LAG DAMPING STUDY OF A VIBRATION CONTROL SYSTEM WITH SEMI-ACTIVE VALVE LAG DAMPERS AND INNER FORCE CONTROLLERS

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Abstract

This paper investigates the changes in the damping associated with the active vibration controller using semi-active valve lag dampers together with inner controllers to improve over force tracking capabilities. Although the technique has proven successful with vibration reduction levels in the cockpit decreased by up to 50%, there have not been investigations on accepted damping losses in order to ensure safe operation when the vibration scheme is enabled The scheme presented in this work is designed for the five-blade rotor-fuselage system of the EH101 helicopter. Investigations are carried out for different flying forward speeds. Damper loads versus piston velocity profiles differ significantly when the controllable orifice of the damper is operated in a fixed manner to when it is operated by means of the inner-loop force controller. Damping measurements at steady-state during part of the working cycle where the behaviour in slightly linear shows that the damping in this region is not reduced by upto 30% approximately for low and medium forward flying speeds (40-80 knots). For higher speeds, a more comprehensive test is required.

1 Introduction

Conventional hydraulic dampers are found in articulated rotors between the main rotor blades and the rotor hub. They are required to deliver high damping levels in order to avoid resonance instabilities encountered during operations over ground (ground resonance), slope landing and high-g manoeuvres [4]. A drawback of such dampers is their lack of adaptability in providing lower damping levels in cruise flight conditions in order to reduce undesirable loads as well as to avoid large damping forces and hence extend the life of the damper itself, their mechanical interfaces and other mechanical components. One current line of research in vibration control investigates the use of so-called semi-active valve lag dampers (SAVLDs), which are able to adapt the level of damping by manipulating the flow of hydraulic fluid between the damper chambers via a controllable valve and thus improve over the afore-mentioned disadvantages. SAVLDs are easier to manufacture and more adapted to deliver high damper forces than magnetorheological fluid-elastomeric dampers [6] designed for similar purposes. In addition, vibration control systems via SAVLDs require less power than pitch-rod links [5] and do not increase the complexity of the blades' structural design, unlike the use of active trailing edge flaps [1, 3], or other active devices which are mounted along the rotor blades. Control vibration via semi-active dampers was initiated with the work of Anusonti-Inthra et al [2]. In their work, the authors carry out a sensitivity study showing that stiffness variation of root elements can reduce hub vibrations, and hence vibration propagation across the helicopter fuselage.

Recent vibration control studies for the five-blade EH101 helicopter [12, 11] have shown that semi-active lag dampers can be used satisfactorily together with Higher Harmonic Control (HHC) laws [7] in order to gain vibration alleviation benefits. HHC algorithms are developed on the representation of the main rotor as that of a linear quasi-static model constructed in the frequency domain which is applicable during steady-state forward flight conditions. The control policies are constructed from the information of vibration sensors strategically located either across the fuselage of the helicopter or on the main rotor hub and thus avoid vibration propagation to the fuselage. The damper, which this work is constructed upon, was proposed by Titurus and Lieven and preliminary studies show that it is very well suited to work under periodic environments [15]. The vibration reduction technique is based on the design of a local controller in order to achieve a satisfactory level of tracking between delivered damper forces and those forces requested by a higher-hierarchy vibration control algorithm in the face of significant disturbances. Although the technique has proven successful with vibration reduction levels in the cockpit decreased by up to 50%, there have not been investigations on accepted damping losses in order to ensure safe operation when the vibration scheme is enabled. Such a limitation might affect the achieved levels of vibration reduction. This work address this important safety aspect and carries out an investigation of the damping levels when the vibration control scheme is on and compare them with the results when no control is implemented. Investigations show that damper behaviour differ significantly when the vibration control scheme is on and that due to the highly non-linear characteristics of the damper, damping reading are not straightforward to obtain. However, conservative measurements suggest that about 30% of the working cycle, the corresponding damping factor is not significantly different to that with no vibration control hence suggesting that the vibration control scheme is safe to implement mainly at forward speeds between 40 and 80 knots.

