Control Engineering Practice 32 (2014) 87–95

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

# An application of adaptive techniques to vibration rejection in adaptive optics systems

Riccardo Muradore [a,*], Lorenzo Pettazzi [b], Richard Clare [b], Enrico Fedrigo [b]

[a] Department of Computer Science, University of Verona, Strada Le Grazie 15, 37134 Verona, Italy
[b] Department of Adaptive Optics, European Southern Observatory ESO, Germany

ARTICLE INFO

*Article history:*
Received 22 October 2013
Accepted 11 July 2014
Available online 30 August 2014

*Keywords:*
Adaptive optics
Vibration rejection
Adaptive control
Atmospheric correction
Ground-based telescope

ABSTRACT

In modern Adaptive Optics (AO) systems, lightly damped sinusoidal oscillations resulting from telescope structural vibrations have a significant deleterious impact on the quality of the image collected at the detector plane. These oscillations can be observed in any mode of a generic modal representation of the AO wave-front sensor. A technique for the rejection of periodic disturbances recently presented in the literature has been adapted to the problem of rejecting vibrations in AO loops. The proposed methodology aims at estimating the harmonic disturbance together with the response of the plant at the vibration frequency. The algorithm has been tested in simulation on realistic scenarios and at the telescope.

© 2014 Elsevier Ltd. All rights reserved.

## 1. Introduction

The effect of telescope vibrations on the performance of high accuracy astronomical instruments and the design of algorithms to mitigate them is a topic that has generated growing interest over the past years (see Kulcsár et al., 2012 for an overview based on the on-sky data recorded at several observatories around the world). Several measures have been taken at the observatories to prevent these lightly damped harmonic oscillations from being generated and propagated to the optical components, like damping or isolation of vibrations sources such as fans and coolers, but not all vibrations could be suppressed in these ways.

The core of modern ground-based telescopes is the Adaptive Optics (AO) system. AO uses in a feedback loop the measurements of one (or more) Wave Front Sensor (WFS) to flatten distorted wave fronts with a deformable mirror to provide diffraction-limited images, Fedrigo, Muradore, and Zilio (2009) and Roddier (1999). AO systems are particularly sensitive to vibrations as discussed in Powell (2011), and a considerable amount of research has been performed in the recent past in order to devise algorithms for the mitigation of such detrimental perturbations. Some of the research activity in this area has led to the development of methodologies based on the internal model principle (Correia, Véran, & Herriot, 2010). These approaches assume prior knowledge of the plant (i.e. deformable mirror, wave-front sensor, computational delay) and of the characteristics of the perturbations. However the performance of model-based techniques is highly sensitive to variations in the characteristics of plant and perturbations. In order to overcome this issue, in Memon, Petit, Fusco, and Kulcsar (2010) batches of closed-loop telemetry data are used to estimate on-line the characteristics of the slowly varying perturbation and to adapt the control law on a regular basis according to the results of the estimation process. This approach is somehow reminiscent of the typical indirect adaptive control paradigm (Åström & Wittenmark, 1998).

This paper proposes the use of a fully recursive adaptive algorithm for vibration rejection in AO systems. The proposed algorithm can be easily integrated in a standard AO control architecture and can cope with variations in both the plant dynamics and the perturbation signal. The present work extends the preliminary results reported in Muradore, Pettazzi, Fedrigo, and Clare (2012) by testing the algorithm in more demanding working conditions and in different control configurations. The Adaptive Vibration Cancellation (AVC) algorithm proposed is derived from the works in Pigg and Bodson (2010a, 2010b) and, unlike other similar approaches (Di Lieto, Haguenauer, Sahlmann, & Vasisht, 2008), is derived without assuming any knowledge of the plant dynamics and thus being able to work in different operational conditions without human intervention.

In this work, the focus is on the vibration rejection on tip/tilt modes that are, usually, the most affected by this kind of disturbance. However, data taken at the telescope shows that vibrations may also affect higher modes. The proposed AVC can also be easily applied to higher modes thanks to its modularity as shown in the experimental section. The paper is organized as follow. In Section 2 the requirements for the algorithm are listed. The approach for the vibration rejection using adaptive control is described in Section 3. The two AO system configurations taken

* Corresponding author. Tel.: +39 045 802 7835; fax: +39 045 802 7068.
*E-mail address:* riccardo.muradore@univr.it (R. Muradore).

http://dx.doi.org/10.1016/j.conengprac.2014.07.003
0967-0661/© 2014 Elsevier Ltd. All rights reserved.

into account and the corresponding results are presented in Sections 4 and 5 using both simulated and real data respectively. Finally some conclusions are drawn in Section 6.

## 2. Requirements for the vibration rejection algorithm

The expected operational conditions and the requirements imposed by the implementation platform (i.e. Standard Platform for Adaptive optics Real Time Application, SPARTA, see Fedrigo et al., 2006 for an overview) define design constraints that in turn guide the choice of the approach proposed in this paper among the many others available in the literature (e.g. Köroğlu & Scherer, 2011; Niedzwiecki, 2010; Pigg & Bodson, 2010a). The following design drivers were identified early in the development process.

