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Estimating the reduction of vibrations in MACAO and ALTAIR AO systems using H_2 control synthesis

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Abstract. Vibrations and external disturbances of various origins (e.g. structural, wind, axis control) have been shown to degrade the image quality at the instrument focus of the telescopes. Furthermore, the next generation of extremely large telescopes (ELTs) and their associated adaptive optics (AO) systems will reach new levels of high angular resolution, thus reducing vibrations represents becomes highly desirable to ensure that the scientific instruments will take full advantage of this unprecedented resolution. We present a method that aims to mitigate the effect of vibrations at Paranal's MACAO and Gemini North's ALTAIR instruments. A frequency-based controller, based on the H_2 synthesis technique [1,2], is used to maximize the performance of the tip and tilt closed-loop systems. The pseudo open-loop slopes are reconstructed from on-sky data and then used to find the controller that minimizes the variance of the tip-tilt residuals in an off-line simulation of the closed-loop system.

1. Introduction

Guesalaga et al. [1], present novel procedure for tip-tilt control that reduces the vibration in adaptive optics systems as well as improving the overall performance of the closed loop system has been presented. Although the technique does not need any previous identification of turbulence or vibration models, it actually delivers a set of parameters for the modeled disturbances as a by-product of an iterative minimization. This optimization is carried out via a frequency domain (H_2) control criterion using residual slope data. The criterion is the H_2 norm of the mixed-sensitivity function [2], which is composed of the sensitivity function weighted by the disturbance spectrum and the noise transfer function weighted by the measurement noise spectrum.

The function representing the measurement noise is easily identified from the higher end of the pseudo-open loop data spectrum. By defining transfer functions with increasing complexity that represent the disturbances and estimating the parameters that minimize the residual slope variance, a controller is synthesized. The method is stopped when increasing the complexity of the disturbance model does not lead to significant reduction in the residual variance and a result for the controller and estimation of the perturbation spectrum is achieved.

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The procedure has been implemented off-line using on-sky data from the instruments GeMS and NACO and the resulting controllers have been programmed in the real time controller (RTC) for tests in the optical bench of GeMS (using the calibration source) and also on-sky [1].

Given the success obtained in [1] in this paper we study the application of this technique to two other instruments, namely MACAO (Paranal) and ALTAIR (Gemini North). We use closed-loop data obtained from on-sky runs to test control algorithms off-line and under different disturbance scenarios. Two control laws have been implemented: the classic integrator and H_2 synthesis methods [1,2]..

2. H_2 control in ALTAIR

ALTAIR (ALTtitude conjugate Adaptive optics for the InfraRed) is the facility natural/laser guide star adaptive optics system of the Gemini North telescope. It can feed a corrected beam to Gemini instruments. ALTAIR uses a 177 actuator deformable mirror (DM) and a separate tip-tilt mirror to correct for image blurring and distortion caused by atmospheric turbulence. It is equipped with a Shack-Hartmann wave-front sensor that uses the visible light to measure the turbulent incident wavefront. The correction is done at a rate of up to 1 kHz. The tip-tilt loop receives centroid values from the Strap sensor at up to 1 kHz, calculates NGS atmospheric jitter and applies corrections to the tip-tilt mirror; this loop is independent from the DM loop.

The length of the sequence that has been used in this study is 61,440 frames which at 1 kHz sampling rate corresponds to a time range of 61.44 seconds.

2.1. Case 1: Highly forested spectrum

The group of panels in Fig. 1 shows one of the typical situations in ALTAIR operation. A spectrum densely populated with vibrations (panel ***a***) forces the optimal integrator gain to values where the AO loop is almost open ($K_i = 0.005$ in panel ***b***). The reduction in residuals after applying an H_2 controller is ***c*** and ***d***, where the spectrum is flattened and the variance approaches only a third of the initial value for H_2 controllers with more than 9 vibration rejection notches. Panel ***e***) shows how accurately the technique can identify the turbulence, vibration and noise. Finally, panel ***f*** presents the difference between the integrator and H_2 error transfer functions (ETF) for this case, where the first is acting only at very low frequencies and in turn, the H_2 controller show a rich dynamics that effectively rejects vibration and also allows for rejection at lower frequencies. The diminishing benefits of using higher order controllers is evident from panel d and the choice of the number of notches must be determined not only from the variance of residuals, but also considering the computational burden for synthesizing the controller and its implementation in the RTC.