This manuscript is structured as follows. Section 2 provides a brief description of the overall control vibration reduction scheme and their main elements. In this section, descriptions of the behaviour of the semi-active valve lag damper are provided together with the control schemes which provides the SAVLD with force tracking capabilities. In this section brief descriptions of the inner SAVLD controller and the HHC control algorithms are provided. Section 3 provides the study of the damping in steady-state forward flight conditions at speeds between 40 and 120 knots. Description of conservative damping estimations and typical damper loads-velocity characteristics are investigated in this section. The works concludes with some final remarks in Section 4.

2 The Overall Control Architecture

The overall architecture of the vibration control strategy using semi-active valve lag dampers is shown in Figure 1. The architecture consists of two hierarchic layers. The outer loop is concerned with the design of a *vibration controller* aiming at reducing vibrations based on a model of the main rotor vibratory system. The vibration controller uses the information collected through vibration sensors (typically accelerometers) and determines the damper forces (r) that need be delivered by the SAVLD (y). An inner feedback loop is added in order to improve the tracking performance of the damper forces. Although there exists alternative control configurations which do not incorporate an inner SAVLD control loop [4], such strategies are expected to provide a lower performance as they do not compensate against uncertainties, nonlinearities and external disturbances found in the SAVLD system.

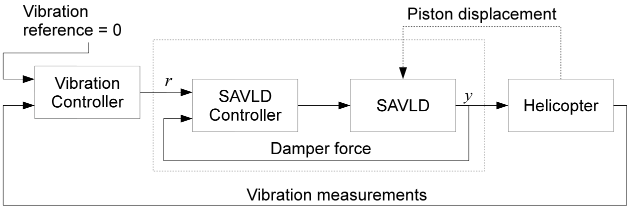

Figure 1: Overall architecture for vibration helicopter control using SAVLDs.

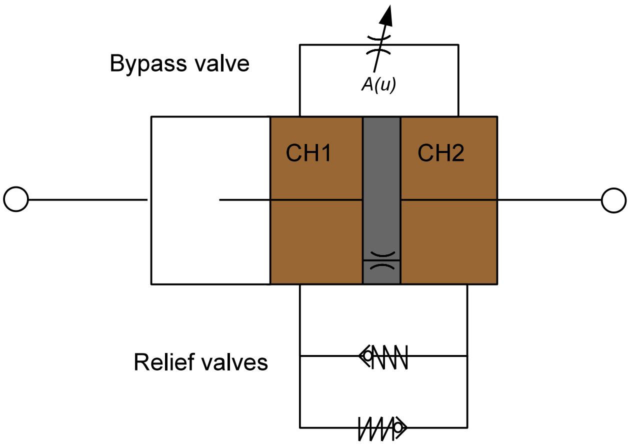

Figure 2: Schematic of the semi-active valve lag damper.

The following subsections provide brief information about three of the main elements of the vibration control system: the SAVLD, the SAVLD controller and the vibration controller.

2.1 The Semi-Active Valve Lag Damper

The semi-active valve lag damper considered in this work was introduced in [15]. The damper has been designed to work in periodic environments and a model for such a damper has been developed in this manuscript. Each damper located in the blade root region consists of two chambers (CH1 and CH2) filled with hydraulic liquid with one end attached to the rotor hub and the piston attached to each of the main rotor blades. An schematic of the internal structure of the damper is illustrated in Figure 2.

