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Residual mode correction in calibrating nonlinear damper for vibration control of flexible structures

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ABSTRACT

Residual mode correction is found crucial in calibrating linear resonant absorbers for flexible structures. The classic modal representation augmented with stiffness and inertia correction terms accounting for non-resonant modes improves the calibration accuracy and meanwhile avoids complex modal analysis of the full system. This paper explores the augmented modal representation in calibrating control devices with nonlinearity, by studying a taut cable attached with a general viscous damper and its Equivalent Dynamic Systems (EDSs), i.e. the augmented modal representations connected to the same damper. As nonlinearity is concerned, Frequency Response Functions (FRFs) of the EDSs are investigated in detail for parameter calibration, using the harmonic balance method in combination with numerical continuation. The FRFs of the EDSs and corresponding calibration results are then compared with those of the full system documented in the literature for varied structural modes, damper locations and nonlinearity. General agreement is found and in particular the EDS with both stiffness and inertia corrections (*quasi-dynamic correction*) performs best among available approximate methods. This indicates that the augmented modal representation although derived from linear cases is applicable to a relatively wide range of damper nonlinearity. Calibration of nonlinear devices by this means still requires numerical analysis while the efficiency is largely improved owing to the system order reduction.

1. Introduction

Structures today are of increasing large flexibility and low inherent damping due to their increasing cantilevered or suspended length, such as stay cables and wind turbine blades. This necessitates supplemental attachments or auxiliary members, of passive, active or semi-active type, for suppressing their vibrations in operational condition [1–3]. Although the structural modification is often limited in terms of supplemented stiffness, damping or mass, it is able to provide adequate dissipation. The control units notwithstanding need proper calibration so that desirable performance is achieved. Considerable studies have been dedicated to this purpose. For example, an extensively studied flexible structure with local attachments is the stay cable in cable-stayed bridges, because it is susceptible to various vibrations owing to the extremely low inherent damping. Dynamic analyses have been conducted for tuning intermediate lateral passive attachment,

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including linear viscoelastic dampers [4–11], tuned mass dampers [12], nonlinear dampers [13–16], and semi-active or active damping strategies [17–19]. Similar studies have been conducted for beam like structures [20–22]. In these studies, the structure without attachments is considered linear without inherent damping, while the damped system has typical non-classical damping and hence requires complex modal analysis for tuning the linear devices [7]. If nonlinearity of the attachment is considered or expected in particular situation, nonlinear numerical analysis is required for the whole structure and general understanding for many of these cases is unavailable yet. In other words, the attachment introduces considerable complexity for the dynamic analysis, posing difficulty in parameter calibration for best control effect.

Noteworthy is that for flexible structures of practical importance are their resonant responses because they are subjected to relatively broad-banded excitations such as wind, wind/rain, traffic and pedestrian loading and therefore dominant by resonant vibrations. Besides, the attachments generally introduce small frequency shifts relative to the structural modal frequencies owing to the limited supplemental mass or the installation location constraint. These facts allow for the development of approximate methods for simplifying the dynamic analysis and further the calibration procedure. Still taking cable vibration control as an example, in modeling the damped system, it is found that sufficient convergence can be achieved by adopting two special mode shapes, corresponding to the free vibration and clamped vibration of the concerned cable mode respectively, as shape functions in modal decomposition using Galerkin method in combination with numerical integration for resonant responses [23]. By this means, the continuous or discrete systems of Multi-Degree-Of-Freedom (MDOF) are reduced to a 2-DOF system, rendering explicit expressions available for the system eigenfrequency and damping if the controller is linear. This method was further elaborated and developed to solve discrete systems with several viscous dampers, interpreted as interpolating between the solutions of two limiting eigen problems [24]: the undamped eigenproblem and the constrained eigenproblem in which each damper is replaced by a rigid link. Further applications have been found in studying collocated active damping [25] and nonlinear dampers [23,26].

Recently, the method based on *residual mode correction* for calibrating resonant controller for flexible structures has received considerable attention [27,28]. The classic concept of *quasi-static correction* of high frequency modes has known importance in predicting the performance of a resonant control system [29–31]. One can find validation and application of this method in optimizing tuned mass absorber and piezoelectric RL shunts for common structures like beams and cables [32,33]. Lately, an inertia correction term is additionally derived to account for the modes below the target mode [28], leading to a *quasi-dynamic correction* for the residual modes. This improved correction technique has been applied to calibrating piezoelectric RL shunts [34].

The quasi-static and quasi-dynamic corrections are derived from the system of a flexible structure with local linear absorbers. The corrections effectively achieve model order reduction and hence lead to explicit calibration formats. Application of this method to a simple damper is straightforward if one compares the dynamic characteristics of a single DOF system damped by a Maxwell damper as studied in [35,36] and those of a particular mode of a cable-/beam-damper system [5,6,20]. However, practical dampers and resonant absorbers exhibit nonlinear behavior. Besides, flexible structures with attachment of nonlinearity usually require numerical analysis for appreciating the damping effect and considerable computational effort is needed for parameter calibration. A reduced order model is valuable for improving the calibration efficiency. It is therefore of both theoretical and practical interest to study whether the *Equivalent Dynamic Systems* (EDSs) [28] obtained from residual mode corrections are still applicable to such nonlinear cases. For this purpose, we consider a representative damped flexible structure, a taut cable with a general viscous damper, which has been studied comprehensively for maximizing damping effect in [16]. Note that the models developed based on residual mode correction are not expected to deal with the cases where the dampers (or generally say, controllers) could induce complicated frequency curve interaction (modal interaction) as observed in [6,8,22]. Those cases are of more theoretical rather than practical importance. Hence, we will still restrict our scope to the small frequency shift regime. Particularly, the nonlinear damper is considered close to the cable anchorage. As nonlinearity is involved, the steady-state responses and further the Frequency Responses Functions (FRFs) are focused for appreciating the damping effect and calibrating the damper parameters [37,38,16]. The FRFs of the full system are to be compared with those of the EDSs and further the parameter calibration based on the FRFs is discussed for examining the applicability.

The rest of this paper is organized as follows. Section 2 introduces the residual mode correction method and formulates the nonlinear problem for the EDSs considering nonlinear control effect. Section 3 describes the cable-damper system and the corresponding EDSs which are analyzed in Section 4 for dynamic characteristics. The obtained frequency responses as well as calibration results are compared with full system analysis results in Section 5. Further, Section 6 presents the corresponding calibration procedure and the work of this study is concluded in Section 7.

2. Problem formulation

The method of calibrating resonant absorbers for flexible structures via residual mode correction is first introduced following [32,28,34]. The notation thereof is retained for the convenience of understanding. The reader is advised to the original work for derivation and interpretation. Subsequently, the augmented modal representation with residual mode corrections is proposed to consider the nonlinearity of control devices in general, resulting in a nonlinear problem.