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Frequency domain based real-time performance optimization of Lur'e systems

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ABSTRACT

Nonlinear effects can lead to performance degradation in (controlled) dynamical systems. This paper provides a practical method to optimally compensate performance degrading nonlinear effects in Lur'e-type systems in an automated way. Using novel frequency domain based techniques, a well defined performance measure is derived and real-time performance optimization is achieved by application of extremum seeking algorithm. This yields a new method for real-time compensation of performance degrading nonlinear effects, which is successfully demonstrated in both simulation and experiment.

1. Introduction

Frequency domain analysis plays an important role in the control of Linear Time Invariant (LTI) systems. For LTI systems, frequency domain methods are often used for modeling and performance analysis. Frequency domain methods provide a framework for optimal control design as well. In general frequency domain methods cannot be applied to nonlinear systems in straightforward manner and the notion of performance is difficult to define for nonlinear systems. However, when applied with care, frequency domain methods yield an insightful, useful and practically applicable way to assess and optimize the performance of certain nonlinear systems [1–6].

Several approaches for the analysis and modeling of nonlinear systems in frequency domain exist [2,7–9]. For example in [8], a nonlinear frequency response function is proposed for convergent nonlinear systems and used to assess the performance of a high precision motion system in [3]. Moreover, in [2,10,11] it is shown that an extension of the sinusoidal input describing function allows frequency domain methods to identify non-parametric models of nonlinear motion systems, subject to a sinusoidal input.

Frequency domain methods have been used for performance optimization of controlled nonlinear systems as well. In [5], frequency domain methods are used to optimally design a feed forward friction compensator in a high precision motion stage of a transmission electron microscope. Recently, these results are extended in [6] yielding a frequency domain methodology that allows us to formulate a novel, practically applicable performance measure and corresponding performance optimization

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problem for Lur'e-type systems. The work presented in this paper extends these results by presenting a novel method for real-time, automated performance optimization for Lur'e-type systems.

The results in the following are intended for engineering practice and require minimal *a priori* knowledge of the nonlinearities while optimization is performed automatically. To motivate the practical use of the method consider a system as depicted in Fig. 1. The system consists of a mass connected with a linear spring and a linear damper. The mass interacts with a magnetic field which exerts a force to the mass. The magnetic force depends nonlinearly on the displacement of the mass and cannot be measured directly. Because of this, the nonlinearity profile is not known and therefore compensating the nonlinearity cannot be achieve by the common inverse approach of the nonlinearity. One of the benefits of the proposed method is that it can tackle this problem because it only requires the input–output measurement of the system instead that of the nonlinearity.

This work is organized the following manners, first in Section 2 the required nomenclature and preliminaries are introduced. Next, Section 3 deals with performance optimization of Lur'e-type systems. This section consists of four main parts: analysis of Lur'e type systems, introduction of a frequency domain performance measure for nonlinear systems, design of static compensators to optimize this performance and finally, the application of extremum seeking algorithms to optimize the design of these compensators in real-time. The resulting framework allows for real-time performance optimization of Lur'e-type systems, based on a frequency domain representation of the systems output. This framework is applied in simulation in Section 4 and used in Section 5 to optimize the performance of a nonlinear amplifier in experiments. Finally, Section 6 presents conclusions and recommendations for future research.

2. Nomenclatures and preliminaries

Let $\mathcal{C}_p$ denote the space of piecewise continuous, bounded functions $\mathbb{R} \mapsto \mathbb{R}_{\geq t_0}, t_0 \in \mathbb{R}$. Then the analysis in this paper focusses on Lur'e-type systems which are defined as follows:

Definition 1 (*Lur'e-type system*). Consider a Lur'e-type system depicted in Fig. 2, such that

$$\begin{aligned} \dot{x}(t) &= Ax(t) + B_u u(t) + B_w w(t), \quad x(t_0) = x_0 \\ \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} &= \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} x(t) + \begin{bmatrix} D_{1,w} & D_{1,u} \\ D_{2,w} & D_{2,u} \end{bmatrix} \begin{bmatrix} w \\ u \end{bmatrix} \\ u(t) &= -\phi(y_2(t)) \end{aligned} \tag{1}$$

with $w \in \mathcal{C}_p$ an external input, $y_1(t), y_2(t) \in \mathbb{R}$ the outputs and $x(t) \in \mathbb{R}^n$ the states of the system. Furthermore, $A \in \mathbb{R}^{n \times n}, B_u \in \mathbb{R}^{n \times 1}, B_w \in \mathbb{R}^{n \times 1}, C_\ell \in \mathbb{R}^{1 \times n}$ and $D_{\ell,u/w} \in \mathbb{R}, \ell = 1,2$ constitute a state space representation (1) of the dynamics and $u(t) \in \mathbb{R}$ is a nonlinear feedback generated by a static nonlinear mapping $\phi : \mathbb{R} \mapsto \mathbb{R}$.

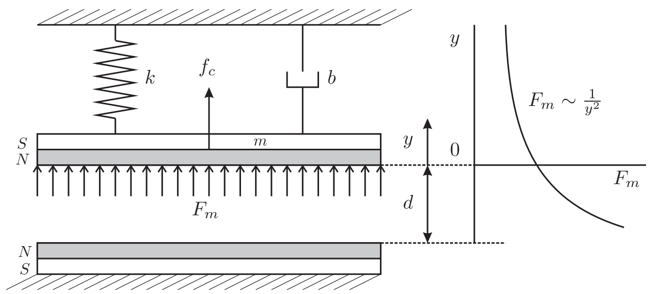

Fig. 1. Schematic depiction of a mass, subject to a nonlinear magnetic field.

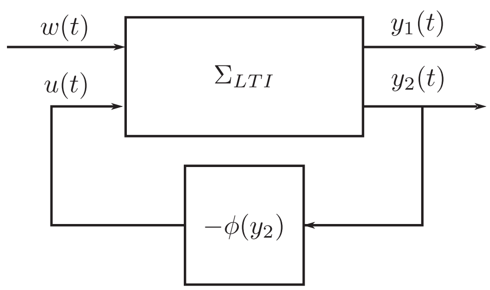

Fig. 2. Lur'e-type system.