The bypass valve allows to manipulate the fluid between the chambers and provides the semi-active characteristics by a corresponding manipulation of the damping. The relief valves are activated when the pressure in one of the chambers reaches a certain level and hence avoid over-pressurisation within the damper. Notice that each of the relief valve allow the fluid to flow only in one direction. The relief valves become active during a small fraction of the working cycle and therefore a simpler state-space description, whereby the effects of the relief valves are not taken into account, can be obtained as shown below:

$$\begin{array}{rcl} \dot{x}(t) & = & B_o\left(\frac{1}{V_1(d(t))}+\frac{1}{V_2(d(t))}\right)(A_P\dot{d}(t)- \\ & & (\alpha_1+\alpha_2 u(t))\sqrt{|x(t)|}\mathrm{sign}(x(t))) \\ \dot{V}_1(t) & = & -A_P\dot{d}(t) \\ \dot{V}_2(t) & = & A_P\dot{d}(t) \\ y(t) & = & A_P x(t) \end{array} \tag{1}$$

where

- $x(t)$ is the pressure difference across the piston.
- $y(t)$ is the damper force induced by the forced movement of the piston.
- $d(t)$ and $\dot{d}(t)$ denote the piston's position and velocity, respectively.
- $u(t)$ is the input which operates the controllable orifice area of the bypass valves.
- $V_1(d(t))$ and $V_2(d(t))$ denote the volumes of the two working chambers of the damper.
- B_o is a constant associated with the fluid within the damper.
- A_p stands for the cross-sectional area of the piston.
- The parameters α_1 and α_2 are defined as

  $$\alpha_1 = C_{Do}A_o\sqrt{\frac{2}{\rho}} \tag{2}$$

  $$\alpha_2 = C_{DA}k\sqrt{\frac{2}{\rho}} \tag{3}$$

  C_{Do} and C_{DA} denote the flow discharge coefficients for the flows through the piston orifice and the bypass orifice, respectively. ρ is the fluid density and A_o is the cross-sectional area of the piston orifice. k is the slope of the linear approximation between the effective area of the bypass valve and the spool position $u(t)$.

The above description is valid for mixed flow models when the pressure difference $x(t)$ can be expressed as a memoryless directional quadratic function of the volumetric flow rate through the piston orifice and the orifice of the bypass valve, see [15] and [10]. For more details on the description of the semi-active valve lag damper, refer to [11].

2.2 The SAVLD Controller

The SAVLD controller used in this manuscript is designed in [12] and [11]. The control strategy is based on a simpler representation of the SAVLD dynamics which captures the main nonlinearities in the behaviour of the damper. Such a reduced representation brings the benefit of facilitating the control design task. Based on such a reduced model, a strategy known as Nonlinear Dynamic Inversion (NDI) [9] is applied in order to linearise first the open loop behaviour by means of a state feedback law. Once the nonlinearities have been significantly reduced (even under ideal modelling conditions, the nonlinearities found in the dynamics of the SAVLD can not be completely removed via state feedback), standard linear control design techniques are implemented to provide the benefits of feedback control [14]. The control law obtained after following such an strategy is described below:

$$u(t) = -k_N\sqrt{|x(t)|}\left(\frac{r(t)\,\mathrm{sign}(x(t))}{\epsilon_N+|x(t)|}-A_p\right) \tag{4}$$

The controller design parameters to be tune are k_N and ϵ, with both being positive. Despite the high nonlinearity of the SAVLD, good levels of force tracking can be achieved. Different values of the parameter k_N sets different levels of tracking of the reference harmonics and it was found that values which requires less control input usage lead to better vibration reduction. The inner control strategy is found to perform satisfactory and when implemented with the vibration controller, vibration levels were reduced by as low as 50%. For more information about the tuning of the controller parameters, the reader is referred to [12] and [11].

2.3 The Vibration Controller

The implemented vibration controller follows the conventional Higher Harmonic Control algorithm [7]. The vibration controller is constructed upon the assumption that the relation between the vectors containing the Fourier coefficients of the main harmonics in the vibratory signal ($\bar{v}$) and the coefficients of the main harmonics in the desired damper forces ($\bar{r}$) is linear:

$$\bar{v}(k) = T\,\bar{r}(k) + \bar{w}_0 \tag{5}$$

The harmonics considered for the 5-blade main rotor of the EH101 helicopter are placed at 4Ω, 5Ω, and 6Ω, with Ω denoting the blade passage frequency in rad/s. The above frequency-domain-based model is valid during steady-state cruise flight conditions. $\bar{w}_o$ is introduced to take into account a constant external disturbance representative of the helicopter operating conditions. The matrix $T = \partial\bar{v}/\partial\bar{r}$ is known as the sensitivity matrix. $\bar{w}_0$ can be obtained from reading the response to a zero input $r(t) = 0$ and T can be obtained by exciting the system with known inputs at the harmonic of interest and estimating the coefficients via least squares [4].

