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Modeling and sensitivity analysis of a pneumatic vibration isolation system with two air chambers

Jun-Hee Moon [a,*], Bong-Gu Lee [b]

[a] Department of Mechatronics, Daelim University College, 526-7, Bisan-dong, Dongan-gu, Anyang-si, Gyeonggi-do, 431-715, South Korea
[b] Department of Mechanical Engineering, Daelim University College, 526-7, Bisan-dong, Dongan-gu, Anyang-si, Gyeonggi-do, 431-715, South Korea

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ABSTRACT

This paper aims at accurate modeling and sensitivity analysis for a pneumatic vibration isolation system (PVIS) as a foundation for practical design. Even though the PVIS is widely used for its effective performance in vibration isolation, its design has depended largely on trial-and-error methods. In previous studies, nonlinear characteristics of the diaphragm and the air flow restrictor, which significantly affect the performance of a PVIS, have been investigated. However, several hurdles, such as the absence of a mathematical model for the diaphragm, still remain with regard to the model-based prediction of performance. Therefore, a fractional derivative model for the diaphragm and a quadratic damping model for the air flow restrictor are newly developed based on the careful examination of previous studies. Then, sensitivities of vibration isolation performance indices with regard to major design variables are analyzed and new approximation formulas are created based on the dynamic characteristics of the PVIS. Our models with a transmissibility-computing algorithm are verified by comparison with experimental data. The sensitivity analyses and approximation formulas are expected to be useful for practical PVIS design owing to their simplicity and accuracy.

1. Introduction

As high precision industries such as semiconductor production, precision metrology, optics, and microbiology continue to grow, higher performance vibration isolation systems are needed to meet the corresponding vibration tolerance requirements [1–3]. To achieve vibration isolation for local precision equipment, a pneumatic vibration isolation system (PVIS) is widely used because it needs no energy supply and no control unit, and performs stable and effective vibration attenuation across a wide frequency range. Even though a PVIS is very useful, its design for better vibration isolation has depended largely on trial and error methods.

Vibration isolation performance enhancement of the PVIS has been attempted by a variety of ways such as reshaping of elastomeric diaphragm [4], usage of an air flow restrictor of porous media [5], energy dissipation by a gimbal piston in oil chamber [6], parallelization with a negative-stiffness device [7] and adoption of active control schemes [8–11]. In all those attempts, the basic work is the modeling of components of the PVIS since effects of design variables on vibration isolation performance can be predicted only with accurate mathematical models and corresponding computational techniques.

In this paper, our goal is accurate modeling and vibration isolation performance evaluation of a PVIS such that our results may be used to predict the performance for practical PVIS design. We examined previous studies and determined that three additional efforts are required.

The first is to make a mathematical model of the diaphragm. Some studies pointed out that the diaphragm has an important role in the elastic and damping characteristic of a PVIS [4,12,13]. However, its nonlinear properties have been thus far neglected in

* Corresponding author. Tel.: +82 31 467 4687; fax: +82 31 467 4869.
E-mail address: junheemoon@gmail.com (J.-H. Moon).

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Nomenclature

A	area
b_1, b_2, b_3	tuned coefficient for approximation formulas
c_{E0}, c_{E1}, c_{E3}	material constants of the diaphragm
C	damping coefficient
d	diameter
E	elastic modulus
f	force variation
F	Fourier transform of f
fr	friction coefficient
g	acceleration of gravity
$\mathbf{G}$	complex nonlinear mapping
h	height
H	transmissibility
i	imaginary unit
I	mechanical impedance
K	stiffness
L	loss coefficient
m	air mass in the chamber
M	tabletop mass
N	volume ratio of damping chamber to spring chamber
P	pressure
Re	Reynolds number
t	time
u	fluid velocity
V	volume
x	displacement
X	Fourier transform of x
$\mathbf{y}$	ordered pair of complex variables
α	acceleration parameter
α_E	shift factor
β	exponent of fractional derivative
γ	the specific heat ratio ($=1.4$)
Δ	variation
ε	strain
η	loss factor
μ	viscosity
ρ	density
σ	stress
τ	time constant
$\boldsymbol{\omega}$	angular velocity
∇	gradient operator

Superscripts

$\wedge$	maximum
$\vee$	minimum
$\cdot$	time derivative
$-$	averaged

Subscripts

0	static or average
a	air
at	atmosphere
b	base
c	capillary tube or air flow restrictor
d	diaphragm