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Extended delayed resonators – Design and experimental verification☆

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ABSTRACT

The key contribution of the paper is in the modification of the well-known delayed resonator concept for vibration suppression using both delayed and non-delayed acceleration feedback control laws together. We further improve the classical resonator setting with lumped delay introducing a distributed delay structure into the control law. It is known that the operable frequency ranges for the delayed resonators are relatively narrow, taking into account both the stability and implementation constraints. As the key result of this paper, in order to widen the operable frequency range, the resonator's feedback is extended by including a non-delayed part to adjust virtually the mass and thus the natural frequency of the active absorber. The proposed extension takes into consideration also the existence of feedback delay and filters to reduce the measurement noise, and retain the simplicity of active controlled resonator tuning against excitations with time varying frequencies. The properties and performance of the resulting algorithms are compared with the delay free PI (proportional and integral) feedback control law. It is shown that the delay-based resonators are easier to implement and can better deal with the measurement noise compared to PI. Spectral theory of retarded and neutral time delay systems are applied to perform a thorough analysis of the resonators. The key theoretical results are validated on a laboratory set-up with voice-coil magnetic shakers.

1. Introduction

In the vibration suppression of mechanical systems, both passive and active absorbers have been widely used. The positive impact of mounting the passive vibration absorber on the primary structure with the objective to reduce the amplitudes of the vibrations has been known for decades, see e.g. [1–4]. The main benefits of passive approach is the inherent stability of the overall setup and no energy needs to be exerted to damp the oscillations. On the other hand, the frequency band where the absorber suppresses the vibrations efficiently is relatively narrow, being centered at the natural frequency of the absorber. Besides, in practice, the vibrations are not damped entirely even if the vibration frequency is identical with the natural frequency of the absorber. This is due to the fact that the physical absorber is never ideal, i.e. it features nonzero damping. This inefficiency can partly be mitigated by tuning the mechanical parameters of the absorber [1,3], particularly the stiffness of the dampers, see also [4] with method to achieve broad-band damping tuned mass-dampers.

In this paper, we consider that the passive absorber is supplemented by an active feedback as shown in Fig. 1 with the objective to turn the physical absorber to an ideal (undamped) absorber with natural frequency equal to the frequency to be suppressed. As a consequence, the vibrations at the given frequency are suppressed entirely, which is the key benefit.

The control feedback can be implemented using position, velocity or acceleration measurements, depending on the type of a sensor selected for a particular vibration control application at hand. In this paper, the acceleration feedback is considered as it allows closing the feedback directly from the accelerometer sensors, which are easy to apply and of relatively low cost. In 1990s, the research group of N. Olgac proposed a delayed resonator, see e.g. [5,6], by applying an active feedback with a lumped time delay. Subsequently, many modifications of the delayed resonator (DR) concept have been worked out. For example, a single-mass dual-frequency DR absorber was reported in [6]. In [7], relative position feedback was applied. In [8,9,10] automatic tuning algorithms were presented to enhance robustness against uncertainties and variations in the parameters of the absorber. The DR concept was also extended to torsional vibration applications in [11],

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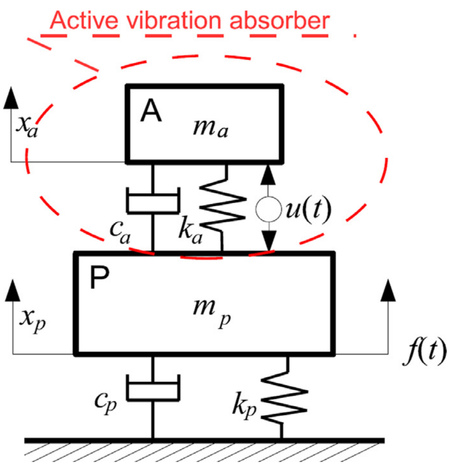

Fig. 1. SDOF Primary Structure (P), with an active vibration absorber (A) to suppress displacement x_p induced by harmonic disturbance force $f(t)$.

where delayed velocity feedback was considered. Subsequently, in [12] and [13], synthesis of the delayed control approach with a centrifugal pendulum absorber was presented. An automatic tuning algorithm based on online absorber parameters identification is proposed in [10] for the case of multi-degree of freedom primary structure with an attached resonator, which is addressed also in [9]. A method based on integration of adaptive-passive vibration absorber and active resonator absorber is analysed in [14], for which the control effort is much smaller than that of simple active absorber. Application example of DR in machine tool chatter phenomenon is discussed in [12]. Concerning alternative applications of time delay in vibration suppression, a delayed feedback vibration control in a two-degree-of-freedom nonlinear system is proposed in [15]. Let us also mention an output multi-mode delayed-acceleration feedback control methodology treated in [16] to mitigate the free vibrations of a flexible cantilever beam and an active absorber based on the time displacement difference feedback in controlling friction-driven vibrations [17]. Theoretical basis of the vibration control strategy based on the time-delayed acceleration feedback is also presented in [18].

