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Control design and experimental validation for flexible multi-body systems pre-compensated by inverse shapers

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ABSTRACT

A complex methodology for control of flexible multi-body systems is proposed with the objective to achieve a favorable distribution of system motion so that the oscillatory mode of the flexible part is not excited. As the key element, the recently proposed concept of a feedback loop with an inverse distributed delay shaper is adopted. Unlike in existing works, the mutual coupling between the primary (controlled) structure and secondary (flexible) structure of oscillatory nature is explicitly taken into account in the controller design. First, an easy to apply method to isolate the flexible mode to be targeted in the shaper design is proposed. Secondly, the interconnection of the system, shaper and the controller is formulated as a set of delay differential algebraic equations. Then the spectral optimization control design technique is applied to achieve fast dynamics of the infinite dimensional system. The viability of the overall methodology is validated by both simulations and experiments in an extensive case study example.

1. Introduction

Input shaping, a well known technique for compensating undesirable oscillatory modes of mechanical systems based on signal shapers with time-delays was firstly published in 1957 by O.J. Smith who introduced the posicast filter [1]. Subsequently, extensive studies have been made by Singer, Seering and Singhose [2,3] who proposed zero-vibration (ZV), zero-vibration-derivative (ZVD) and extra-insensitive (EI) shapers. Further extension of the shapers for multi-modes flexible structures has for example been proposed in [4,5] and with a discrete version in [6]. A typical application of input shaping is pre-compensation of payload oscillations suspended at a crane trolley, [7,8]. For an extensive review on input shaping over last 50 years, see [9].

Next to the classical feed-forward arrangement of the shapers which can only handle the effect of the reference command, there was an impulse to place shapers in a feedback interconnection in order to eliminate the effect of unmeasurable disturbances on the excitation of the flexible modes. This technique was analyzed already by Smith in [10], where he developed a basic scheme with a compensator and a shaper in the feedback. However, it is important to mention that, as shown in [11], the application of the proposed scheme is applicable if and only if both the controller and the system are bi-proper as their inversion is needed in the compensator. Subsequently a direct augmentation of the standard feedback loop with a pre-tuned input shaper was proposed in [12]. A further investigation of the system and stability of the closed loop using the root locus was done in [13] and [14]. It was shown that placing the signal shaper in the loop between the controller and the system is not effective in the objective of suppressing the vibration caused by disturbance variables, except the sensor disturbance.

Following the preliminary results in [15], a novel feedback loop architecture was proposed in [11], along with both simulation and experimental verification. See also [16] for the double mode compensation task. This method is based on including an inverse shaper into the feedback loop. As has been reported, by the shaper inversion in the feedback interconnection, the high frequency zeros of the shaper are turned into the closed-loop poles. This fact eliminates applicability of classical shapers with the lumped delays to this task as their spectrum is neutral with the high frequency zeros lying either at or close to the imaginary axis. Instead, new types of shapers based on distributed delays need to be applied [17–19], resulting in a relatively safe retarded distribution of the closed-loop poles. As studied in detail in [11], favorable properties of the shaper in distributing the closed-loop responses in time so that the oscillatory mode is not excited are transferred to the closed-loop system *if and only if* a *sufficiently fast* controller is applied. Too slow dynamics of the closed loop may result in disruption of the 'notch' characteristics brought by the shaper.

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To position approaches using inverse shapers in a broader context, let us point to article [20], where a scheme with an inverse shaper was compared with a classical control scheme, where the desired 'notch' filter characteristic at the flexible mode frequency was achieved by the controller. The following advantages of the architecture with an inverse shaper were revealed: (i) achieving the mode compensation in the channels from both reference and disturbance signals, which cannot be achieved by a classical scheme, (ii) more favorable responses of the primary structure — in the shaper free scheme the mode compensation was achieved at the cost of considerably larger overshoots.

Another point that needs to be mentioned is that in the scheme with the inverse shaper applied in [11,15,16], it was assumed that there is no backward coupling from the flexible system part to the controlled main body. Recently, it was shown in [21] that when the mutual coupling between these two subsystems takes place, a special attention needs to be paid to deriving the mode to which the shaper needs to be tuned. Note that as a rule, this mode is not present in the overall system dynamics. To determine the mode a method has been proposed in [21] based on an input–output transformation of the multi-body system into the controlled subsystem, the attached residual oscillatory dynamics, and an internal feedback loop representing the dynamical coupling. The transformation eliminating the system input is performed over the time domain system equations. The oscillatory mode to be targeted is determined as complex eigenvalue of the reduced order flexible system.

Even though the benefit of including an inverse shaper to the feedback loop for the oscillation compensation task has been recognized [11,21], the control design of arising infinite dimensional system has not been properly addressed. As documented in [11], for simple structure systems, no special attention needs to be paid to the controller design as including the inverse shaper to the loop does not affect the closed-loop characteristics substantially. Only a number of rules need to be followed when designing the PID controllers. However, extension of this *rather heuristic* approach towards coupled multi-body systems for which controllers of higher complexity are needed is problematic. In this case, the infinite dimensionality of the closed loop brought by the input shaper needs to be taken into account.

