ENOC-2008, St. Petersburg, Russia, 1-4 July 2008

SUPPRESSION OF AEROELASTIC INSTABILITIES BY BROADBAND PASSIVE TARGETED ENERGY TRANSFERS

Young S. Lee
Department of Aerospace Engineering
University of Illinois, Urbana - Champaign
USA
yslee4@uiuc.edu

D. Michael McFarland
Department of Aerospace Engineering
University of Illinois, Urbana - Champaign
USA
dmmcf@uiuc.edu

Alexander F. Vakakis
Mechanics Division
National Technical University of Athens
Greece
vakakis@central.ntua.gr

Lawrence A. Bergman
Department of Aerospace Engineering
University of Illinois, Urbana - Champaign
USA
lbergman@uiuc.edu

Gaetan Kerschen
Department of Aerospace and Mechanical Engineering
University of Liege
Belgium
g.kerschen@ulg.ac.be

Abstract

We study passive and nonlinear targeted energy transfers induced by transient resonant interactions between an essentially nonlinear attachment and an in-flow rigid wing model. We show that it is feasible to partially or even completely suppress aeroelastic instabilities in the wing (limit cycle oscillations - LCOs) by passively transferring broadband vibration energy from the wing to the attachment in a one-way irreversible fashion. We study the nonlinear dynamical mechanisms that govern TET and show that they are series of transient or sustained resonance captures in different resonance manifolds of the dynamics. Aeroelastic instability suppression is performed by partially or completely eliminating the triggering mechanism for aeroelastic instability. Through numerical parametric studies we identify three main mechanisms for suppressing aeroelastic instability, and investigate them in detail, both numerically by Empirical Mode decomposition (EMD), and analytically by slow/fast partitions of the transient dynamics.

Key words

Targeted energy transfer, aeroelastic instability suppression.

1 Introduction

The triggering mechanism of limit cycle oscillations (LCOs) of a wing due to aeroelastic instability was studied recently [Lee et al., 2005]. It was shown that a cascade of resonance captures constitutes the LCO triggering mechanism. It was also concluded that an initial excitation by the flow of the heave mode acts as the triggering mechanism for the eventual activation of the pitch mode through nonlinear interactions involving the aforementioned resonance captures; the eventual excitation of the pitch mode signifies the excitation of the LCO.

In this work we study suppression of aeroelastic instabilities (LCOs) in a 2-DOF rigid wing model with an attached essentially nonlinear element, termed *nonlinear energy sink (NES).* We demonstrate (at least) three fundamental mechanisms of passive LCO suppression by means of targeted energy transfers (TETs), e.g., of one-way passive and directed vibration energy transfer from the wing to the NES, where this energy is localized and locally dissipated. We investigate the dynamical mechanisms that govern TET and study robustness of LCO suppression by bifurcation analysis.

2 Passive LCO Suppression Mechanisms

We consider the two-DOF rigid in-flow wing model integrated with a single-DOF NES in Figure 1. Assuming small motions and quasi-static flow, the equations of motion of the wing-NES assembly are given in [Lee et al., 2007]. There are two sources of nonlinearity in this system: the structural nonlinearities of the pitch and heave modes of the rigid wing (denoted by the nonlinear grounding stiffnesses in Figure 1), and the essential cubic stiffness nonlinearity of the NES. Moreover, the NES interacts not only with the heave mode, but also with the pitch mode through the offset d from the elastic axis of the wing.

First, We now perform computational parametric studies to identify parameter subsets where LCOs of the wing can be suppressed or even completely eliminated. Initial conditions close to the trivial equilibrium position are considered; e.g., we set all initial conditions equal to zero except for a small initial velocity of the heave mode [Lee et al., 2007].

Our methodology for performing the computational parametric study is as follows. We integrate the equations of motion for sufficiently long time to assure that transients die out. Then we compute the root-mean-square (r.m.s.) amplitude of the resulting steady-state response. Comparing the steady-state pitch (or heave) amplitudes in r.m.s. with and without NES attached, we may infer partial or complete LCO suppression.