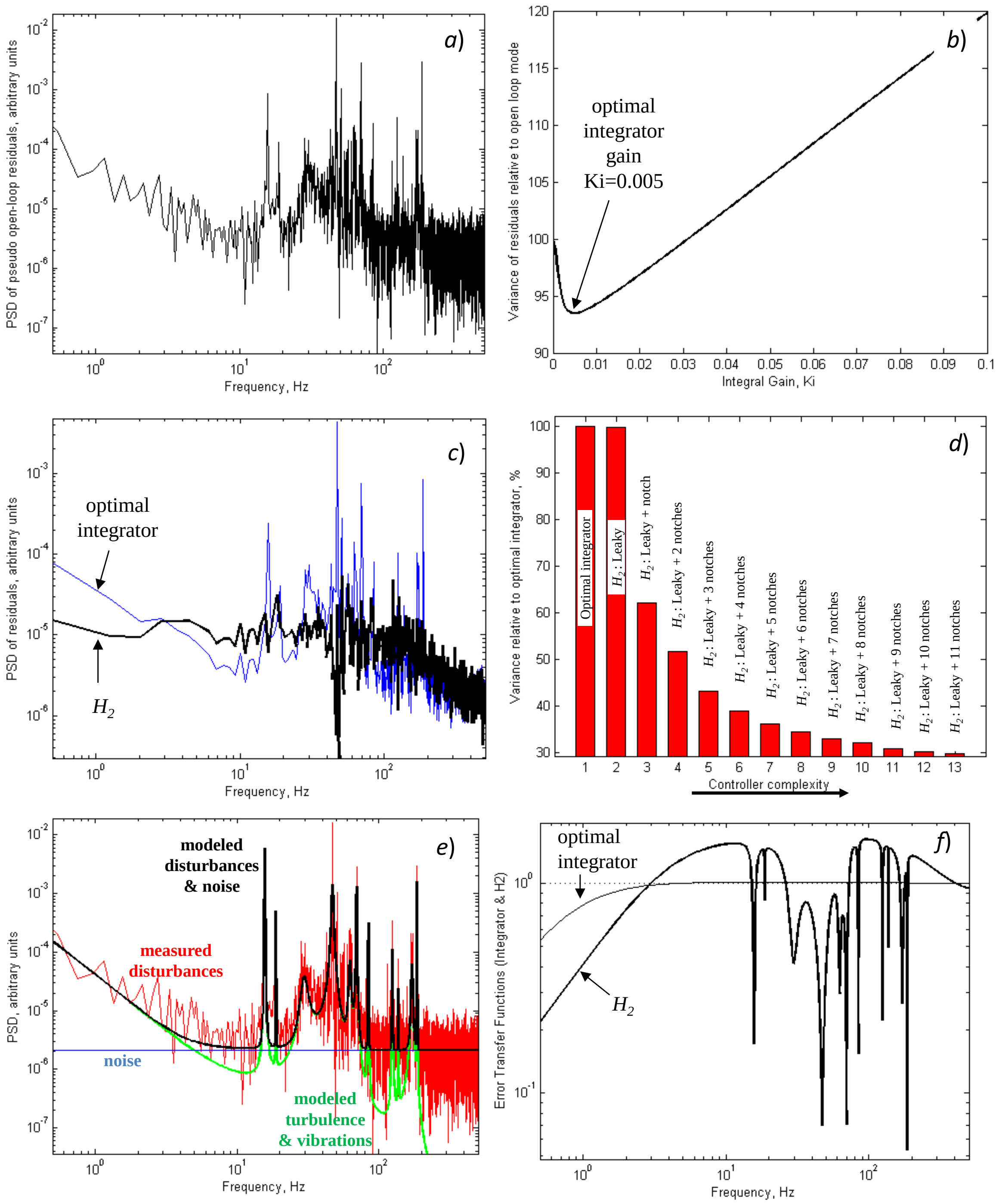

Figure 1. Results for case 1 (Tip): a) Disturbances from pseudo-open-loop slopes; b) Best integrator; c) Integrator and H_2 tip residual; d) Error Transfer Functions; e) Disturbance and noise models fitting; f) Reduction in variance of residuals for increasingly complex H_2 controllers.

2.2. Case 2: Standard spectrum

Figure 2 presents another common case of disturbances, with individual vibrations and a more clear presence of turbulence, especially at lower frequencies. In this case, the optimal integrator is effectively reducing the residuals with a significant gain (K_i = 0.45). However, the performance of the H_2 is still superior.