The sampling time of the discrete-time process is usually chosen so the update of the control actions and readings of the vibrations is done at multiples of the blade passage period $t_k = k\ (N\Omega/(2\pi))$, where $N \geq 1$. N is chosen large enough to ensure that the system has reached steady-state conditions before implementing the following control actions.

Defining the following performance index

$$J(k) = \bar{v}(k)^T Q \bar{v}(k) + \bar{r}(k)^T R \bar{r}(k)^T \tag{6}$$

with matrices Q and R being positive definite, the following control actions are chosen

$$\bar{r}^* = -\left(T^T Q T + R\right)^{-1} T^T Q \bar{w}_o \tag{7}$$

so $J(k)$ is minimised. Note that the cost function J is chosen to encapsulate the energy levels of both the vibrations and the control efforts. By choosing appropriate weights Q and R, the designer trades off between achieved performance (vibration reduction) and control input usage. For more information about the robustness properties and variants of the HHC algorithm, refer to [13].

3 Damping Analysis in Forward Steady-State Flying Conditions

Damping studies have been carried out for operation of semi-active valve-lag dampers in HHC systems without an inner loop force controller [4]. The purpose in this section is to investigate damping variations when operating the controllable orifice valve via the inner control system for improvement of force tracking capabilities. The results shown below are the same as those presented in [11]. The results are obtained via the comprehensive simulation environment CRFM [8] developed by AgustaWestland. The model simulates the behaviour of the EH101 helicopter with 5 blades operating at cruise flying conditions and includes the dynamics of the rotor-fuselage system. The vibration technique is assessed via accelerometers places strategically across the cockpit. The SAVLD controller has been incorporated into the CRFM model in order to assess the success of the vibration technique.

For small piston displacements and velocities, the associated damping factor can be estimated as the ratio between the damper force and the piston velocity:

$$c = -\frac{\partial y}{\partial \dot{d}} \tag{8}$$

A simple analysis suggests that under no significant changes in the stiffness and mass of the corresponding spring-mass-damper representation associated with in-plane motions of the damper-blade system, relative reductions in the damping ratio can be estimated as follows:

$$\Delta\zeta = \frac{c_{\text{on}} - c_{\text{off}}}{c_{\text{off}}} \tag{9}$$

The subscripts *on* and *off* indicate the ratio between changes in the damper force and changes in the piston velocity when the inner force controller is activated and disabled, respectively. When the control strategy is disabled, the input of the controllable orifice area is fixed at zero (the corresponding orifice area of the controllable valve is not zero, but very small, due to parasitic flows, see [15]). A negative(positive) value of $\Delta\zeta$ indicate a relative reduction (increase) in the damping ratio when the inner control loop is activated with respect to the damping ratio when the inner control loop is disabled. Typical damper characteristics which illustrates the damper loads versus the piston velocity are shown in Figures 3 - 7 for several forward flight speeds. The plots are obtained for one rotor revolution once steady-state conditions have have been reached for each operating condition.