The first mechanism for LCO suppression (cf. Figure 2) is characterized by *a recurrent series of suppressed burst-outs of the heave and pitch modes of the wing, followed by eventual complete suppression of the aeroelastic instabilities*. In the initial phase of transient burst-outs, a series of developing instabilities of predominantly the heave mode is suppressed by proper transient 'activation' of the NES, which tunes itself to the fast frequency of the developing aeroelastic instability; as a result, the NES engages in 1:1 transient resonance capture (TRC) with the heave mode, passively absorbing broadband energy from the wing, thus eliminating the burst-out. In the latter phase of the dynamics, the energy fed by the flow does not appear to directly excite the heave and pitch modes of the wing, but, instead, seems to get transferred directly to the NES until the wing is entirely at rest and complete LCO suppression is achieved. At the initial stage of the recurrent burst-outs, at time instants when the pitching LCO is nearly eliminated, most of the energy induced by the flow to the wing is absorbed directly by the NES with only a small amount being transferred to the heave mode, so that both the NES and the heave mode reach their maximum amplitude modulations. This is followed by suppression of the burst-out, and this process is repeated until at a later stage complete suppression of the aeroelastic instability is reached. The beating-like (quasi-periodic) modal interactions observed during the recurrent burst-outs turn out to be associated with Neimark-Sacker bifurcations [Kuznetsov, 1995] of a periodic solution and is critical for determining domains of robust LCO suppression.

The second LCO suppression mechanism (cf. Figure 3) is characterized by *intermediate or partial suppression of LCOs*. The initial action of the NES is the same as in the ¯first suppression mechanism; TET from the wing to the NES then follows under conditions of 1:1 TRC, followed by conditions of 1:1 sustained resonance capture (SRC) where both heave and pitch modes attain constant (but nonzero) steady-state amplitudes. We note that the heave mode response can grow larger than that in the corresponding system with no NES attached (exhibiting an LCO), at the expense of suppressing the pitch mode. In this case the action of the NES is nonrecurring, as it acts at the early stage of the motion stabilizing the wing and suppressing the LCO.

Finally, the third mechanism for LCO suppression (cf. Figure 4) is governed by a 1:1 TRC. Both heave and pitch modes as well as the NES exhibit exponentially decaying responses resulting in *complete elimination of LCOs*. In general, higher NES masses are required for complete elimination of LCOs.

As discussed in [Young et al., 2007] there are values of the NES parameters for which no LCO suppression occurs; on the contrary, the steady state amplitudes achieved by the wing may be larger than the corresponding values of the wing with no NES attached. This underscores the need for performing a careful study of robustness of passive LCO suppression to changes in initial conditions and system parameters.

3 Analysis by Empirical Mode Decomposition

In order to numerically prove that the basic underlying dynamic mechanism of instability suppression is a series of TRCs, we utilize the *Empirical Mode Decomposition (EMD)* introduced in [Huang et al., 1998]. EMD through a sifting process yields a collection of *intrinsic mode functions (IMFs)*, which are functions satisfying the following two conditions: (i) the numbers of extrema and of zero crossings of each IMF must either be equal or must differ at most by one in the entire data set considered; and (ii) the mean value of the two envelopes defined by the local maxima and local minima must be zero at any time instant. Note that an IMF can be both amplitude- and frequency-modulated; e.g., the IMF can be non-stationary. Once EMD is performed, the resulting IMFs are suitable for applying Hilbert transform, which yields the instantaneous amplitude and phase of each IMF at any given instant of time. By differentiating the instantaneous phase one computes the temporal evolution of the instantaneous frequency of each IMF, which, when compared with the WT spectrum of the corresponding time series, enables one to judge the relative contribution of each IMF in the time series and, thus, its relative importance in the decomposition of the signal.

We apply EMD to analyze the responses of the NES and pitch and heave modes of the wing, for the first suppression mechanism, in order to numerically prove that it is governed by a series of repeated TRCs followed by escapes from capture. Figure 5 depicts the leading IMFs of the time series depicted in Fig. 2 (the value on the upper right part of each plot represents the maximum amplitude of the corresponding IMF), we conclude that the leading

IMFs are the dominant oscillatory components of all three transient responses considered.

