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Using continuation analysis to identify shimmy-suppression devices for an aircraft main landing gear

Yuan Li, Chris Howcroft, Simon A. Neild, Jason Zheng Jiang *

Faculty of Engineering, University of Bristol, Bristol BS8 1TR, UK

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ABSTRACT

This paper considers several passive shimmy-suppression devices for a dual-wheel main landing gear (MLG) and proposes a method of selecting the device parameter values for which no shimmy occurs. Two of these devices include an inerter, a novel mechanical element with the property that the applied force is proportional to the relative acceleration between its terminals. A nonlinear mathematical model is developed to represent the MLG dynamics. A bifurcation study is then carried out to investigate the effects of the shimmy-suppression devices on the gear steady-state response. The aircraft forward speed and the device damping are chosen as the continuation parameters. A range of device parameter values that ensure the aircraft is free from shimmy instability for any forward speed within its operating region are identified. It is shown that the use of a proposed spring-damper configuration can result in a more robust device in terms of the device damping over that of a conventional shimmy damper. Two inerter-based shimmy-suppression devices are then considered and yield further benefits on expanding the zero-shimmy regions in the two-parameter bifurcation diagrams.

1. Introduction

The landing gear of any civil aircraft is required to be free from excessive vibrations and any dynamic instabilities over a conservative range of operating conditions [1]. A key source of such vibrations or instabilities is the phenomenon called shimmy. In the design process, the demand for suppressing shimmy instability may impose several design constraints on the structural stiffness and geometry of landing gear [2]. However, if modifications to geometry, stiffness or weight are infeasible or undesirable, a shimmy damper is often introduced to alter the response [3]. Normally passive dampers are used to suppress shimmy oscillations. However alternatives are available. For example, it has been proposed that the control orifice, present in some nose-gear hydraulic steering actuators, can be used to suppress shimmy [4]. Typically the shimmy damper is modelled as a damping coefficient in parallel with the gear torsional stiffness [5]. Recently, studies have proposed semi-active or active shimmy-suppression strategies, such as using fuzzy adaptive control [6], magnetorheological damping [7], and sliding mode control [8]. However, while such semi-active or active controllers outperform passive ones, passive devices do have some advantages. They are typically simpler, requiring no power source, and are unconditionally stable. For example, under some circumstance when the electrical power is lost, the powered active damping systems may fail to function. So current shimmy-suppression methods are typically still passive shimmy dampers [8].

* Corresponding author.
E-mail address: z.jiang@bristol.ac.uk (J.Z. Jiang).

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Concentrating on passive solutions, studies have been reported in which the performance of various passive devices have been assessed in conjunction with linear gear model, see for example [1,9,10]. In this paper, a method of selecting the network layout and parameter regions for shimmy-suppression devices is proposed. This method ensures no sustained shimmy oscillations will occur over the aircraft operating velocity range. This approach is different from previous design methods in the literature and is applicable to different mechanical structures, for example, the lag damper for helicopters.

Firstly a passive device consisting of a linear spring and damper in parallel (which we term the *shimmy damper*) is considered. The response of a dual-wheel MLG equipped with this shimmy damper is assessed. Then we investigate the effects of a proposed layout which adds a linear spring in series with the shimmy damper. In addition, configurations which include an inerter will be considered. The inerter is a commercially-available component, first proposed by Smith [11], that generates a reaction force proportional to the relative acceleration between its two terminals. It completes the analogy between mechanical and electrical systems, allowing a wide range of passive absorber structures to be realised by mechanical networks. Performance advantages of suppression devices that include inertance have been identified for various systems, including vehicle suspensions [12,13], motorcycle steering systems [14], building vibration-suppression systems [15,16] and railway suspensions [17,18]. The effects of the inerter on landing gear shimmy behaviour have been reported in [19,20], with [20] discussing the advantages of inerter-based shimmy-suppression configurations in terms of landing gear transient response.