It is observed that when the vibration control scheme is operating, the force-velocity characteristics differ significantly from those without the inner controller. Indeed, the nonlinearities of the inner loop are evident suggesting that a representative damping factor is difficult to obtain. The behaviour of the damper force seem to differ much more from that of an idealised damper as the flying speed of operation is increased, particularly above 100 knots. It is noticed however that for normalised damper velocities in the range $0.4 \leq \dot{d} \leq 0.6$ and flying speed between 40 and 80 knots, the behaviour is slightly linear and measurements of $\Delta\zeta$ can be obtained. Comparing the slopes of the force-velocity plots in this speed range, it is noticed that the damping is not significantly different, suggesting that enabling the vibration control system does not compromise the damping obtained in these flying conditions. A quantitative analysis provides that at 40 knots, the damping ration is descreased by around 30% and suprisingly, increased at 60 and 80 knots. At 100 and 120 knots the behaviour is significantly less linear for such relative piston velocities hence a more comprehensive tests would be require to determine whether the losses in damping could be dangerous.

4 Concluding Remarks

This paper has considered the damping of an active vibration control scheme with inner force controllers. The inner force controller was expected to

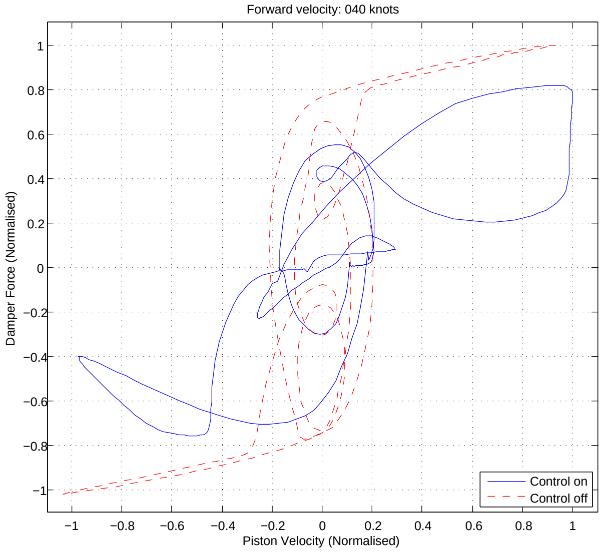

Figure 3: Normalised Force-velocity characteristics with and without the inner force tracking control system operating at 40 knots in steady-state forward flying conditions.

improve over the highly nonlinear characteristics of the damper, however as shown by the damping analysis, it is still difficult to obtain good estimation of any damping losses when the active control is activated. The variation of damper loads versus piston velocity profiles differ significantly when the controllable orifice of the damper is operated in a fixed manner to when it is operated by means of the inner-loop force controller. Damping measurements at steady-state conditions during part of the working cycle where the behaviour in slightly linear shows that the damping in this region is decreased by upto 30% approximately for low and medium forward flying speeds (40-80 knots). For higher speeds, a more comprehensive test is required.

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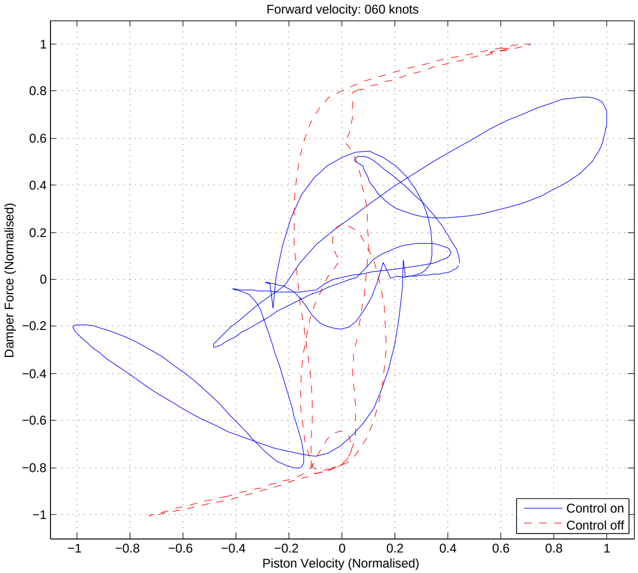

Figure 4: Normalised Force-velocity characteristics with and without the inner force tracking control system operating at 60 knots in steady-state forward flying conditions.