Let $\theta_i, i = 1,2,3$ be the phase variables of the three aforementioned leading IMFs of the heave mode, pitch mode, and the NES, respectively (computed by Hilbert transform). Then, $\theta_{12} \equiv \theta_1 - \theta_2$ denotes the corresponding phase difference between the heave and pitch modes; $\theta_{13} \equiv \theta_1 - \theta_3$, the phase difference between the heave mode and the NES; and $\theta_{23} \equiv \theta_2 - \theta_3$ the phase difference between the pitch mode and the NES. Figure 6 depicts the temporal evolutions of these phase differences; in time windows where the phase differences monotonically increase or decrease, they are considered to be *time-like*, otherwise, they are said to exhibit *non-time-like* behavior. If a phase variable is time-like, it can be considered as a 'fast angle' of the dynamics, and it may be removed from the dynamics (as non-essential) by simply averaging it out of the problem. If, however, the same phase difference is non-time-like, it may not be averaged out of the dynamics and it is expected to influence the (essential) slow dynamics through resonance captures. Indeed, when the dynamics is captured transiently on a *resonance manifold* [Arnold, 1988] defined by an integral relation between the instantaneous frequencies of the corresponding IMFs. The resulting TRC leads to TET in this system [Vakakis and Gendelman, 2001].

From the results depicted in Figure 6, we note that there exist domains where nontime-like behavior of certain phase differences occurs. In these time intervals 1:1 TRCs occur, which appear as spirals in the phase portraits of Figure 6b. We note that, not only do TRCs occur between the heave mode and NES and between the pitch mode and NES, but, between the heave and pitch modes (as in the case of the LCO triggering mechanism [Lee et al., 2005]). Figure 6c depicts the instantaneous frequencies of the dominant IMFs, and the occurring frequency lockings between the wing modes and the NES can be clearly inferred.

4 Slow-Fast Partitions of the Dynamics

We note that analytical modeling of the transient wing-NES interactions can be performed by slow-fast partitions of the dynamics as discussed in [Lee et al., 2007]. To this end, the responses of the heave, pitch wing modes and of the NES are expressed as,

$$y(\tau) = y_1(\tau) + y_2(\tau),\ \alpha(\tau) = \alpha_1(\tau) + \alpha_2(\tau), \\ v(\tau) = v_1(\tau) + v_2(\tau) \tag{1}$$

respectively; components with subscripts 1 and 2 correspond 'slowly' modulated 'fast' frequency components, $e^{j\Omega\tau}$ and $e^{j\tau}$, $j = (-1)^{1/2}$, respectively (where Ω and unity are the normalized frequencies of the heave and pitch modes, respectively). Introducing the new complex variables,

$$\psi_1 = y_1' + j\Omega y_1 \equiv \varphi_1 e^{j\Omega\tau},\ \psi_3 = y_2' + jy_2 \equiv \varphi_3 e^{j\tau} \\ \psi_2 = \alpha_1' + j\Omega\alpha_1 \equiv \varphi_2 e^{j\Omega\tau},\ \psi_4 = \alpha_2' + j\alpha_2 \equiv \varphi_4 e^{j\tau} \\ \psi_5 = v_1' + j\Omega v_1 \equiv \varphi_5 e^{j\Omega\tau},\ \psi_6 = v_2' + jv_2 \equiv \varphi_6 e^{j\tau} \tag{2}$$

Substituting these expressions into the equations of motion, and performing two-frequency averaging over the two fast components $e^{j\Omega\tau}$ and $e^{j\tau}$, we obtain a set of six complex-valued modulation equations governing the slow dynamics,

$$\underline{\varphi}' = \underline{F}(\underline{\varphi}) \tag{3}$$

where $\underline{\varphi} \in C^6$. Analysis of these equations recovers the EMD results of Section 5. By performing bifurcation analysis of the slow-flow dynamics (3) we study robustness of the suppression mechanisms.

7 Conclusions

We detected (at least) three suppression mechanisms for suppressing aeroelastic instabilities in the wing-NES system. The underlying dynamic mechanisms governing these mechanisms were series of TRCs, e.g., of transient resonances either between the NES and the heave and/or pitch modes, or between the wing modes themselves. The detailed study performed in [Lee et al., 2007] showed that the issue of robustness of the suppression can be addressed by performing bifurcation analysis of steady state responses. In the same reference it is found that NESs attached with negative offsets can provide robust aeroelastic instability suppression within wide ranges of system parameters.

