Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 50-1 (2017) 1251–1256

Flexible Mode Compensation by Inverse Shaper in the Loop with Magnitude Saturated Actuators [⋆]

Baran Alikoç * **Jaroslav Bušek** ** **Tomáš Vyhlídal** **
Martin Hromčík *** **Ali Fuat Ergenç** *

* *Department of Control and Automation Eng., Faculty of Electrical and Electronics Eng., Istanbul Technical University, 34469 Turkey (e-mails: baran.alikoc@itu.edu.tr, ali.ergenc@itu.edu.tr)*
** *Department of Instrumentation and Control Eng., Faculty of Mechanical Eng., and CIIRC - Czech Institute of Information Robotics and Cybernetics, Czech Technical University in Prague, 16607 Czech Republic (e-mails: jaroslav.busek@fs.cvut.cz, tomas.vyhlidal@fs.cvut.cz)*
*** *Department of Control Eng., Faculty of Electrical Eng., Czech Technical University in Prague, 12135 Czech Republic (e-mail: martin.hromcik@fel.cvut.cz)*

Abstract: An input shaping architecture for vibration suppression of flexible systems controlled with magnitude saturated actuators is considered. It is shown that the distributed-delay shapers with the inverse form in the feedback path have the capability of canceling the undesired vibration caused by saturation limit of actuators. The main idea is to treat the saturation effect as a disturbance on the control input of the actuator which can be canceled by the shapers in the feedback control loop. The inverse form of a recently proposed distributed-delay shaper is utilized to dispose of the undesired vibrations subject to saturation. The theoretical results are compared with an existing solution and verified on a laboratory set-up.

Keywords: input shaping, inverse shapers, saturation, flexible systems

---

1. INTRODUCTION

Time-delay based input shaping is a widely used technique to suppress oscillatory modes of flexible systems, see Singhose (2009). The input shapers are typically used in feed-forward path for filtering reference commands. *ZV*, *ZVD*, *UM* and *EI* are classical shapers with lumped delays proposed in Smith (1958); Singer and Seering (1990); Pao and Singhose (1996); Singhose et al. (1994, 1997) and have been investigated in a broad sense Singhose (2009). Alternative to the lumped delay shapers, a novel type of shaper with an equally distributed delay was proposed in Vyhlídal et al. (2013a) and this work was generalized with fully analytical design in Vyhlídal and Hromčík (2015) by combining a lumped and distributed delay of a preselected shape. These new shaper structures lead to a retarded distribution in the spectrum of the zeros. Vyhlídal et al. (2016) has utilized the retarded type shapers in the feedback architecture by the inverse form and it has been shown that the proposed architecture provides a successful performance for disturbance rejection and reduced sensitivity to residual vibrations.

An important interest point in the design of input shapers are the "hard" non-linearities in control action. Magnitude saturation in the control input is one of the most common ones to be dealt with. The classical shaper design can not suppress the oscillations fully when the saturation effect on control action exists. Despite the importance of the problem, a few studies have been done to overcome this issue. A switching algorithm was proposed in Eloundou and Singhose (2002) for saturation compensation with respect to the saturation limit; *ZV* and *UM* shapers in the feed-forward path were parametrized via numerical optimization for this case. Robertson and Erwin (2007) offered the feed-forward *Saturation-Reducing ZV* (*SRZV*) shaper for specific PD controlled flexible systems, namely lightly damped with natural frequency greater than or equal to 1 Hz. Note that the feed-forward design of input shapers is problematic due to lack of disturbance rejection capability. An artificial saturation block followed with the *ZV* shaper has been used in the feed-forward path within the closed-loop in Sorensen et al. (2007); Huey et al. (2008) to suppress undesired effects of actuator saturation.

In this study, we focus on the rejection of undesired saturation effects on residual vibrations via the recent progress on input shaping. A common structure in applications, namely a flexible system connected to a single PD controlled system (the actuator), is considered. As the main result, it is shown that the *inverse distributed delay shaper* in the feedback loop is successful and more efficient

---

[⋆] The presented research has been supported by the Czech Science Foundation under the project No. 16-17398S. The work of the first author, which was performed during his study stay at CTU in Prague, was supported under scholarship programme 2214-A of The Scientific and Technological Research Council of Turkey.

2405-8963 © 2017, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved.
Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2017.08.350

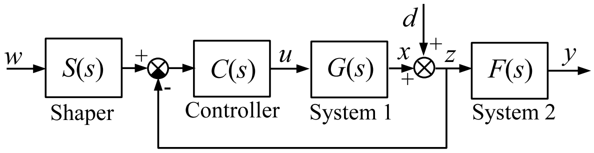

Fig. 1. Input shaper in open-loop scheme

for the design to compensate the effects of saturation in control input. We performed the proposed structure on an experimental set-up and validated the theoretical results.

The paper is organized as follows. In Section 2, the preliminaries and the recent results on input shaping are given. Saturation effect on input shaping and existing solutions are represented in Section 3. The problem solution by inverse feedback shaper is proposed in Section 4, and then applied to an experimental set-up in Section 5 besides the comparison with an existing solution. Finally, the paper is concluded with the results summary.