The MLG steady-state response will be analysed using a nonlinear low-order model in this work. Here the tyre will be modelled using the exact stretched-string formulation [21], an extension of the model proposed by Von Schlippe and Dietrich in [22]. For the representation of the landing gear structure, the torsional motion is a vital consideration in capturing the shimmy mechanism, see [23] for example. Since real landing gear systems exhibit various nonlinearities, the nonlinear dynamics of landing gear have attracted significant research interest. One approach to studying the gear's nonlinear response is to use a bifurcation analysis [24]. In [25,26], Thota et al. performed a bifurcation study to investigate the effects of the geometric nonlinearity raised by a non-zero rake angle. They found that a lateral bending motion becomes coupled with the torsional motion. Further examples of bifurcation analysis applied in nonlinear systems can be found in [27–30] where [28–30] focused on aircraft shimmy analysis in particular. Other analytical analyses have been conducted in the literature to investigate the nonlinear aircraft shimmy problem, based on the techniques of perturbation analysis [31] and the incremental harmonic balance method [32].

In this paper, we investigate the influences of the passive shimmy-suppression devices on the MLG steady-state response via continuation analysis. In Section 2, a nonlinear mathematical model of a typical MLG configuration reported in [28] is discussed. In Section 3, a passive device consisting of a linear spring and damper in parallel (the shimmy damper) is considered. A bifurcation study is carried out using the continuation software AUTO [33], which is integrated into a Matlab environment via the Dynamical Systems Toolbox [34]. This allows us to identify the device parameter region in which no sustained shimmy oscillations occur over the entire operating speed range. This region in parameter space will be defined as the *zero-shimmy region*. A beneficial shimmy-suppression device with spring-damper layout is introduced, and its ability in expanding the zero-shimmy region are assessed. Based on this layout, two inerter-combined devices are proposed in Section 4. Their effects on the bifurcation diagrams are then studied and the performance advantages discussed. Finally, in Section 5 we draw some conclusions.

2. Main landing gear shimmy model

In this section, a typical dual-wheel MLG system reported in [28] is considered and the formulation of a low-order mathematical model of the MLG is presented. The MLG motion is modelled in terms of two degrees of freedom (DOFs); the gear torsional rotation and the lateral bending. The dynamics of the shimmy-suppression device and elastic tyres are also considered.

2.1. Dynamics of a MLG system

A sketch of the dual-wheel MLG is shown in Fig. 1 from different views. A global frame O *XYZ* is used here, which is fixed to the ground. The *X* axis points in the aircraft direction of travel, the *Z* axis vertically downwards, and the *Y* axis completes the right-handed coordinate system. The MLG consists of a main strut, side-stay, torque links, axle assembly connected with two wheels, etc. The top of the MLG is attached to the aircraft fuselage at the point A. We consider a typical orientation of the side-stay here, which is mounted laterally with respect to the main strut and is attached to the fuselage at the point F, as illustrated in Fig. 1(a). The main strut which is inclined to the *Z* axis by a non-zero rake angle ϕ is constructed of two cylinders or tubes. To keep the alignment of the wheels, a pair of torque links is employed, with the upper link attached to the upper strut cylinder and the lower one to the lower cylinder (piston), see Fig. 1(b). The end point of the piston is labelled C and the wheel axle is offset from the point C via a caster of length *e*.

As can be seen from Fig. 2(a), a body frame B $\xi\eta\zeta$ is used in order to describe the dynamics of the MLG system in the disturbed state. The axis ζ is rotated from the *Z* axis along the *Y* axis by the rake angle ϕ, and is aligned with the strut axis. The axis ξ is parallel with the caster while the axis η completes the right-handed coordinate system. With a radius l_δ, the lower gear is allowed to bend laterally about point B along the ξ axis by the angle δ to represent the lateral compliance of the gear. We consider k_δ and c_δ to capture the structural stiffness and damping of such lateral motion. The gear below point B has