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Passive suppression of helicopter ground resonance using nonlinear energy sinks attached on the helicopter blades

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ABSTRACT

This paper investigates the passive control of a rotor instability named helicopter Ground Resonance (GR). The passive device consists of a set of essential cubic nonlinear absorbers named Nonlinear Energy Sinks (NES) each of them positioned on a blade. A dynamic model reproducing helicopter GR instability is presented and transformed to a time-invariant nonlinear system using a multi-blade coordinate transformation based on Fourier transform mapping the dynamic state variables into a non-rotating reference frame. Combining complexification, slow/fast partition of the dynamics and averaging procedure, a reduced model is obtained which allowed us to use the so-called geometric singular perturbation analysis to characterize the steady state response regimes. As in the case of a NES attached to the fuselage, it is shown that under suitable conditions, GR instability can be completely suppressed, partially suppressed through periodic response or strongly modulated response. Relevant analytical results are compared, for validation purposes, to direct integration of the reference and reduced models.

1. Introduction

A Nonlinear Energy Sink (NES) is a passive nonlinear absorber which introduces nonlinear coupling between the main structure and the absorber for controlling the vibratory response of the structure under external excitation. A NES consists of a nonlinear oscillator with an essentially nonlinear restoring force and generally a small mass compared to the main structure. The objective of the NES is to capture the energy of the main structure and to dissipate it. This is done through the Targeted Energy Transfer (TET) concept. TET is based on the capacity of the essential nonlinear oscillator to be resonant at any frequencies giving possible tuning with the main structure to be controlled. TET has been widely studied in the literature [1–4].

NES also represents an alternative device for control systems with self-excitation. The possible suppression of the limit cycle oscillations of a van der Pol oscillator coupled to a NES is demonstrated numerically in [5] and the self-excitation response regimes are investigated theoretically in [6] where an asymptotic analysis of the system related to slow/super-slow decomposition of the averaged flow reveals periodic responses, global bifurcations of different types and basins of attraction of various self-excitation regimes. A series of papers [7–10] are dedicated to aeroelastic instability. It is demonstrated that a

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NES coupled to a rigid wing in subsonic flow can partially or even completely suppress aeroelastic instability. The suppression mechanisms are investigated numerically in [7] and [9] for one and multi-DOF NES respectively. Several aspects of the suppression mechanisms are validated experimentally in [8]. Finally an asymptotic analysis is reported in [10] demonstrating the existence of the three passive suppression mechanisms based on TET. Suppression of aeroelastic instability of a long span bridge model is also considered in [11] whereas [12] is dedicated to a general class of nonlinear multi-degree of freedom system including aeroelastic forces. In [13,14] it is shown that a NES is able to quench chatter instability in turning process whereas in [15] the stabilization of drill-string systems is considered. Note that in [16], it is demonstrated that a nonlinear tuned vibration absorber possessing a linear spring and a nonlinear spring whose mathematical form is determined according to the nonlinearity in the host system can suppress limit cycle oscillations.

In this paper, we focus on the instability in helicopter rotor named Ground Resonance (GR) problem. GR is related to the coupling of the rotor blade in-plane motion with the airframe motion on its landing gear. The standard reference of the GR analysis is the paper by Coleman and Feingold [17] where it is established, considering an isotropic rotor, that GR is due to a frequency coalescence between a lag mode and the fuselage mode. The range of rotor speeds for which this frequency coalescence occurs is predicted analytically. More references can be found in [18–21] and a recent analysis of helicopter GR with asymmetric blades can be found in [22]. Traditionally, GR instability is prevented by increasing damping in the landing gear and blades [23,24]. A robustness analysis is discussed in [25]. Active control of GR has been also studied in [21].

The initial application of a NES to control GR instability was considered in [26,27]. A theoretical/numerical analysis of the steady-state responses of a helicopter model with a minimum number of degrees of freedom that can reproduce Helicopter Ground Resonance instability when a NES is attached on the fuselage in an ungrounded configuration was performed. The system was first simplified using successively Coleman transformation [17] and binormal transformation [23] followed by a complexification-averaging method together with geometric singular perturbation. Four steady-state responses are highlighted and explained analytically: complete suppression, partial suppression through strongly modulated response, partial suppression through periodic response and no suppression of the Helicopter Ground Resonance.

In this study, the same problem is considered but now the NES on the fuselage is removed and it is replaced by a set of NES, each of them been positioned on a blade. A similar configuration has been considered in [28,29] where the efficiency of NES on rotating part of a rotor has been analyzed under mass eccentricity force [28] and under an external forcing [29]. One of the advantages of this configuration is to reduce the weight due to the additional absorbers. Here, response regimes are investigated extending the theoretical/numerical analysis developed in [26] using a Fourier coordinate transformation as in [30]. In contrast to the Colman transformation, this multi-blade coordinate transformation can be easily combined with the complexification-averaging method together with geometric singular perturbation.

The next section introduces the helicopter model including a fuselage and four blades with a NES attached on each blade. Only one direction of the fuselage motion, the lag motion of each blade and the lag motion of each associated NES are considered. Based on Fourier coordinate transform, the model is reduced to a time-invariant nonlinear system involving complex variables. In Section 3, linear stability analysis is performed on this reduced model showing that this model is able to reproduce GR phenomenon. In Section 4, the analytical procedure [26] based on averaging method together with geometric singular perturbation theory is adapted to the reduced system. It is shown that it is able to characterize the situations for which trivial solution is unstable. In Section 5, numerical analysis is performed and discussed considering analytical results validated from direct integration of the reference model and the reduced model. Finally in Section 6, few words about the comparison between blade and fuselage NES attachments are expounded.

2. The model

2.1. Initial equations of motion

The helicopter model studied is shown Fig. 1. It consists of a fuselage and a 4-blade rotor rotating at a constant speed Ω. This model is very similar to that described for example in [18,19,21].

The fuselage is a simple mass–spring damped system with mass m_y, spring constant k_y, viscous damper of damping coefficient c_y and the translational DOF y. It is assumed that the center of inertia G_f of the fuselage at rest coincides with the origin O of the earth-fixed system of coordinates (O, x_0, y_0, z_0). Each blade is assumed to be a point mass $G_{\delta,i}$ (with $i \in [1, 4]$) with mass m_δ linked to the axis (O, z_0) with a bar without mass of length L_δ and an articulation with torsional spring k_δ and viscous damper of damping coefficient c_δ. Only lag motions of the blades, characterized by the lag angle δ_i (with $i \in [1, 4]$), are taken into account.

This simple model is used to study the effect of attaching a NES in ungrounded configuration on each blade of the helicopter (as shown in Fig. 2) in order to control lagging motion and consequently ground resonance instability.

Each NES is a nonlinear-spring mass damped system (see Fig. 2) with mass m_h at the mass point $G_{\varphi,i}$ (with $i \in [1, 4]$), linear spring constant k_{1h}, cubic spring constant k_{3h}, and viscous damper of damping coefficient c_h. Each NES is placed at distance L_φ from the axis (O, z_0) and it is characterized with only the lag angle DOF φ_i which is related to the relative displacement h_i by $h_i = L_\varphi \sin(\varphi_i - \delta_i)$.

Starting from the position of the center of inertia and the corresponding velocity of the i-th blade (respectively the i-th NES) in the plane (O, x_0, y_0), defined as