References

Arnold, V. (1988). *Dynamical Systems III, Encyclopaedia of Mathematical Sciences*, Springer Verlag: Berlin and New York.

Huang, N., Shen, Z., Long, S., Wu, M., Shih, H., Zheng, Q., Yen, N.-C., Tung, C., and Liu, H. (1998). The Empirical Mode Decompostion and the Hilbert spectrum for nonlinear and nonstationary time series analysis, *Proc. Royal Soc. London, Ser. A*, **454**, pp. 903-995.

Kuznetsov, Y. (1995). *Elements of Applied Bifurcation Theory*, Springer-Verlag, New York.

Lee, Y.S., Vakakis, A., Bergman, L., McFarland, D., and Kerschen, G. (2005). Triggering mechanisms of limit cycle oscillations in a two-degree-of-freedom wing flutter model, *J. Fluids Str.*, **21**, pp. 485-529.

Lee, Y.S., Vakakis, A.F., Bergman, L.A., McFarland, D.M., Kerschen, G. (2007). Suppression of aeroelastic instability by means of broadband passive targeted energy transfers I: Theory, *AIAA J.*, **45**(3), pp. 693-711.

Vakakis, A. and Gendelman, O. (2001). Energy pumping in coupled mechanical oscillators II: Resonance capture, *J. Appl. Mech.*, **68**, pp. 42-48.

Figures

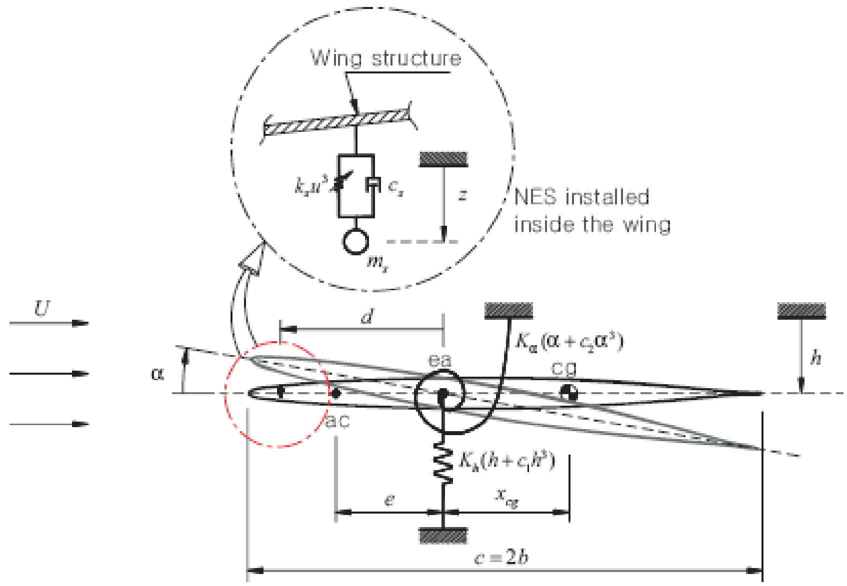

Figure 1. Two-DOF rigid wing model with SDOF NES attached.

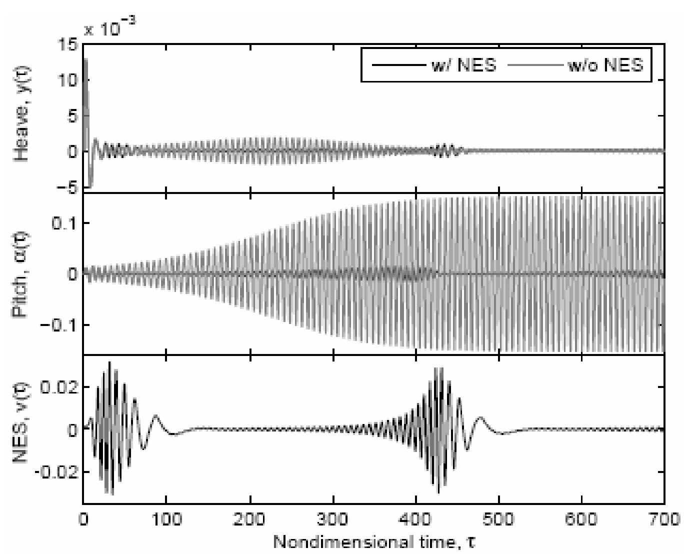

Figure 2. The first suppression mechanism: Recurring burst-outs and instability suppressions.