The first contribution of this paper consists of a transfer function based method for determining the target oscillatory mode of the systems based on transfer function approach, which is easier to apply compared to relatively complex methodology presented in [21]. As the second, key contribution, a modified closed-loop scheme with an inverse shaper and a fixed order controller is proposed to control efficiently multi-body flexible systems. In order to fulfill the requirement on the fast dynamics of the closed-loop system, the spectrum is optimized using the method of [22], yet as the presented control design framework is generic, other characteristics such as H_∞ criteria can be optimized as well. The work follows preliminary results presented in [23], where however, the coupling between the primary and secondary structure was not considered.

For the controller design by the spectral method, the model of *Multi-Degree Of Freedom* (MDOF) system will be interconnected with an inverse shaper forming the overall model in *Differential Algebraic Equations* (DDAEs), which are amendable for describing interconnected systems. The controller will then be obtained by minimization of the spectral abscissa, the real part of the rightmost eigenvalue, as a function of the controller parameters. This procedure has originally been proposed in [24] for retarded systems, and extended to DDAEs in [22], including a MATLAB tool.[1] Finally, note that the overall control scheme can be considered as a delay-based controller. Currently, there is an increasing interest on this class of controllers due to their practical implications [25,26].

The paper is organized as follows. First, preliminaries on input shaping are given in Section 2 together with inverse application of the shaper in the feedback loop. Then, a method for decoupling is presented in Section 3 together with the introduction of the modified control scheme with an inverse shaper. In Section 4, the model with an inverse shaper is formulated as a set of delay differential algebraic equations and the spectrum optimization based control design method is adjusted for this specific task. Then, a thorough case study application follows in Section 5, where all the proposed techniques are validated by both simulations and experiments. Finally, the conclusions are given in Section 6.

2. Preliminaries on input shaper and its application in feedback loop

The objective of applying an inverse shaper in a feedback interconnection with a system is to fully or partially compensate oscillatory modes of a secondary (typically flexible) structure. The mode has to remain unexcited either by a set-point change or by external disturbances. Before outlining the key properties of the scheme with an inverse shaper, let us briefly recall fundamental properties of input shaping.

A general description of a delay based input shaper is as follows,

$$v(t) = aw(t) + (1-a)\int_0^T w(t-\mu)dh(\mu), \qquad (1)$$

where w and v are the shaper input and output, respectively, $a \in \mathbb{R}^+$, $a < 1$ is the gain parameter, and the distribution of the delays is prescribed by the non-decreasing function $h(\mu)$, with length T. Note that in the classical input shapers [3,4,10], the lumped delays with step-wise response are applied. Alternatively recently proposed shapers [17,19] include distributed delays.

The transfer function of the shaper (1) is given by

$$S(s) = a + (1-a)F(s,T),$$

where $F(s,T) = \mathcal{L}\left\{\int_0^T w(t-\mu)dh(\mu)\right\}$ is the Laplace transform of delay. The shaper is designed in a way that its transfer function contains only zeros, some of which play crucial role in compensating the oscillatory modes of the system linked to the shaper in feed-forward manner. The simplest *zero-vibration* (ZV) shaper is for example designed so that its dominant zeros cancel the oscillatory poles [2,10]. Denoting the mode to be compensated by $r_{1,2} = -\zeta\omega \pm j\omega\sqrt{1-\zeta^2}$, where ω is the natural frequency of oscillations and ζ is the damping, the shaper parameters are tuned to achieve $S(r_1) = 0$. An enhanced robustness in mode compensation can be achieved by a shaper of higher complexity known as EI (extra insensitive) shaper [27], see also references therein, where the design is done by optimizing the *residual vibration* characteristics. The feedback interconnection with the inverse shaper proposed in [11] is shown in Fig. 1. If the shaper $S(s)$ is tuned to compensate the oscillatory mode of $G(s)$ (e.g. by zero-pole cancellation for ZV), this property has a potential to be transferred to all the transfer functions $T_{y_s r}(s) = G(s)\frac{C(s)H(s)S(s)}{S(s)+C(s)H(s)}$, $T_{y_s d_1}(s) = G(s)\frac{H(s)S(s)}{S(s)+C(s)H(s)}$ and $T_{y_s d_2}(s) = G(s)\frac{1S(s)}{S(s)+C(s)H(s)}$, because $S(s)$ appears in their numerators. Thus, the oscillatory mode is precompensated not only in the responses induced by the reference r, but also in the responses induced by the disturbances d_1, d_2.

2.1. Distributed zero-vibration shaper and its inverse form

In this work, we apply a distributed-zero-vibration (DZV) shaper (see [17] for more details), with transfer function

$$S(s) = a + (1-a)\frac{1-e^{-sT}}{Ts}e^{-s\tau}. \qquad (2)$$

[1] Available from: http://twr.cs.kuleuven.be/research/software/delay-control/.