Modeling and Testing of a Semiactive Hydraulic Damper in Periodic Working Regimes

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This paper presents analytical and experimental studies of a modified semiactive hydraulic damper operating in periodic working regimes. This work was completed as a part of the Rotor Embedded Actuator Control Technology project sponsored by the Technology Strategy Board in the United Kingdom. The damper tested is based on modifications to an industrially employed helicopter damper. The work presented covers the relevant aspects of the model development, damper modification, test planning, and analysis, as well as a model-simulation correlation study. The model of the damper directly reflects the actual hydraulic modification, enabling a semiactive mode of operation. Pressure-flow representations used in the damper modeling are based on a novel testing methodology using triangular piston excitation waveforms. A specific test structure based on varying the relative phase difference between two harmonic input signals is used to assess the damper properties in periodic working regimes. The test configuration with a base harmonic piston excitation combined with a harmonic modulation at a frequency 3 times higher than the base frequency leads to significant changes in the second and fourth harmonic components of the resulting periodic damper forces. A successful model-simulation correlation study suggests that a simple one-state dynamic model of this damper features good predictive properties, equally applicable in the extended simulation contexts.

Nomenclature

\( A_j, B_j \) = Fourier coefficients  
\( A_p \) = cross-sectional area of the symmetric piston  
\( A_v \) = cross-sectional area of the valve opening  
\( B_{0,\text{eff}} \) = constant effective bulk modulus of a hydraulic fluid  
\( C_D \) = discharge coefficient  
\( C_L, C_Q \) = linear and quadratic pressure-flow coefficients  
\( f \) = frequency  
\( F_D \) = damper force  
\( p \) = absolute and homogeneous pressure in the fluid container  
\( q, q^{-1} \) = volumetric flow rate, inverse of the function \( q \)  
\( \text{sign}(\cdot) \) = signum function  
\( T \) = fundamental period  
\( t \) = time  
\( V \) = volume of the fluid chamber  
\( \dot{V} \) = auxiliary volume function  
\( xR \) = number of the cycles per one revolution  
\( x_v \) = valve spool displacement  
\( y_p \) = piston displacement  
\( W_{(i,j)} \) = work done per one cycle with \( j \)th excitation frequency and \( i \)th phase shift  
\( \beta \) = isothermal tangent compressibility of the hydraulic fluid  
\( \Delta p \) = pressure difference due to pressure losses  
\( \rho \) = density of hydraulic fluid  
\( \varphi \) = phase difference between damper piston and valve spool harmonic motions  
\( \omega \) = angular frequency of harmonic damper piston excitation  
\( |\cdot| \) = absolute value

I. Introduction

This paper provides analytical and experimental studies of a hydraulic damper in a periodic operational regime. The studies are presented as a combination of laboratory experiments and simulations, with correlation studies between the two. The subject of the current study is a modified industrial hydraulic damper. The motivation behind this work is the improvement of our understanding of the operation of semiactive hydraulic dampers in periodic working conditions. These conditions are relevant to structural components located in systems exposed to sustained periodic excitation. These conditions are often induced in rotating systems such as rotors. One approach to damper modeling is low-order physics-based modeling. This approach is useful, particularly in systems covering or interacting with domains other than fluid, e.g., mechanical or electrical domains. Hydraulic system modeling is often applied in these contexts [1]. This approach abstracts the system into a lumped one-dimensional dynamic system. Semiactive dampers are particularly apt candidates for this modeling approach. Semiactive damping technology [2] is increasingly applied in many industrial applications. Various conceptual approaches to semiactive vibration control have been studied in the past. The classical approach is represented by hydraulic semiactive dampers with controllable flow restrictors [2–5]. However, other alternative and novel approaches have been investigated recently, including dampers using the properties of electrorheological [6] and magneto-rheological [7,8] fluids, dampers with combinations of magnetorheological fluids and elastomeric materials [9], Coulomb friction dampers [10], damping systems with magnetized particles [11], and colloidal dampers by using water-based ferrofluids [12]. The range of applications of these controllable devices spans early applications in car suspension systems [2], civil engineering applications [3,4], and aerospace vibration and damping augmentation systems [5,8–10,13]. The classical approach to semiactive hydraulic damping is studied here. This topic was discussed in theoretical terms in [14]. The general working context can be associated with the steady operation of rotating machinery [15] or helicopters [16,17]. The research presented in this paper is a continuation of the investigations.