2. PRELIMINARIES ON INPUT SHAPING

First, consider a classical scheme with an input shaper within a control system, which is shown in Fig. 1. The task of a shaper $S(s)$ is to shape (filter) the set-point command w of the control loop in such a way that a given oscillatory mode of the attached flexible sub-system $F(s)$ is not excited. Note that the compensation is done in the feed-forward manner and output y of the flexible part is not measured. For example, in the crane application, the System $G(s)$ represents the dynamics of the trolley and $F(s)$ represents dynamics of the suspended load with an oscillatory mode. The purpose of the controller $C(s)$ is to control the position z of the trolley following the command w modified by the shaper $S(s)$.

Consider that the oscillatory mode of $F(s)$ is given by a single oscillatory mode

$$r_{1,2} = -\beta \pm \Omega j \tag{1}$$

where $\beta = \omega\zeta$, $\Omega = \omega\sqrt{1-\zeta^2}$; and ζ, ω are the damping ratio and the natural frequency of the mode to be compensated. For the compensation purpose, it is sufficient that a couple of shaper $S(s)$ zeros $s_{1,2}$ is placed on the poles $r_{1,2}$. Thus, the shaper performs the task of a notch filter. However, thanks to the presence of delays, better time-domain responses can be achieved compared to finite dimensional notch filters.

2.1 Neutral vs. Retarded Type Shapers

The shapers can be classified as neutral and retarded type regarding to the distribution of their zeros. The zeros of neutral shapers are distributed within a vertical strip of the complex plane while the the zeros of retarded shapers depart from the imaginary axis as their moduli increase, as discussed in Vyhlídal and Hromčík (2015).

As an example of neutral shapers, the well-known ZV shaper has the transfer function

$$S(s) = \mathcal{A} + (1-\mathcal{A})e^{-s\mathcal{T}} \tag{2}$$

where the gain and the delay are parametrized as

$$\mathcal{A} = \frac{e^{\beta\pi/\Omega}}{1+e^{\beta\pi/\Omega}},\ \mathcal{T} = \frac{\pi}{\Omega} \tag{3}$$

to compensate the damped oscillatory mode (1), see Singhose et al. (1994).

The retarded type shaper has been proposed in Vyhlídal et al. (2013a), see also Vyhlídal and Hromčík (2015). As a recent example, we present a distributed delay shaper (let us call it as $D^\beta ZV$), which was proposed in Alikoç et al. (2016), given by

$$S_{\mathrm{D}^\beta\mathrm{ZV}}(s) = A + (1-A)\frac{\beta(1-\eta e^{-sT_1})}{(1-\eta)(s+\beta)}e^{-sT_2} \tag{4}$$

where $\eta = e^{-\beta T_1}$, T_1 is the distributed delay chosen freely in the range $(0, \frac{2\pi}{\Omega})$ and T_2 is the lumped delay to be parametrized. The parameters of the $D^\beta ZV$ shaper (4) to cancel the oscillatory mode (1), can be given in a simpler form comparing with the original paper as follows:

$$A = \frac{2\beta\ \mathrm{Sin}\left(\frac{\Omega \mathrm{T}_1}{2}\right)\mathrm{e}^{\frac{\beta\pi}{\Omega}}\sqrt{\eta}}{2\beta\ \mathrm{Sin}\left(\frac{\Omega \mathrm{T}_1}{2}\right)\mathrm{e}^{\frac{\beta\pi}{\Omega}}\sqrt{\eta}+\Omega(1-\eta)}, \tag{5a}$$

$$T_2 = \frac{\pi}{\Omega} - \frac{T_1}{2}. \tag{5b}$$

Note that the distribution of the delay T_1 within the shaper is exponentially weighted which leads also to retarded characteristics.

2.2 Inverse Shaper Design in the Feedback Loop

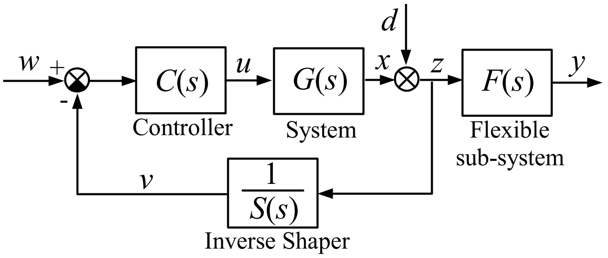

Fig. 2. Closed-loop system with inverse signal shaper

The feedback architecture for the shaper design shown in Fig. 2 has been proposed in Vyhlídal et al. (2016). The main motivation for this architecture is to cancel the effect of the disturbance d on the residual vibrations of the flexible sub-system $F(s)$, as well as the effect of the reference input w. To see this fact, consider the transfer functions,

$$T_{wy}(s) = \frac{S(s)C(s)G(s)}{S(s)+C(s)G(s)}F(s), \tag{6}$$

$$T_{dy}(s) = \frac{S(s)}{S(s)+C(s)G(s)}F(s) \tag{7}$$

from the reference and the disturbance, respectively, to the output y of the flexible sub-system. It is clear that the zeros of the shaper $S(s)$, which are also the zeros of the closed-loop transfer functions (6) and (7), can be assigned to cancel the oscillatory modes of $F(s)$ given by (1).

It is noted in Vyhlídal et al. (2016) that the most convenient shapers in the feedback architecture as in Fig. 2 are of retarded type with distributed delays, considering the closed-loop stability issues. The retarded spectrum of the distributed delay shapers, which is departing from the imaginary axis with increasing moduli of zeros, results the closed-loop poles moving left hand side (stable region) in