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A compensator for attenuation of wave reflections in long cable actuator–plant interconnections with guaranteed stability ☆

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Abstract

The wave reflection phenomenon that appears when actuator and plant are connected through long cables is studied in this paper. In several applications, the perturbation induced by the presence of these reflected waves is non-negligible and seriously degrades the performance of the control and the operation of the system. Standard compensation schemes are based on matching impedances at specific frequencies (possibly infinity) and are realized with the addition of linear RLC filters. Impedance matching is ineffective if there is no single dominant frequency in the system and/or the plant is highly uncertain. In a recent paper the authors proposed a novel compensator design framework, based on the scattering representation of the transmission line, which is applicable for the latter scenario. In contrast with standard schemes the compensators are *active* and require for their implementation regulated sources placed either on actuator or on plant side. The use of active compensators raises the issues of *well-posedness* and *stability* of the design. The former was addressed in our previous work making a critical discretization assumption that generated an approximated finite-dimensional model; on the other hand, the stability question was left open. Both issues are fully solved in the present note for the complete infinite-dimensional system. We propose a family of adaptive compensators that requires only knowledge of the line propagation delay and guarantees stable asymptotic regulation for all (unknown) linear plants and actuators with passive impedances. Furthermore, under some additional reasonable assumptions, transient performance improvement is ensured. Some simulation results on a benchmark example of voltage overshoot suppression in AC drives are shown.

Keywords: Indefinite dimensional systems; Adaptive control; Delay-differential systems; Electrical systems

1. Introduction

In this paper, we are interested in the problem of compensation of the wave effects that appear when a controlled plant, with uncertain dynamic impedance, is coupled to an actuator through long feeding cables. The connecting cables behave as a transmission line inducing wave reflections that deform the transmitted signals and degrade the quality of the control. In some applications, including the classical power distribution and digital communications problems, attention can be centered on one dominant operating frequency. In these cases, and assuming the plant is linear and known, it is possible to design linear time-invariant (LTI) RLC filters that will match—*at that particular frequency*—the load impedance to the impedance of the (compensated) line, hence avoiding the wave reflection problem. If the plant parameters are uncertain, adaptive implementations are needed, see Cottee and Duncan (2003) for a recent interesting application. Unfortunately, the resulting adaptation problem is nonlinearly parameterized and a series of approximating assumptions are needed to get a working design. It should be mentioned that the overall concept of impedance matching is far from clear if the plant is nonlinear.

Wave reflection reduction is an important problem also in robotic teleoperation where, as first suggested in Anderson and

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Spong (1989), introducing a scattering codification scheme that "transforms" the data transfer pure delays into a transmission line ensures stability for all passive human operators and contact environments. However, to enhance performance, the high frequency gains of the impedances must be matched. As originally shown in Niemeyer and Slotine (1991), this can be done with PI (velocity) control compensators. See also Stramigioli, van der Schaft, Maschke, and Melchiorri (2002) and Section 5 of this paper.

There are some applications where there is no single dominant frequency and/or the plant is unknown. A prototypical example is the overvoltage problem in high-performance AC drives (Persson, 1992), where the actuator is a PWM inverter that sends through the long cables a fast rising step that should be reproduced without distortion on the motor side. The reflecting waves generate high voltage spikes at the motor terminals that can produce potentially destructive stress on the motor insulation, constituting a serious practical problem. The behavior of the motor at high frequencies is highly uncertain, and we have to rely on experimental data to obtain a linear approximation. Using this model, or the on-line measurements, it is possible to determine the dominant frequency that we would like to suppress via impedance matching (or aim at infinite-frequency matching as in teleoperation). To achieve impedance matching, RLC filters must be added on the motor terminals that are, unfortunately, not accessible in many applications, hence it is necessary to install the filter at the inverter terminals with significantly reduced effectiveness (Lee & Nam, 2002).