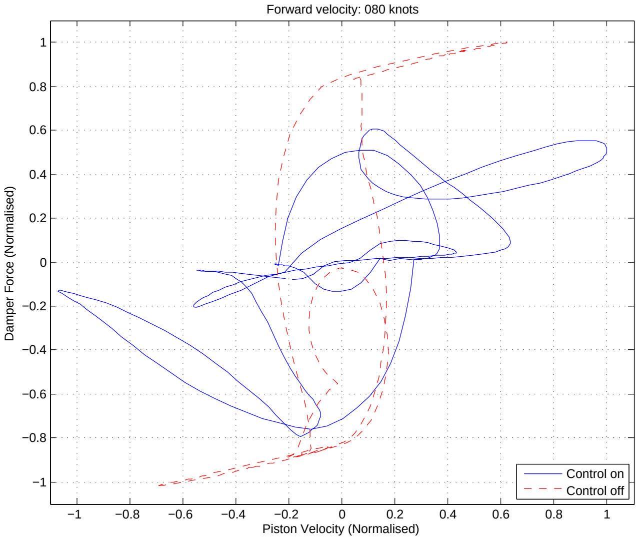

Figure 5: Normalised Force-velocity characteristics with and without the inner force tracking control system operating at 80 knots in steady-state forward flying conditions.

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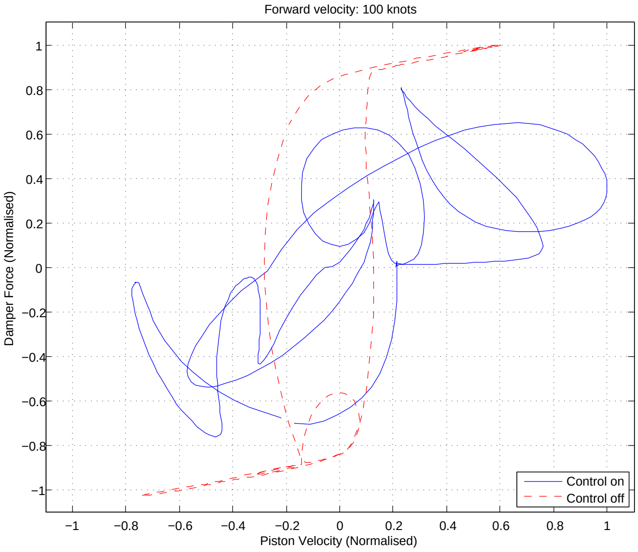

Figure 6: Normalised Force-velocity characteristics with and without the inner force tracking control system operating at 100 knots in steady-state forward flying conditions.

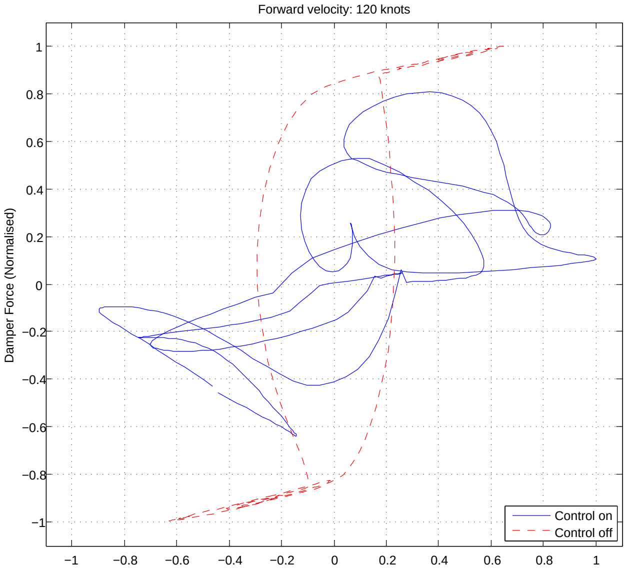

Figure 7: Normalised Force-velocity characteristics with and without the inner force tracking control system operating at 120 knots in steady-state forward flying conditions.

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