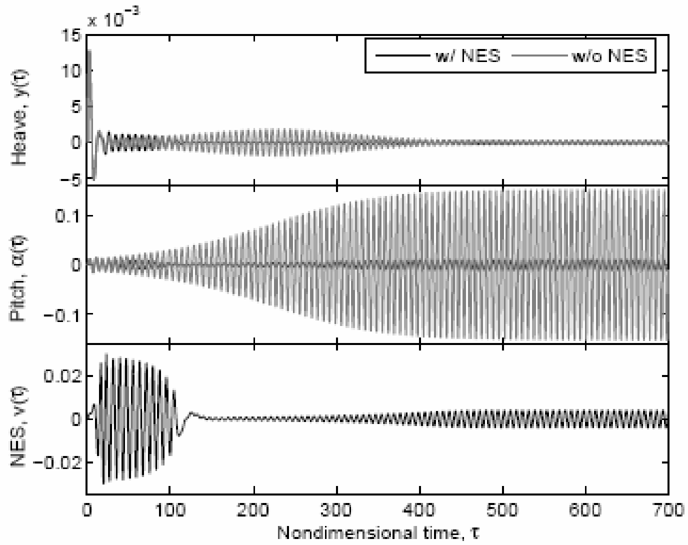

Figure 3. The second suppression mechanism: Partial LCO suppression.

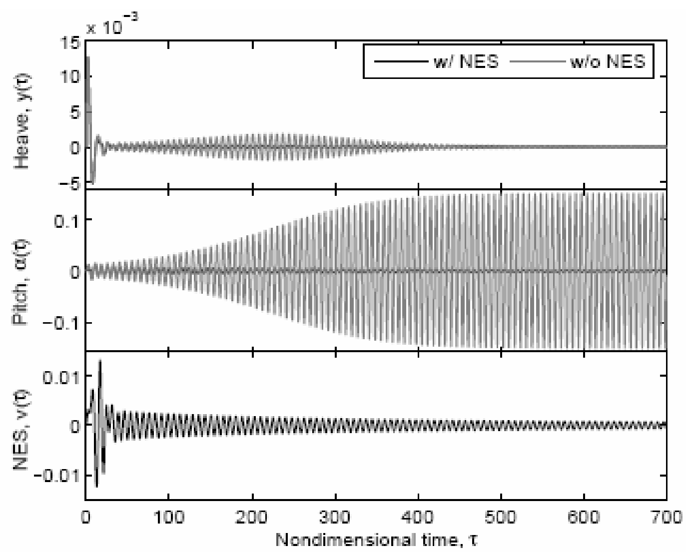

Figure 4. The third suppression mechanism: Complete LCO suppression.

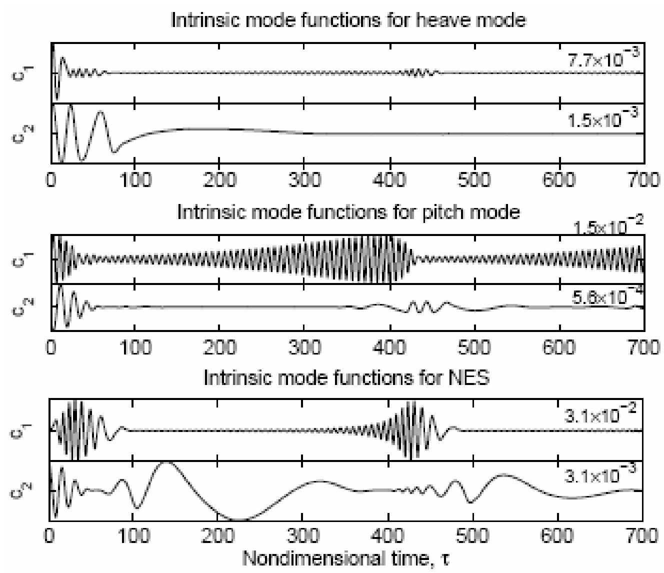

Figure 5. EMD of the transient responses of Figure 2 (first suppression mechanism).