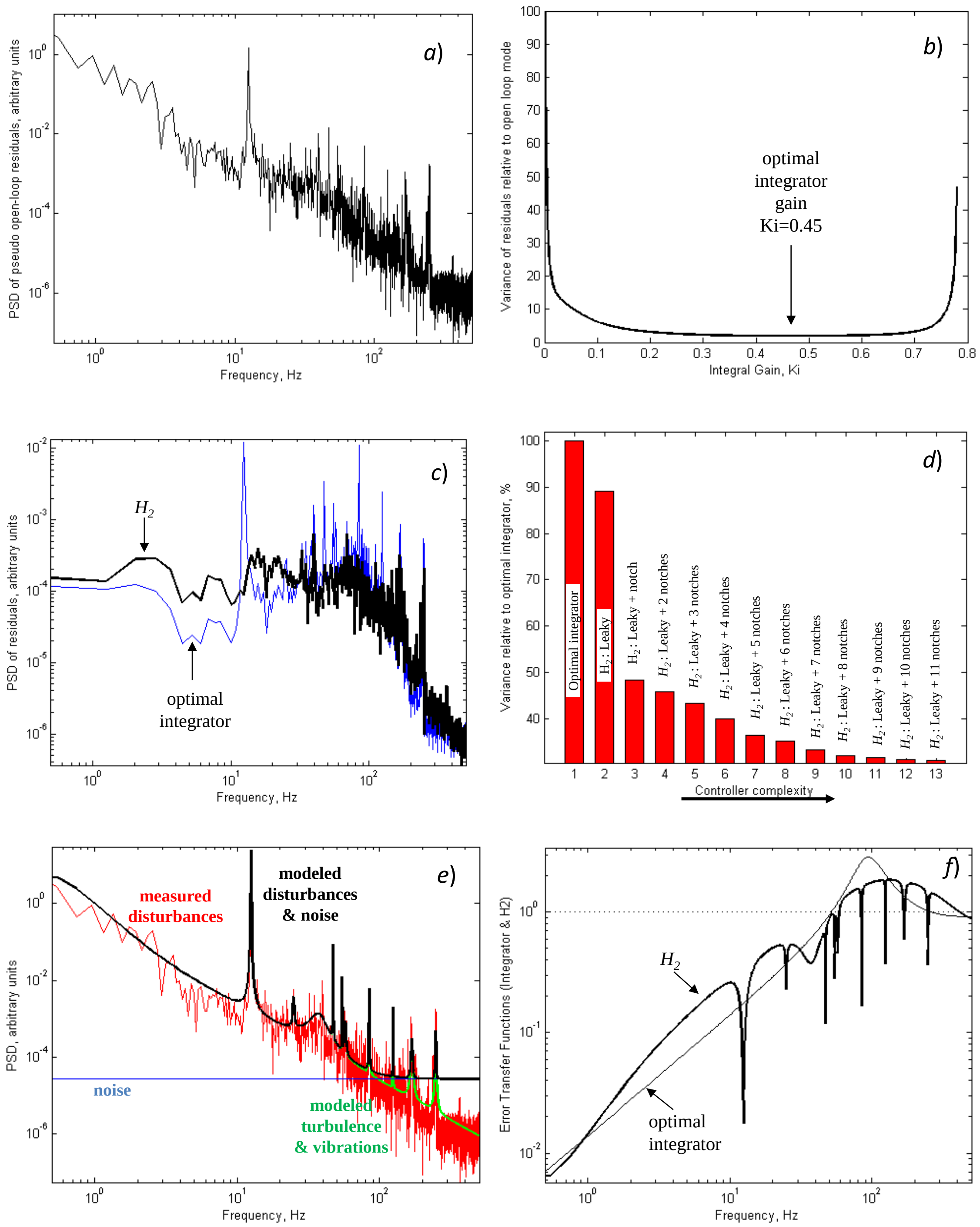

Figure 2. Results for case 2 (Tip): a) Disturbances from pseudo-open-loop slopes; b) Best integrator; c) Integrator and H_2 tip residual; d) Error Transfer Functions; e) Disturbance and noise models fitting; f) Reduction in variance of residuals for increasingly complex H_2 controllers.

3. H_2 control in MACAO

MACAO (Multi-Application Curvature Adaptive Optics) is an ESO in-house developed curvature adaptive optics system. The MACAO-VLTI system is installed at the F#47.6 Coude focus of each VLT UTs. It corrects the atmospheric perturbations for the interferometric applications of the VLT. The corrective optics is based on a 60 element deformable bimorph mirror mounted on tip-tilt mount. It also contains a separate tip-tilt sensor, which is based on quad cell avalanche photodiodes (APD).