*Characteristics of the disturbance signal*: The typical telescope operation scenario of an AO system assumes that at the beginning of the observation the new astronomical target is quickly acquired. In this stage, accuracy is of no concern and the AO system is switched off. Once the target is acquired, the telescope switches to tracking mode in which it rotates at very low speeds, very quiet and stable conditions are enforced, and the AO system is switched on. During tracking the telescope represents by design a very steady plant. However, small variations of the perturbation signal can happen at any time. Typical examples are jitter of the vibration central frequency (see for example data in Di Lieto et al., 2008) or amplitude variations (the expected perturbation can have a non-purely harmonic behavior with damping factors up to 0.8% as demonstrated in the data shown in Bourlon, Ducros, & Faucherre, 1992).

*Modularity*: The standard AO loop control architecture is based on the static decoupling and pure integral controllers, Roddier (1999). It shall be possible to introduce the VC in such an architecture as an add-on module, e.g. without requiring a complete re-design of the AO control system. To this end the algorithm needs to be encapsulated into a self-contained module to be executed in real-time in parallel to the already existing AO controller.

*Flexibility*: The VC algorithm shall be able to work in a fairly large spectrum of conditions dictated by the different science cases (e.g. different sampling rates, switching among different measurement sources) requiring the least possible direct operator intervention. This functional requirement means that the algorithm should be parameterized in terms of the integration time of the WFS and could be switched on and off without affecting the overall control architecture and should not rely on a priori models of the system.

## 3. Adaptive cancellation algorithm

The approach proposed in the present work is a modification of an adaptive algorithm by Pigg and Bodson (2010a,b) that appeared recently in the literature. After briefly recalling the idea behind this approach, our version of the algorithm that better fits the specific requirements in an AO system will be reported. In the following remarks it is explained that our modified version of the algorithm does not affect the equilibrium point analysis and the stability results reported in Pigg and Bodson (2010b).

The algorithm belongs to the family of adaptive vibration controllers and consists of a three-step procedure:

1. online estimation of the time-varying harmonic perturbation parameters: amplitude, pulsation ($\omega_t = 2\pi f_t$ or vibration frequency $f_t$), and phase,
2. online estimation of the frequency response of the plant at the vibration frequency $f_t$,
3. update the control command $u_{AVC}$ to cancel/minimize the vibration.

The equations related to these steps are reported within the *state equation* (Steps 1 and 2) and the *output equation* (Step 3) of a non-linear state-space representation.

The main advantage of this algorithm is that it also works when the plant is an unknown time-varying system. Moreover, even though the original algorithm assumes a basic feedback control configuration without reference signals and colored noise, in the simulation section it will be shown that this method also performs well when those time-varying exogenous signals are involved.

Assume that the measurement takes the form

$$y_t = P(s)u_t + v_t \tag{1}$$

where $P(s)$ is the (stable linear) transfer function of the plant (unknown) and $v_t$ is the vibration to be rejected by the control signal $u_t$. According to Pigg and Bodson (2010a), the time-varying sinusoidal signal $m_t \cos(2\pi f_t t + \varphi_t)$ describing the vibration at frequency $f_t$ can be re-written as

$$v_t = \lambda_c(t)\cos(\alpha_t) + \lambda_s(t)\sin(\alpha_t) = w_t^T \lambda_t \tag{2}$$

where

$$w_t = \begin{bmatrix} \cos(\alpha_t) \\ \sin(\alpha_t) \end{bmatrix}, \quad \lambda_t = \begin{bmatrix} \lambda_c(t) \\ \lambda_s(t) \end{bmatrix}, \quad \alpha_t = \alpha_0 + \int_0^t 2\pi f_\tau \, d\tau$$

A control signal of the form

$$u_t = \theta_c(t)\cos(\hat{\alpha}_t) + \theta_s(t)\sin(\hat{\alpha}_t) = \hat{w}_t^T \theta_t \tag{3}$$

where

$$\hat{w}_t = \begin{bmatrix} \cos(\hat{\alpha}_t) \\ \sin(\hat{\alpha}_t) \end{bmatrix}, \quad \theta_t = \begin{bmatrix} \theta_c(t) \\ \theta_s(t) \end{bmatrix}. \tag{4}$$

for the right $\theta_t$ and $\hat{w}_t$ (i.e. $\hat{w}_t \simeq w_t$) can be used to cancel out the vibration $v_t$ in (1). The steady-state output of the plant takes the form

$$y_t = P(s)u_t + v_t = w_t^T(G_t\theta_t + \lambda_t) \tag{5}$$

where the matrix

$$G_t = \begin{bmatrix} P_R(t) & P_I(t) \\ -P_I(t) & P_R(t) \end{bmatrix}$$

contains the unknown real and imaginary parts of the plant's frequency response at $f_t$ ($P(j2\pi f_t) = P_R(t) + jP_I(t)$). The value $y_t$ will be close to zero (i.e. perfect rejection) if the unknown parameters $\theta_t$ and $G_t$ are chosen to guarantee

$$G_t\theta_t + \lambda_t \simeq 0. \tag{6}$$

In the next section, the equations of the adaptive estimator will be presented; for a more detailed discussion on the steady-state case when the vibration frequency is fixed and on the comparison with the least square solution, refer to Pigg and Bodson (2010a).

### 3.1. State equation

Collecting in the state vector $x$ the unknowns related to the plant and vibration amplitude and phase, i.e. $x := [P_R \ P_I \ \lambda_c \ \lambda_s]^T$, Eq. (5) can be rewritten as

$$y_t = W(t,\theta)^T x_t \tag{7}$$

Download English Version:

https://daneshyari.com/en/article/700021

Download Persian Version:

https://daneshyari.com/article/700021

Daneshyari.com