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A method for the identification of hydraulic damper characteristics from steady velocity inputs

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ABSTRACT

The research presented in this paper investigates the possibility of precise experimental identification of steady damper characteristics. The paper considers velocity sensitive and nominally symmetric hydraulic dampers. The proposed identification methodology is based on a piecewise constant velocity excitation. One goal of the paper is to analyze the transient nature of the damper response in the context of finite permissible piston displacements and first order transient effects due to elastic elements in the damper structure. The proposed methodology is formalized in a framework suitable for experimental design, allowing the detailed study of steady state damper performance. The second goal of the paper is to demonstrate the practical application of the proposed methodology. It is applied to the case of a safety critical hydraulic damper used for stability augmentation in production helicopters. The research work presented shows that this methodology can be used for identification in a finite but relatively wide range of piston velocities. The case study demonstrates a successful example of damper property identification where the resulting characteristics prove useful as a tool for model validation. Finally, the identification results are related to the results of a more traditional test with harmonic piston excitation.

1. Introduction

It is shown in the published literature, for example [1–3], that complex fluid dynamics phenomena occurring in hydraulic dampers can be, in the low frequency range (from 0 to 30 Hz according to Duym [4] and Yung and Cole [5]), efficiently modelled on the basis of hydraulic system theory, described in Ref. [6]. This theory addresses first order dynamic effects observed particularly in the damper velocity-force characteristics in the form of the "hysteretic" loops. These loops are manifestations of the internal dynamic relationships and the physical effects occurring typically in high-pressure hydraulic systems, [7,8], which include fluid compressibility [6], fluid inertial effects [9] and other dynamic effects. Hydraulic system theory can accommodate these effects during the modelling process and it has traditionally been used in the damper and hydraulic actuator modelling communities for the last few decades, [1,10]. Moreover, this theory is amenable to other physical domains such as mechanical [11] and thermal domains [12]. Also, it is often used in the context of multi-disciplinary [13] and mechatronic studies [14].

Important elements in hydraulic system modelling are steady state models of the flow transporting or restricting elements such as pipes, valves, orifices or leakage paths. Characterisation of these elements was a traditional field of

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Nomenclature

A_O	cross-sectional area of the orifice
A_P	cross-sectional area of the symmetric piston
B	constant isothermal bulk modulus of a hydraulic fluid
B_{eff}	effective bulk modulus
B_G	gas or air bulk modulus
C_α	coefficient of the general exponential pressure-flow model
C_D	discharge coefficient
c_i	coefficient of the general polynomial pressure-flow model
c_1,c_2	coefficient of the laminar and turbulent pressure-flow models
D_L,D_Q	coefficient of the linear and quadratic force–velocity damper model
d	normalised piston stroke
d_C	mean diameter of the damper cylinder
E	Young's modulus of the damper cylinder material
F_D	damper force
$\tilde{F}_D^{\pm}$	identified steady level of the overall damper force
$F_{D,h}$	hydraulic component of the damper force
F_f	friction force
f^{-1}	inverse function to function f
G_1,G_2,G_3	laminar, turbulent and laminar–turbulent pressure differential convergence coefficients
h_C	wall thickness of the damper cylinder
K_1,K_2	coefficients of the damper model representing Maxwell viscoelastic unit
k_C,k_P	stiffnesses of the cylinder and piston damper attachment points
k_i	ith exponent in the polynomial pressure-flow model
l_O	orifice pipe length
m_P	mass of the damper piston
N_F	number of flow paths between the damper chambers
N_j	number of pressure reducing segments in jth flow path
N_S	number of polynomial terms in the polynomial pressure-flow model
N_V	number of test points
p,$\mathcal{P}$	absolute and homogeneous pressure
p_i	pressure in ith damper fluid chamber
Q	volumetric flow rate
Q_j	flow rate through jth flow path
$Q_{j,k}$	flow rate through kth pressure reducing segment located in jth flow path
Q_β,Q_N,Q_P	flow rates due to fluid compressibility, flow transfer and piston displacement
$R(d)$	function of normalised piston stroke and piston starting position
T	time interval
$T^{\pm}$	positive and negative slope half-periods for the time interval T
T_{max},T_{lim}	maximum test time and limit test time for the damper piston travel
T_R	relaxation time
t	physical time
V	lumped volume of the hydraulic fluid
V_C,V_G	volume of the container and the total volume of the gas or air entrapped in the container
$V_{0,i}$,V_i	initial and variable volume of ith hydraulic chamber
$\mathcal{V}$	composite volume function
W_P	constant piston velocity
Y_P	amplitude of the triangular piston excitation
y_P,$\dot{y}_P$,$\ddot{y}_P$	piston displacement, velocity and acceleration
α	exponent in the exponential pressure-flow model
β	fluid compressibility factor related to the fluid bulk modulus, $\beta=1/B$
$\beta_{0,F}$,β_{eff}	nominal and effective fluid compressibility
Δp	pressure difference between two damper chambers
Δp_j	pressure difference in jth flow path
$\Delta p_{j,k}$	increment in the pressure difference in jth flow path due to kth pressure reducing segment
μ	dynamic fluid viscosity
ρ	density of hydraulic fluid
ϕ	normalised pressure difference
$\varphi(\Delta p)$	adjusted measure of the pressure difference
φ_P	phase of the triangular piston displacement excitation
Ω	angular frequency of triangular piston excitation
$\mathcal{E}(\circ)$	auxiliary function for the triangular waveform generation
tri $(\circ)$	function generating the triangular waveform
$\lvert \circ \rvert$	absolute value

experimental hydraulic studies [15,16], and recently also computational fluid dynamics investigations (e.g. [17]). Another important element in hydraulic system modelling describes the transient or dynamic effects in hydraulic systems, for instance those caused by fluid compressibility and other elastic effects [6]. The combination of the two basic elements mentioned is usually used along with the laws of conservation to provide system dynamic equations, with pressures frequently representing the dynamic states (for example Refs. [2,3,9–11]).

The goal of this paper is to evaluate a framework for experimental characterisation of damper behaviour. The approach adopted here focuses on the characterisation of velocity-sensitive hydraulic dampers. Semi-empirical characterisation of the components is known to be used in hydraulic system modelling. For example, Ferreira et al. [18] applied this approach in the case of static and dynamic servo-valve modelling and Hayashi et al. [19] used an experimentally determined and parameterised representation of the relief valve discharge coefficient. In the current paper, a similar approach is used to address the problem of damper modelling.