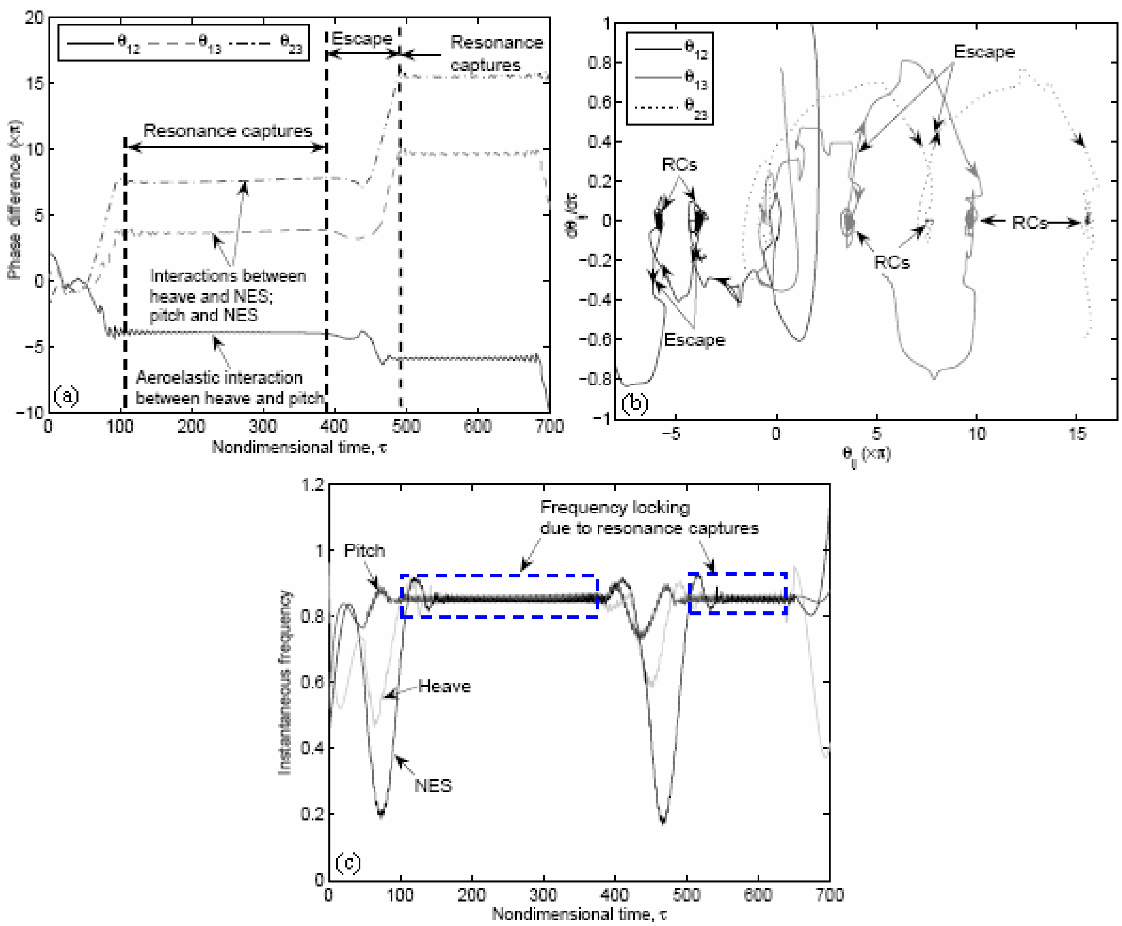

Figure 6. TRCs occurring in the first suppression mechanism: (a,b) phase differences of dominant IMFs, and (c) instantaneous frequencies of the transient responses of the wing modes and NES.