Next, a short analysis of off-line H_2 control in MACAO instruments at UT1 UT2 and UT3 is carried out. Tip-tilt data is stored at around 410 Hz in files containing 32,000 frames.

Figure 3 presents the results obtained for UT1 in tip with a 11th order H_2 controller comprising 4 notch filters. Notice that only one notch is actually required to reduce most of the variance (centre panel). The leftmost image shows the effective rejection of the strongest frequency that accounts for this mitigation. The rightmost image shows the fit to the disturbances and measurement noise obtained with the method. As shown in Fig. 4, for the case of the UT1-tilt axis the story is quite different. At least 5 notches are required to reduce the variance significantly and the gain of incorporating the H_2 controller gives lower but still considerable benefits.

For telescopes UT2 and UT3 the results of only one axis are shown in each case, with reductions of 60% and 20% respectively.

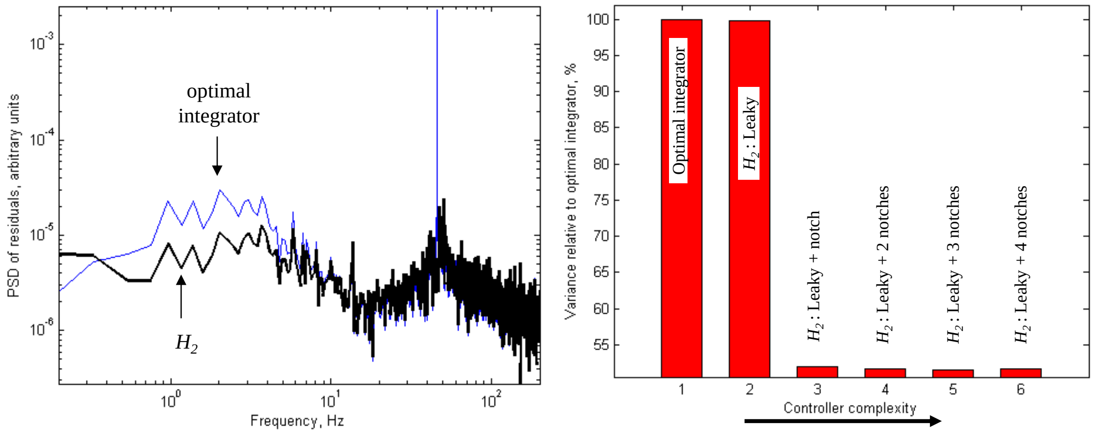

Figure 3. UT1-tip axis. Variance of residuals (left); Benefit of increasing the complexity of the controller (center); Fitting of disturbance and noise (right).

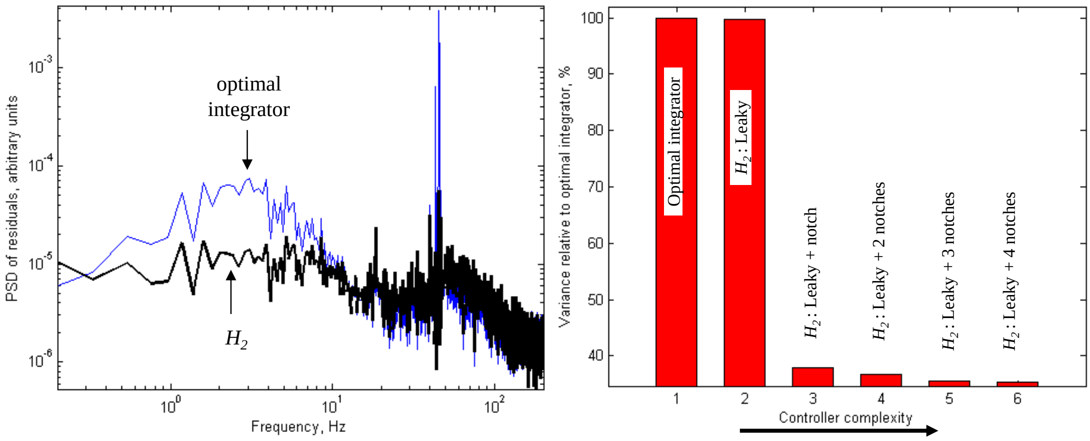

Figure 4. UT1-tilt axis. Variance of residuals (left); Benefit of increasing the complexity of the controller (center); Fitting of disturbance and noise (right).

