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Adaptive narrow band disturbance rejection applied to an active suspension—an internal model principle approach☆

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Abstract

This paper presents a methodology for feedback adaptive control of active vibration systems in the presence of time varying unknown narrow band disturbances. A direct adaptive control scheme based on the internal model principle and the use of the Youla–Kucera parametrization is proposed. This approach is comparatively evaluated with respect to an indirect adaptive control scheme based on the estimation of the disturbance model. The comparative evaluation is done in real time on an active suspension system.

Keywords: Active vibration control; Active suspension; Adaptive control; Feedback control; Internal model principle

1. Introduction

One of the basic problems in active vibration control is the attenuation (rejection) of narrow band disturbances of unknown or varying frequency.[2]

Solutions for this important practical problem have been proposed by the signal processing community and a number of applications are reported (Elliott & Nelson, 1994; Elliott & Sutton, 1996; Beranek & Ver, 1992; Fuller, Elliott, & Nelson, 1995). However, these solutions (inspired by Widrow's technique for adaptive noise cancellation (Widrow & Stearns, 1985) ignore the possibilities offered by feedback control systems and require an additional transducer. The disadvantages of this approach are: (1) It requires the use of an additional transducer. (2) Difficult choice for the location of this transducer. (3) It requires adaptation of many parameters.

To achieve the rejection of the disturbance (at least asymptotically) without measuring it, a feedback solution can be considered. The common framework is the assumption that the narrow band disturbance is the result of a white noise or a Dirac impulse passed through the "model of the disturbance".[3] Several problems have been considered within this framework leading to adaptive feedback control solutions: (1) Unknown plant and disturbance model (Feng & Palaniswami, 1992). (2) Unknown plant model and known disturbance (Sun & Tsao, 2000; Zhang, Mehta, Bitmead, & Johnson, 1998). (3) Known plant and unknown disturbance model (Bodson & Douglas, 1997; Amara, Kabamba, & Ulsoy, 1999; Valentinotti, 2001; Marino, Santosuosso, & Tomei, 2003; Ding, 2003; Gouraud, Gugliemi, & Auger, 1997; Hillerstrom & Sternby, 1994).

The present paper belongs to the last category, since in the context of active suspension the model of the plant can be obtained by standard system identification and does not

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[2] Disturbance with energy concentrated in a narrow band around an unknown or varying frequency.

[3] Throughout the paper it is assumed that the order of the disturbance model is known but the parameters of the model are unknown (the order can be estimated from data if necessary).

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normally change during operation. The same situation is encountered in other application areas (Valentinotti, 2001; Amara et al., 1999). Among the various approaches considered for solving this problem, one can mention: (1) Use of the internal model principle (Francis & Wonham, 1976; Johnson, 1976; Bengtsson, 1977; Tsypkin, 1997; Valentinotti, 2001; Amara et al., 1999; Gouraud et al., 1997; Hillerstrom & Sternby, 1994) (2) Use of an observer for the disturbance (Marino et al., 2003; Ding, 2003) (3) Use of the "phase-locked" loop structure (Bodson & Douglas, 1997). Of course since the parameters of the disturbance model are unknown all these approaches lead to an adaptive implementation which can be of *direct* or *indirect* type.

From the user point of view and taking into account the type of operation of existing adaptive disturbance compensation systems one has to consider two modes of operation of the adaptive schemes :

- *Self-tuning* operation (the adaptation procedure starts either on demand or when the performance is unsatisfactory and the current controller is frozen during the estimation/computation of the new controller parameters).
- *Adaptive* operation (the adaptation is performed continuously and the controller is updated at each sampling).

The paper explores the use of the internal model principle for the rejection of time-varying unknown narrow band disturbances. The controller should incorporate the model of the disturbance (Francis & Wonham, 1976; Johnson, 1976; Bengtsson, 1977; Tsypkin, 1997). Therefore the rejection of unknown disturbances raises the problem of adapting the internal model of the controller and its re-design in real-time.

One way for solving this problem is to try to estimate in real time the model of the disturbance and re-compute the controller, which will incorporate the estimated model of the disturbance (as a pre-specified element of the controller). While the disturbance is unknown and its model needs to be estimated, one assumes that the model of the plant is known (obtained for example by identification). The estimation of the disturbance model can be done by using standard parameter estimation algorithms (see for example Landau, M'Sirdi, & M'Saad, 1986; Ljung, 1999). This will lead to an indirect adaptive control scheme. This approach has been investigated in Bodson & Douglas (1997), Gouraud et al. (1997), Hillerstrom & Sternby (1994).

However, by considering the Youla–Kucera parametrization of the controller (known also as the Q-parametrization) (see Fig. 1) it is possible to insert and adjust the internal model in the controller by adjusting the parameters of the Q polynomial. It comes out that in the presence of unknown disturbances, it is possible to build a direct adaptive control scheme where the parameters of the Q polynomial are directly adapted in order to have the desired internal model without recomputing the controller (polynomials R_0 and S_0 in Fig. 1 remain unchanged). The number of the controller

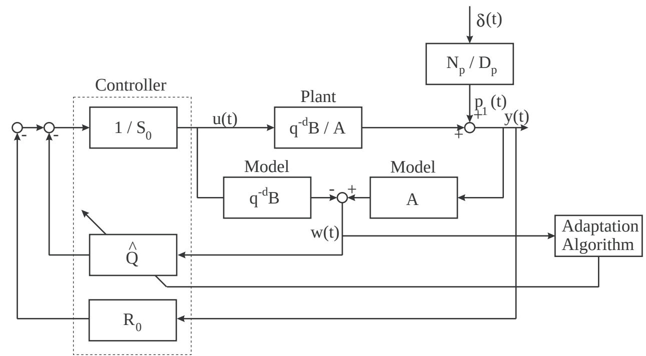

Fig. 1. Direct adaptive control scheme for rejection of unknown disturbances.

parameters to be directly adapted is roughly equal to the number of parameters of the denominator of the disturbance model. In other words, the size of the adaptation algorithm will depend upon the complexity of the disturbance model.

This paper focuses on the development of the direct feedback adaptive control for the case of unknown and time-varying frequency narrow band disturbances applied to an active suspension. Specifically, variable frequency sinusoidal disturbances are considered. The direct adaptive control scheme to be presented takes advantage of the Youla–Kucera parametrization for the computation of the controller. This algorithm takes its roots from an idea of Tsypkin (1991).[4] A similar approach has been considered in Valentinotti (2001) for an application to a chemical reactor but a theoretical analysis of the scheme is not provided. A related paper is Amara et al. (1999) where the application field is the active noise control in an acoustic duct. However, the theoretical analysis is limited to a BIBO property of the scheme. In the present paper an analysis of the asymptotic properties of the scheme in terms of disturbance rejection and parameters convergence is provided. For evaluation purposes (complexity and performance) an indirect adaptive control scheme based on the Internal Model Principle has been also developed.

The paper is organized as follows. In Section 2 the active suspension on which we shall test the algorithms is presented. Section 3 is dedicated to a brief review of the plant, disturbance and controller representation as well as of the Internal Model Principle. The direct adaptive control scheme is presented in Section 4 and the corresponding stability analysis is given in Section 5. Section 6 presents the results obtained in real time on the active suspension. Some concluding remarks are given in Section 7. The indirect adaptive control scheme is presented in Appendix A.

[4] Note that the adaptive rejection of unknown disturbances using the Youla Kucera parametrization is not considered in the survey (Anderson, 1998).