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Delay Scheduling for Delayed Resonator Applications

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Abstract: This paper is on suppression of carbody vibrations utilizing multiple-delay Delayed Resonator (DR) with combination of speed and position feedback. The resonance frequency of DR under varying excitation frequency is tuned by delay scheduling concept. Characteristic Treatment of Characteristic Roots (CTCR) method with Extended Kronecker Summation is used to assess both the operation frequency of DR and overall stability of the system. An experimental study is included to present the effectiveness of the method.

***Keywords**:* Delayed Resonator, Multiple Time Delay, Active Suspension, Delay Scheduling.

1. INTRODUCTION

Vehicle carbody vibrations are one of the main concerns of design engineers compromising ride comfort and safety. There are numerous research on active suspension systems for both road and railway vehicles. While active systems are widely used in road vehicles, railway applications are limited to running tests (Sugahara et al. 2009). Examining different control strategies proposed for the active vertical suspension systems like LQG (Zamzuri et al. 2007), LQR (Foo and Goodall 1999), H_∞ (Hirata and Takahashi 1993) and skyhook control (Li 1999), it is observed that at least 20% ride comfort improvement may be obtained comparing to passive systems.

On the other hand, it is possible to utilize Delayed Resonators (DRs) for suppressing carbody vibrations. Classical DRs are well-known active vibration absorbers based on the idea to oscillate a simple mass-spring-damper system at a desired frequency using a delayed partial state feedback (Olgac and Holm-Hansen 1994). DRs are implemented in various ways such as using relative position feedback (Olgac and Hosek 1997), speed feedback (Filipovic and Olgac 2002) and acceleration feedback (Olgac et al. 1997). Although tuning of the DR operation frequency is straight forward, stability analysis of the overall structure maybe complicated especially with the acceleration feedback which presents itself inherently neutral system. A recent study reported complete stability analysis of DR with acceleration feedback using spectral methods (Vyhlídal et al. 2014).

Implementations of the DRs are easy and independent from the bogies or the secondary suspension system which marks them proper particularly for railway applications. Earlier research regarding to the use of DRs on active suspension systems of railway vehicles (Eriş et al. 2014, 2015) exhibited successful results compared to semi-active suppression systems. This study aims to present a different control strategy, delay scheduling, for suppressing vertical carbody vibrations in a various frequency range. Delay scheduling concept is utilizing delay as the only parameter to control the system for varying conditions. The advantage of this strategy is to compute control parameters ahead and tune the controller online against the operation conditions (Olgac et al. 2005, Ergenc et al, 2007).

In this study, we introduce a new strategy for DRs which utilizes both position feedback and speed feedback. In principle, both feedbacks have time delays independent from each other. Here, delay scheduling concept is utilized to tune the resonance frequency of the modified DR.

The paper is organized as follows. In Section 2, DR with double feedback is proposed and stability analysis is given. Section 3 consists of experimental validation and results. Section 4 is the conclusion.

2. DELAYED RESONATORS

2.1 Modified Delayed Resonator

A DR is a controlled harmonic force generator to suppress undesired vibrations of a primary structure. A DR attached to a SDOF (single degree-of-freedom) system as in Fig. 1 aiming to suppress the vibrations of the system that are caused by the force $f(t)$.

Dynamic model of a single DR is obtained as

$$m_a\ddot{x}_a(t) + c_a\dot{x}_a(t) + k_a x_a(t) = u(t) \tag{1}$$

where, m_a, k_a, c_a are mass, stiffness and damping coefficients of the DR, respectively.

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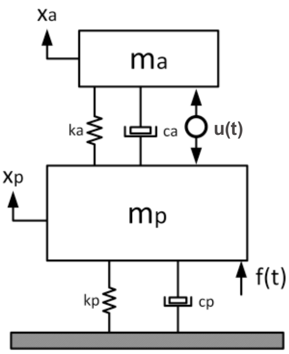

Fig. 1. Delayed Resonator attached to a SDOF system

One of the conventional ways to utilize a classical DR is to use a delayed speed feedback

$$u(t) = g_1 \dot{x}_a(t - \tau_1) \quad (2)$$

where, controller parameters, g_1 and τ_1 are feedback gain and time delay, respectively.