In Ortega, de Rinaldis, Spong, Lee, and Nam (2004) we suggested a novel framework for the design of *active compensators* to reduce the wave reflections when the plant is unknown, when there is no single dominant frequency in the system and when compensation is restricted to the actuator side. The qualifier "active" is important since we depart from the standard passive LTI RLC filter implementations and assume that regulated sources can be placed at the actuator terminals. The main features of the approach are the adoption of the port interconnection viewpoint for the controller design, and the use of the scattering variable representation of the transmission line. Using port representations of the four components—actuator, compensator, transmission line and plant—allows one to formulate this (non-standard) controller design problem in terms of achievable behaviors between the terminals of the first and the third ports, *without the knowledge* of the plant (or the actuator). On the other hand, the scattering representation relates voltages and currents at the line extremes via a simple delay transfer matrix, with the delay being the line propagation. Henceforth, the interconnection of the line with a linear compensator will also be an LTI system, albeit *infinite-dimensional*, and the characterization of the achievable (actuator-to-plant) behaviors becomes an algebraic problem. Using this framework, and motivated by the robotic teleoperation application explained above, we studied in Ortega, de Rinaldis, Spong et al. (2004) an ideal compensator that—decoupling voltages *and* currents—transforms the transmission line into a pure delay. This controller is the exact dual of the one used in teleoperation. It was shown that, unfortunately, the controller is not physically realizable, and an approximation that decouples only the current behavior was proposed. The motivation to consider current decoupling was the possibility of an adaptive implementation of the compensator that reduces the required prior knowledge on the transmission line.

In this paper we complement and extend the material presented in Ortega, de Rinaldis, Spong et al. (2004) solving, in particular, the fundamental problems of *well-posedness* and *stability* that arise due to the use of active compensators. The first point was addressed in Ortega, de Rinaldis, Spong et al. (2004) making a critical discretization assumption that generated a finite-dimensional purely discrete-time *approximation* of the infinite-dimensional delay-differential system. The question of stability was left open in our previous work. Both issues are fully solved in the present note for the complete infinite-dimensional system, where we prove that, thanks to current decoupling, well-posedness and stability can be ensured under practically reasonable assumptions on the plant and actuator impedances. More specifically, we characterize a family of compensators (that contains as a particular case the scheme proposed in Ortega, de Rinaldis, Spong et al., 2004), such that the port variables of the compensated line—from the actuator and the plant sides—satisfy a *passivity* condition. In this way, stability will be ensured for all plants and actuators with passive impedances. An additional contribution of our work is the proof that, under some additional assumptions, transient performance is also improved with respect to the performance achievable with LTI RLC filtering. Finally, to underscore the methodological aspect of our approach and broaden its target audience, we emphasize the importance of the use of scattering variables and elaborate on the connection between our wave attenuation problem and the well-known teleoperation tasks.

Notation: The dynamics of the system under study is infinite dimensional and is described by *linear delay-differential equations*. To simplify the notation we use the differentiation and advance-delay operators, acting on continuous-time signals $x : \mathbb{R}_+ \to \mathbb{R}$, as $(p^k x)(t) := (\mathrm{d}^k/\mathrm{d}t^k)x(t)$ and $(q^{\pm k}x)(t) = x(t \pm kd)$, respectively, where $d \in \mathbb{R}_+$ and $k \in \mathbb{Z}_+$. Their Laplace transform counterparts, which are used to define (possibly two-dimensional) transfer functions, are s^k and e^{kds}, respectively. The set of rational functions, i.e., ratio of polynomials, in μ will be denoted by $\mathbb{R}(\mu)$, $\mathbb{R}^{m\times p}(\mu)$ is the set of $m \times p$ matrices with elements in $\mathbb{R}(\mu)$, while $\mathbb{R}(\mu_1, \mu_2)$ will denote ratios of polynomials of the form $\sum_{i,j} c_{ij}\mu_1^i \mu_2^j$, with $c_{ij} \in \mathbb{R}$. The relative degree of the elements of $\mathbb{R}(\mu)$, i.e., the difference between the degrees of the denominator and the numerator polynomials, is denoted with $rel\,deg(\cdot)$.

Caveat: In order to comply with the page limitations all lemmata and propositions are presented without proofs. A full version of the paper is available upon request to the second author.

2. Systems model

To model the plant connected to the actuator through long cables we consider the configuration shown in Fig. 1, where we model the *connecting cables* as a two-port system whose