A delay free alternative to the DR was proposed in [19], applying a PI acceleration feedback. However, as demonstrated, the integrator of the acceleration signal needs to be supplemented by a properly designed high-pass filter in order to mitigate the negative effects of measurement noise and other types of common imperfection of acceleration sensors, bias level drift in particular. As examples of another delay free methods to solve the task of vibration suppression, we also wish to mention pole placement based design method proposed to suppress stationary random vibration in flexible structures using a hybrid vibration absorber [13] and implementation of acceleration and displacement feedback control on a beam-type tuneable vibration absorber [10], see also references therein. A method for real-time auto-tuning of the absorber was proposed in [20]. A combination of classical sky-hook feedback and feedforward control is proposed in [21], where control strategy is enriched by nonlinear compensator to eliminate hysteresis of the actuators. More advanced method for vibration isolation for active suspension involving system uncertainties, saturations and performance constraints is analysed in [22].

Before highlighting the most recent results on the DR resonators, let us point to another aspect of considering the acceleration feedback. As demonstrated in [23,24] under the presence of feedback delays in the state derivative (acceleration) feedback, the closed loop dynamics becomes a neutral time delay system. This applies also for DR with acceleration feedback, as its partial state feedback involves both state derivative and delay. Neutral class of time-delayed systems contain delays in the highest order derivative terms. This class is notoriously known for some weird and unexpected stability displays, especially for infinitesimally small changes in delays. The neutrality induces considerable difficulties in the dynamic analysis and requires special attention in the feedback design [25,26]. However, under specific conditions, the neutrality can be removed by a properly designed low pass filter [24].

Recently, in [27], a complete dynamics analysis of the DR with a delayed acceleration feedback is performed by the authors. As demonstrated, closing the delayed feedback from the accelerations leads to the neutral time delay system not only for the absorber itself, but also for its coupling with the vibrating system base. As the main result of [27], the stability maps of the absorber are created with respect to the damping ratio of the absorber and to the vibration frequencies to be suppressed. Consequently, in [28] an alternative structure of the acceleration feedback is proposed, which instead of a classical delay uses a distributed delay. All the results concerning the stability and dynamics features are compared with the results derived in [27] for the classical DR, using analogous spectral methods as in that paper. The main benefits of the resonator with a distributed delay are (i) retarded dynamics (not neutral) for both the delayed resonator and the overall system and (ii) noise reduction due to the filtering properties of a distributed delay. Compared to [27], also experimental verifications of the theoretical results are presented for the resonator with a distributed delay.

From theoretical and practical analysis, both types of delayed resonators perform the best for suppressing vibrations at a relatively narrow frequency band close to the natural frequency of the resonator absorber. The applicable frequency band is bounded from below by the stability boundary of the resonator and from above, by the prohibitively high sampling rates needed to implement the delay which itself decays rapidly with growing excitation frequencies.

This paper is a subsequent step to the detailed analysis of delayed resonators performed in [27] and [28]. The main objective is to extend the operable frequency range of the resonators by adding a non-delayed acceleration feedback which helps adjust the natural frequency of the absorber. Thus, the overall feedback is analogous to the PI controlled resonator [19], except instead of an integrator term, a term with either lumped or distributed delay is applied. As the main contribution, the applicable frequency range for the delayed resonators and PI resonator is improved. Next, practical implementation aspects of the resonator dynamics are considered, such as the impact of the filters on the quality of vibration suppression. Finally, numerical and experimental validations of the results are presented.

2. Preliminaries

In this section, the concept of vibration suppression of SDOF system by an active resonator absorber is outlined. Then, existing resonator feedback rules, their parametrization formulas and basic properties are outlined for i) delay free PI resonator proposed by Rivaz and Rohling in 2007 [19], ii) 'classical' delayed resonator with a lumped delay proposed by Olgac, et al. in 1990 s [5,11,29], and iii) most recent resonator with a distributed delay proposed by Pilbauer, Vyhlidal and Olgac in 2016 [28]. Finally, a brief properties of retarded and neutral time delay systems are provided to enhance consistency of presented results.

2.1. Concept of the resonator absorber

In Fig. 1, an active vibration absorber (A) is depicted, attached to the SDOF (single degree-of-freedom) primary structure (P). The