Stability and performance of the overall system is closely related to the physical parameters and the tuning of the DR. As the operating frequency (ω) shifts from the design frequency of the DR it is harder to maintain the same performance and stability. Earlier studies (Eriş et al. 2015) proposed that, stability problems may be reduced by introducing an additional position feedback as

$$u(t) = g_1 \dot{x}_a(t - \tau_1) + g_2 x_a \quad (3)$$

Position feedback affects stiffness of the structure which shifts natural frequency of the DR to a new operating point. On the other hand, the new challenge is to tune DR with three parameters which are not independently obtainable. Here, tuning of DR includes both gain scheduling and delay scheduling. In classical DR concept the gain and delay terms are computed easily while the new method is lacking straight entities to construct schedules.

In this study, we propose another tuning method which only employs delay scheduling. The new feedback term again consists of both speed and position feedback but both are delayed with independent time delay values. The new feedback force is

$$u(t) = g_1 \dot{x}_a(t - \tau_1) + g_2 x_a(t - \tau_2) \quad (4)$$

In this new control strategy there are four parameters which are used to tune the DR. Naturally this is cumbersome procedure but it is simplified when the gains g_1 and g_2 are fixed to certain values. Then the problem becomes only a delay scheduling of both delays.

2.2 Delay Scheduling

The delay scheduling is a technique to use the delay terms as control parameters (Olgac et al. 2005, Ergenc et al. 2007). Adjusting delay terms during operation is a continuous process which is practically quite beneficial.

The characteristic equation of the modified DR is follows

$$CE(s) = m_a s^2 + c_a s + k_a - g_1 s e^{-s\tau_1} - g_2 e^{-s\tau_2} \quad (5)$$

The system is linear time invariant multiple time delayed system (LTI-MTDS) which has infinitely many characteristic roots interspersed on the complex plane.

In DR technique there are two issues to be considered. First one is to tune resonator such that all the energy is absorbed by the secondary mass. Secondly, the overall system maintains the stability. Since in our new technique we offer to control the system only by delay scheduling, the gain parameters has to be primarily assigned and kept fixed during the operation. Then, only time delay terms are left as control parameters.

Although there are auto-tuning mechanisms (Olgac, N., and Holm-Hansen, B.T. 1995) which update controller parameters according to the changes of the operating frequency (ω_c), it is known that performance of the classical DR may be reduced due to stability issues which has to be checked separately. In our methodology, we follow a different path and first assign feedback gains as

$$g_1 = c_a \quad (6)$$

$$g_2 = m_a \cdot \omega_c{}^2 - k_a \quad (7)$$

while we are considering zero delays at feedback line. The speed feedback gain aims to withdraw the damping effect and position feedback gain provides resonance at the excitation frequency. At this point, the system seems to resonate at the desired frequency with zero delay at the feedback but the stability of the system is at stake.

Once the gains are fixed, delay terms which provide both resonance at DR and stability overall system is determined using CTCR method with Extended Kronecker Summation (Ergenc et al. 2007). First the critical values of the multiple delays (τ_1, τ_2) which convey dominant characteristic roots of the DR at $s_{1,2} = \pm j\omega_c$ are obtained exhaustively using this method. In addition, notice that the feedback has two delays which provide us a two dimensional delay space where we can schedule our delays to operate at different resonance frequencies. This flexibility enables us to suppress the vibration when excitation frequency changes. The method is further explained in example section.

In following subsection, stability analysis of the system is addressed.

2.3 Stability of the System

Assessment of overall stability of the system is investigated utilizing CTCR method with Extended Kronecker Summation for entire system. The governing equations of the system are as follows,

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{A_0}\boldsymbol{x}(t) + \boldsymbol{A_1}\boldsymbol{x}(t - \tau_1) + \boldsymbol{A_2}\boldsymbol{x}(t - \tau_2) + \boldsymbol{B}f(t) \quad (8)$$

where, $\boldsymbol{x}(t) = [x_a(t)\ \dot{x}_a(t)\ x_p(t)\ \dot{x}_p(t)]^T$ state vector, A_0, A_1, A_2 are non-delayed system matrix, speed feedback matrix and position feedback matrix respectively. B is the input matrix and $f(t)$ represents external excitation force.

The system matrices are as follows: