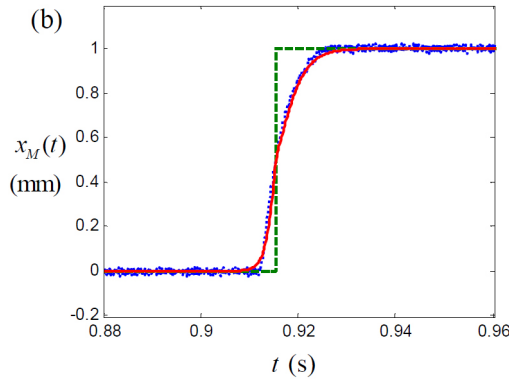


Fig. 3 (cont). Excitation profiles for the transient experiment. (a) Ideal step-up and step-down pulse; (b) Smoothed step-up excitation. Key:....., measured step excitation; —, analytical approximation; —, ideal step function.

MATHEMATICAL MODELS

Model I for Two Parallel Flow Passages

A fluid system model of the hydraulic path of a bushing with two passages in parallel is proposed in Figure 1 based on the lumped parameter method. These include an internal long passage such as the inertia track (#i), though shown as external tubing for the sake of clarity in Figure 1, and/or a short passage (#s) with a flow restriction or controlled leakage element (such as the orifice). The long and short flow passages are represented by the fluid inertances I_i and I_s and fluid resistance R_i and R_s , respectively. The rubber element (#r) is modeled by rubber stiffness k_r and viscous damping coefficient c_r . The compliances of the two fluid chambers (#1 and #2) are C_1 and C_2 , respectively, with effective pumping areas A_1 and A_2 .

For better illustration of the mechanism of a hydraulic bushing, an analogous mechanical system model is developed in Figure 4, where the hydraulic path includes long (inertia track) and short passages in parallel. The reason for selecting the mechanical model is that it should facilitate an easier implementation into structural models of the vehicle system. The rubber path is still approximated by the Kelvin-Voigt model with rubber stiffness k_r and damping coefficient c_r . The effective fluid path parameters based on the fluid system model are defined as follows: Equivalent mechanical stiffness of two fluid chamber compliances $k_1 = A_1^2/C_1$ and $k_2 = A_2^2/C_2$, effective cross-sectional area of the inertia track $A_{ie} = \sqrt{(A_1^2 C_2 + A_2^2 C_1)/(C_1 + C_2)}$, effective fluid velocity in the inertia track $\dot{x}_{ie}(t) = q_i(t)/A_{ie}$, effective mass of the inertia track fluid $m_{ie} = A_{ie}^2 I_i$, effective viscous damping of inertia track fluid $c_{ie} = A_{ie}^2 R_i$, effective cross-sectional area of the

short fluid passage $A_{se} = \sqrt{(A_1^2 C_2 + A_2^2 C_1)/(C_1 + C_2)}$, effective fluid velocity in the short passage $\dot{x}_{se}(t) = q_s(t)/A_{se}$, effective mass of the short passage fluid $m_{se} = A_{se}^2 I_s$, and effective viscous damping of the short passage fluid $c_{se} = A_{se}^2 R_s$.

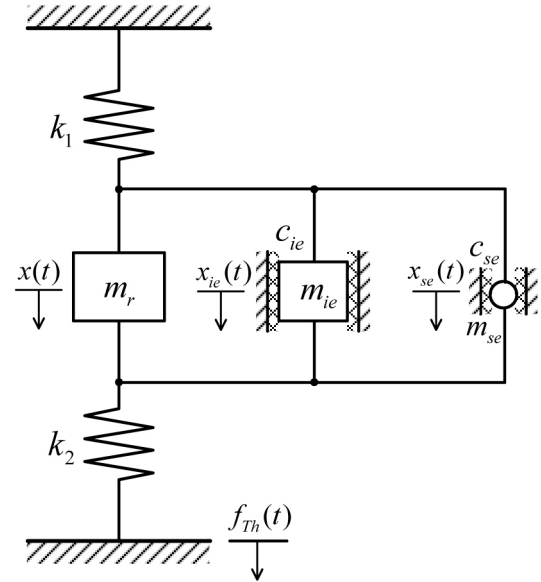


Figure 4. Analogous mechanical model of the hydraulic path with long and short flow passages in parallel

Since the mass (m_r) of the hydraulic bushing is usually negligible, the transmitted (dynamic) force is given as:

$$f_T(t) = f_{Tr}(t) + f_{Th}(t) = [k_r x(t) + c_r \dot{x}(t)] + (k_1 + k_2)[x(t) + x_{ie}(t) + x_{se}(t)] \quad (1)$$

Application of Newton's second law to the effective masses of the inertia track and short passage fluid elements yields the following equations:

$$m_{ie} \ddot{x}_{ie}(t) + c_{ie} \dot{x}_{ie}(t) + (k_1 + k_2) x_{ie}(t) = -(k_1 + k_2)[x(t) + x_{se}(t)] \quad (2)$$

$$m_{se} \ddot{x}_{se}(t) + c_{se} \dot{x}_{se}(t) + (k_1 + k_2) x_{se}(t) = -(k_1 + k_2)[x(t) + x_{ie}(t)] \quad (3)$$

By transforming Eqs. (1), (2), (3) into the Laplace domain, the dynamic stiffness K_d is obtained. Since m_{se} is usually negligible at the lower frequencies, Eq. (3) is simplified and expressed by a reduced order form as follows: