

ENHANCEMENT OF SQUEEZE-FILM DAMPER PERFORMANCE WITH POROELASTIC MATERIALS

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ABSTRACT

Squeeze-film dampers provide a damping force when a viscous fluid is forced to flow between two surfaces moving relative to one another. Squeeze-film dampers are a compact method of adding damping without hysteresis but suffer from some disadvantages such as a small range of travel, sensitivity to misalignment, and nonlinear behavior. In this paper, we investigate the damping attainable by filling the gap between the surfaces with a very compliant porous medium saturated with viscous fluid. At low frequencies the foam acts as a spring and the fluid acts as a damper due to the flow through the porous medium. At high frequencies the fluid flow is restricted by the porous medium and the impedance is dominated by the inertial bulging movement of the foam and fluid together.

INTRODUCTION

A typical squeeze film damper is sketched in Figure 1. Its damping value is given by

$$c = \frac{3\pi\mu D}{16} \left(\frac{D}{h}\right)^3$$

where μ is the viscosity of the fluid, h is the gap height between the surfaces, and D is the diameter of the piston. Because the damping scales with h^{-3} , a small gap can provide very high damping. However, in applications requiring a large range of travel or adjustments relative to the gap size, this strong dependence on gap can be a detriment. Jackson [8] derived the effect of inertia, which will tend to dominate at relatively high frequencies

$$F = \frac{\pi R^4}{4} \left(6\mu \frac{\dot{h}}{h^3} - \rho \left(\frac{48}{70} \left(\frac{\dot{h}}{h}\right)^2 - \frac{3}{5} \ddot{h} \right) \right)$$

Poroelastic mechanics is widely studied across a variety of fields, from soil and rocks in geology and hydrology to synovial fluid flow in skeletal joints to cellular mechanics. Biot [1, 2] and Zwikker Kosten [3] developed derived governing equations that are still widely used. Lang et al [1] are among several references to model the transient fluid mechanics of a fluid-filled porous film subject to squeezing. Zhang and Yan [6]

demonstrated the use of a porous sintered metal as the outer race for damping rotor vibration via the squeeze-film effect. In that application the porous squeeze material is very stiff but serves as a reservoir to provide fluid flow as needed. Chow and Pinnington [7] sandwiched polyester open-cell foam and a viscous fluid between two plates to damp machinery panels. Gent and Rusch [15], Hilyard [12, 13, 14], Okuno and Kingsbury [16] have studied the mechanical behavior of fluid filled foams under small oscillatory motions, but typically not at the high frequencies often of concern in many precision systems. Dawson [9] and Pascovici [10,11] have studied the use of fluid filled foams under squeezing as applicable to impact absorption.

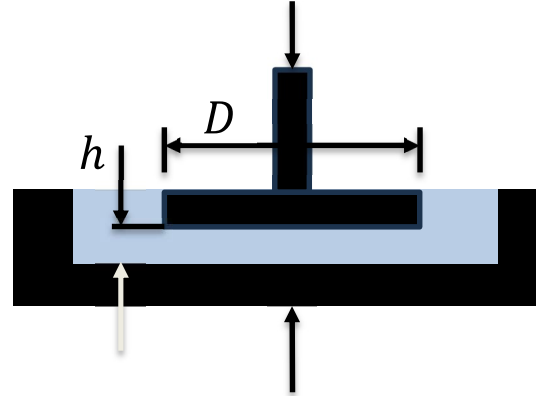


FIGURE 1. Sketch of a typical squeeze film damper consisting of a piston and a plate separated by a thin layer of viscous fluid.

MODELING

Frequency response functions for the impedance foam samples under sinusoidal compression are derived using the methods of Gent and Rusch [15] and Hilyard [13]. At low frequencies the forces are due to the compression of the foam and the fluid flow through the matrix. At high frequencies, fluid flow relative to the foam is restricted by the porous nature of the foam and causing the fluid and foam to move together as a nearly incompressible block of rubber.

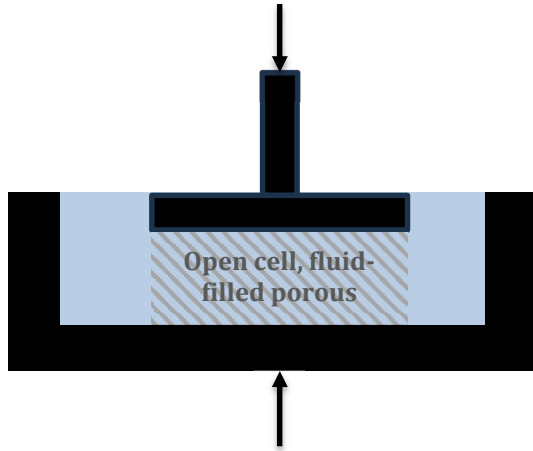


FIGURE 2. Sketch of a squeeze film damper consisting of a piston and a plate separated by a layer of open-cell porous material containing a viscous fluid.

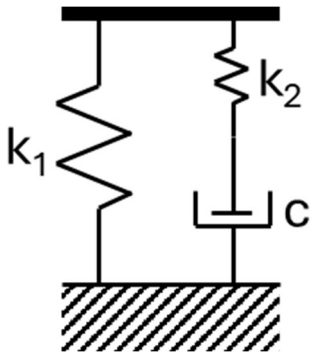


FIGURE 3. Lumped parameter model as used by Gent and Rusch [15]

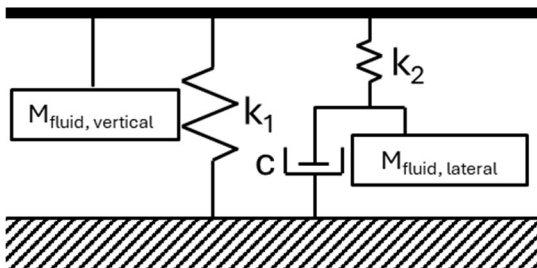


FIGURE 4. Lumped parameter model as used by Hilyard and Kanakkanatt [13]

An impedance model based on Hilyard's approach but modified for a circular disk of foam can be written in the form

$$\frac{\sigma}{\varepsilon} = \frac{j\omega}{A + \frac{j\omega}{B+C} + E_0 - \frac{\rho h^2 \omega^2}{3}}$$

where σ is the average stress, ε is the displacement normalized by the gap height h , A is the viscous damping from Darcy's porous flow model

$$A = \frac{12\phi K}{\mu R^2}$$

where ϕ is the porosity (volume fraction of the fluid), K is the permeability of the foam, μ is the viscosity of the fluid, and R is the radius of the foam. B is a stiffness term

$$B = \frac{E_0 R^2}{3h^2}$$

where E_0 is the Young's modulus of the foam, and C is an inertia term for the bulging motion of the fluid plus foam

$$C = \frac{-\rho \omega^2 R^2}{15}$$

where ρ is the density of the fluid and ω is the angular frequency.

TABLE 1. Permeability of foam samples as estimated using the relation [Dawson].

Foam	Pores per inch (PPI) from manufacturer	Permeability [m ²]
Z65GR	65	4e-9
Z80CH	80	2e-9
Z100CH	100	1e-9

EXPERIMENTAL RESULTS

An electromagnetic shaker is used to measure the impedance of foam samples soaked with a combination of water and glycerin as shown in Figure 6. Glycerin is water-soluble, and therefore the viscosity of the liquid can be varied by mixing water and glycerin together in a prescribed ratio. In the experimental results shown in Figures 7-9,

a mixture of 5 parts glycerin to 2 parts water by volume is used. The resulting viscosity is 0.035 Pa-s, and the density is 1200 kg/m³. The foam samples are nominally 3.2 mm thick and 19 mm in diameter. They are compressed during testing to a thickness of approximately 3 mm.

Polyurethane foam samples with pore sizes ranging from 65 to 100 pores per inch (PPI) were obtained from McMaster-Carr (see Figure 5). Permeability of the foam samples is estimated using the relation in [17] $K = Ad^2$ where A is a constant and d is the cell size. The permeability is an important parameter for the model, but it is difficult to predict from estimates of pore sizes alone. The constant in the above equation varies by almost an order of magnitude in the literature and many resort to measurements. Unfortunately, the parameter is rarely provided by manufacturers. Because the values we estimate in Table 1 are highly approximate, we retain only one significant figure.

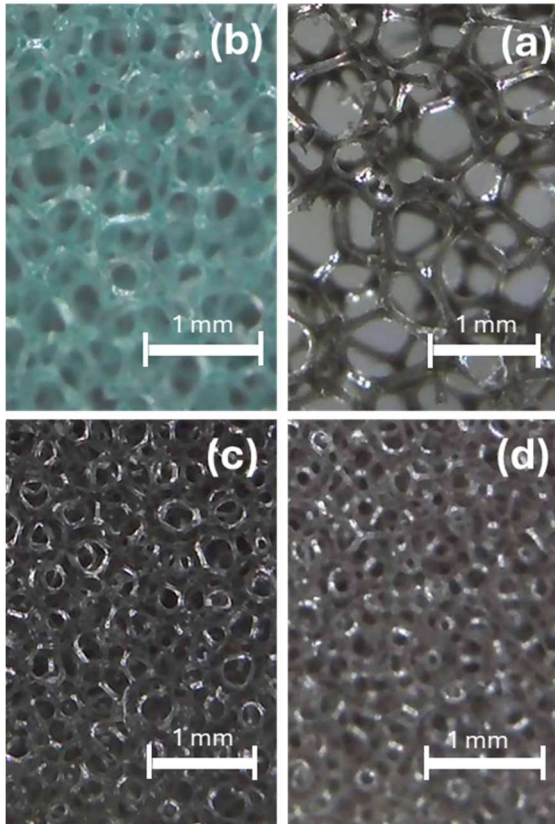


FIGURE 5. Foam samples viewed with a microscope: (a) Z45CH, (b) Z65GR, (c) Z80CH, (d) Z100CH.

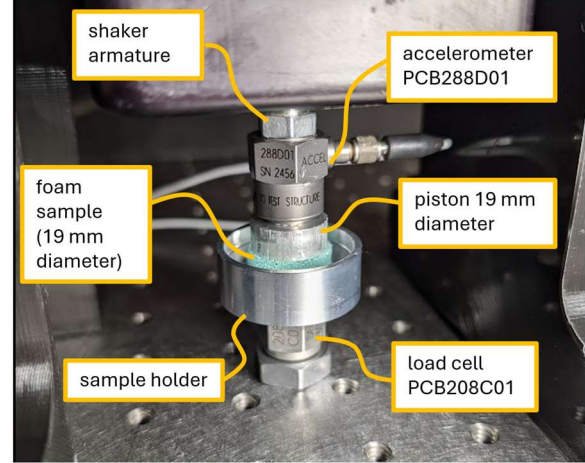


FIGURE 6. Experimental setup of the porous squeeze film damper.

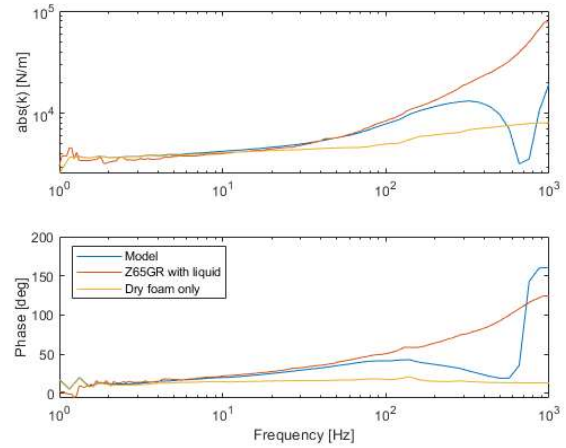


FIGURE 7. Complex stiffness comparison of the Z65 foam with and without liquid filling (5 parts glycerin, 2 parts water by volume) to the model.

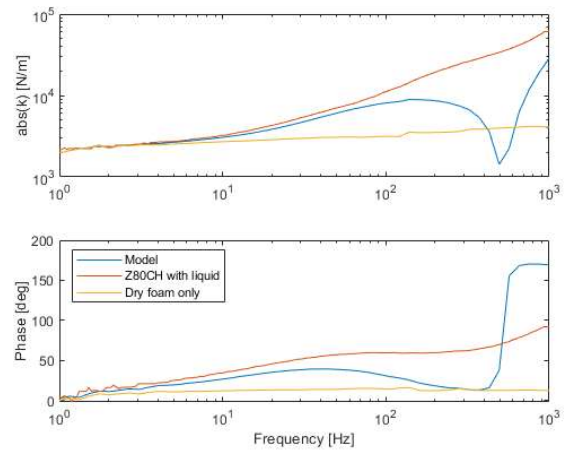


FIGURE 8. Complex stiffness comparison of the Z80 foam with and without liquid filling (5 parts glycerin, 2 parts water by volume) to the model.

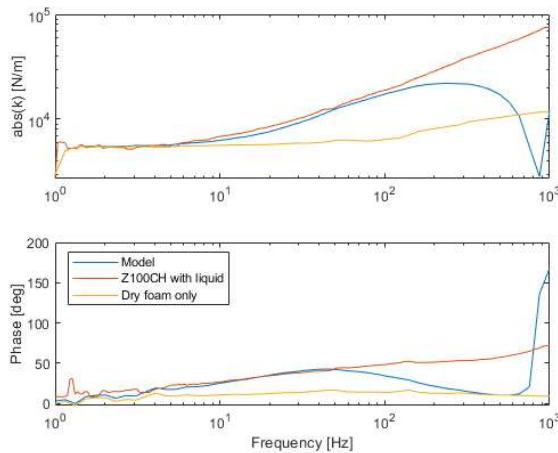


FIGURE 9. Complex stiffness comparison of the Z100 foam with and without liquid filling (5 parts glycerin, 2 parts water by volume) to the model.

CONCLUSIONS

The model and measurements shown in Figures 7-9 agree up to about 100 Hz. The model shows that the stiffness of a liquid-filled foam is small at low frequencies. At high frequencies, the model predicts a drop in the magnitude and phase of the complex stiffness, but the measurements increase monotonically with frequency.

Although the model predicts a large phase (and hence high damping) from about 10-100 Hz, our measurements indicate that the high damping persists out at least to 1 kHz. Further work is required to explain the discrepancy between model and experiments.

Liquid-filled foams are an efficient way to provide damping in precision mechanical systems. The low stiffness behavior at low frequencies with significant damping at high frequencies aligns with the requirements of many precision systems.

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