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Transient vibration control using nonlinear convergence active vibration absorber for impulse excitation

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This paper presents a nonlinear convergence algorithm for active dynamic vibration absorber (ADVA) to control the transient vibration caused by the impulse excitation. The proposed nonlinear ADVA is made up of equivalent dynamic modeling equations and frequency estimator. The ADVA is mathematically imitated by a mass body and a voice coil motor (VCM). The VCM plays two roles in this study. On one hand, the algorithm-controlled Lorentz force of the VCM is actively utilized to suppress the transient response of primary system. On the other hand, the VCM also acts as a magnetic damper, which helps attenuate the transient vibration passively. The nonlinear convergence estimator is applied to simultaneously satisfy the requirements of fast convergence rate and small steady state frequency error, which are incompatible for the linear convergence estimator. The experiments demonstrate that the nonlinear ADVA can shorten 70% of the convergence time than the linear ADVA. The nonlinear ADVA and VCM magnetic damper work together and help eliminate 95% of the uncontrolled transient vibration at 1.5 s.

1. Introduction

In order to control the transient vibration caused by the impulse excitation, a nonlinear convergence active vibration absorber (nonlinear ADVA) for impulse excitation is studied in this paper. Vibration caused by impulse excitation widely exists. For example, the vibration caused by impulse excitation should be attenuated to micrometers or even nanometers level to improve the image quality and line-of-sight precision of satellites [1]. The water waves and missile firing bring impulse excitation to the ships and vessels whose structural strength is always enough, but the transient vibration caused by the impulse excitation is difficult to control [2,3]. The vibration of building floor subjected to footsteps and the spacecraft subjected to impact or thruster force both need to be suppressed [4,5].

Dynamic vibration absorbers (DVA) are usually applied to suppress the steady state vibration caused by a harmonic excitation with a given frequency [6]. Due to the narrow effective bandwidth, the vibration may increase significantly and the DVAs lose efficiency when small changes occur with respect to exciting frequency of the primary system [7].

Therefore, lots of achievements focus on making the passive DVAs' natural frequency tunable [8–10]. Semi-active method is easy to achieve the adjustment of stiffness or inertia value by getting the feedback signal from the response. A flexible cantilever beam attached with a mass was used to develop the DVA, and the stiffness of the beam varied with the change of the effective length of the beam [11]. The electromagnetic DVA was presented in [12,13] to avoid the uncertainty in

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mechanical direct driving process, and it consisted of a clamped-clamped beam and a permanent magnet, the stiffness of the absorber changed when the current in the coil was adjusted. Piezoelectric element was applied to realize stiffness variation for the semi-active DVAs in [14,15], and the natural frequency of the absorbers was tuned to the required frequency electrically. Shape memory alloy was another kind of smart material which could be used as a variable stiffness element of DVAs, the Young's modulus of the element was changed by adjusting the temperature of the alloy by passing electrical current through it, thus it resulted in the changing of the natural frequency [16–18]. Magneto-rheological fluid was also used to achieve stiffness changing, and the shear stiffness of the fluid was adjusted by changing the magnetic field applied to the fluid [19–21]. The harmonic vibration can be attenuated effectively using these DVAs, but the efficiency is low when the traditional DVAs are applied to control the impulse excitation. Although the passive and semi-active DVAs are simple and stable, few efforts aim to suppress the transient vibration caused by impulse excitation.

Active control is an effective method to suppress the impulse vibration by adapting characteristics and parameters of the absorber according to the variation of exciting force. A virtual-vibration-absorber was introduced in [22,23], its stiffness, inertia and damping coefficient were online tunable to mathematically equivalent to DVA, and the efficient algorithm allowed improving the frequency resolution by active vibration control method. Similarly, the delayed resonator was proposed in [24,25], and this algorithm included the position feedback and the time delayed controller. However, these achievements all aim to control the steady state vibration of harmonic excitation.

Few efforts have done to study the transient vibration suppressing under impulse excitation using DVAs. An adaptive DVA using magnetorheological elastomer was applied to reduce vehicular powertrain transient vibration, but it was designed for the vehicular powertrain vibration happened during the transient stage of acceleration [26]. A control algorithm was proposed for semi-active absorber to control the transient response [27], and the analytical model was based on the perturbation method [28,29], but this model had assumed that the natural frequencies of the primary system and the absorber were equal all the time, so it couldn't be applied to the tunable transient absorber. Our preliminary study of the transient response for DVA system was reported in [30], and it demonstrated that the transient vibration couldn't be suppressed quickly by the semi-active method of changing the stiffness of the absorber. Thus, an active absorber is proposed based on equivalent dynamic modeling equations and frequency estimator in this paper. The equivalent dynamic equations are used to produce the virtual absorber. And the frequency estimator can obtain frequency of the damped response. A five order adaptive estimator was introduced in [31], and this algorithm was expanded to the online estimation of n frequencies. The order of the estimators was cut down to four to accelerate the arithmetic speed [32,33]. In order to reduce the estimator computation, another frequency estimator using adaptive identifiers was proposed, and the number of order was reduced to three [34], but the identifier parameters were difficult to decide. The dynamic order of the algorithm proposed in [35,36] equaled to three, which was fewer than the most known results.

To the best of our knowledge, few achievements have been reported to study the ADVA to suppress the transient vibration caused by impulse excitation, which can simultaneously shorten the convergence time of vibration suppressing and achieve faster decrements for oscillation attenuation. Thus, in this paper the nonlinear ADVA for transient vibration control is studied. The rest of this paper is organized as follows. In Section 2, after introducing the impulse excitation and fundamental idea of the transient ADVA, the nonlinear convergence estimator is improved from linear estimator, which is introduced in [35,36]. In Section 3, the advantages of nonlinear algorithm in frequency estimating and vibration control are demonstrated by simulations. In Section 4, experimental tests are employed to verify the effectiveness of the proposed ADVA, and the experimental results coincide with the simulation results well. Finally, some conclusions are summarized.

2. Nonlinear convergence active vibration absorber

2.1. The impulse excitation

The impulse excitation is simplified as sine wave shown in Fig. 1 to establish the common analytical model in our previous work [30]. The response of the primary system and the absorber is divided into two stages (Stage I and Stage II). The impulse excitation can be expressed by

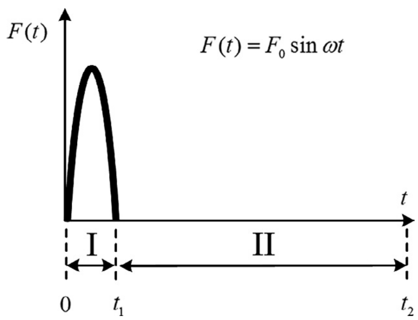

Fig. 1. Impulse vibration of half-sinusoidal wave.