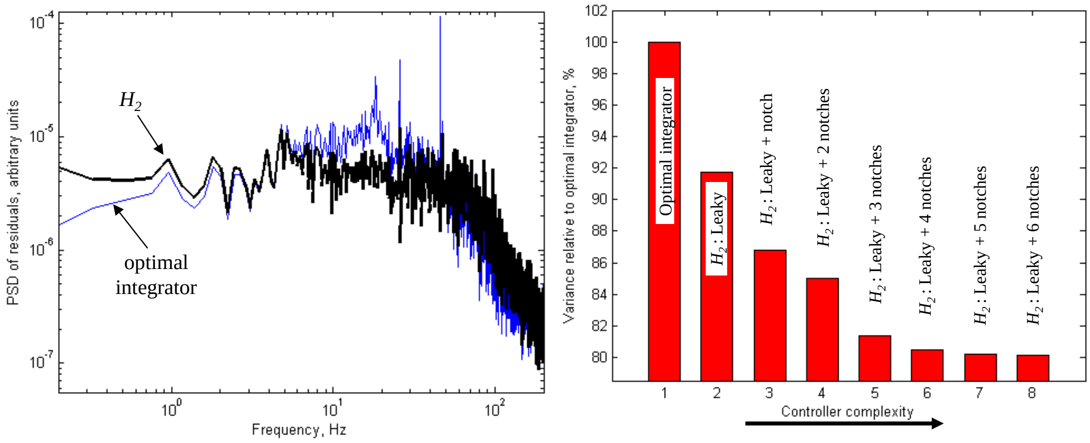

Figure 5. UT2-tip axis. Variance of residuals (left); Benefit of increasing the complexity of the controller (center); Fitting of disturbance and noise (right).

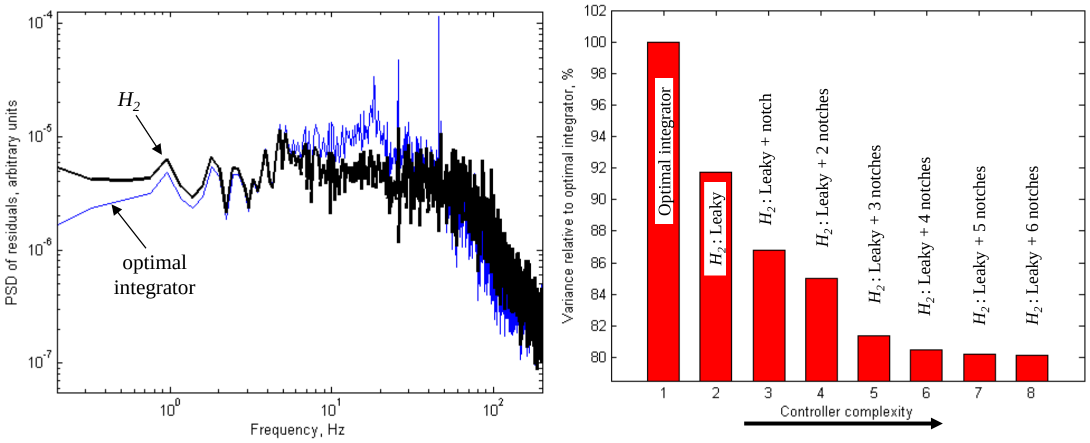

Figure 6. UT3-tilt axis. Variance of residuals (left); Benefit of increasing the complexity of the controller (center); Fitting of disturbance and noise (right).

4. Conclusions

A study of applying advanced techniques for the mitigation of vibrations in two types of instruments has been carried out. Substantial improvements in the performance of the current operating AO systems are expected by implementing these techniques.

Despite its mathematical complexity, the technique proposed has the potential to become a totally unsupervised procedure. It is robust and simple to use and can automatically adapt the order of the controller according to the existing conditions for turbulence and vibrations, i.e. it is not only a vibration rejection method but also a means to optimize the closed-loop performance by adapting to the changing turbulence conditions. Furthermore, the progressive approach in the complexity of the controller guarantees a minimum performance given by an optimal integrator (worst case).

The computation time for a typical controller structure of a leaky integrator plus two notches is currently in the order of 2 mins for a commercial PC. We think that this is not an issue, as the characteristics of the turbulence and vibrations should be fairly stable over this time scale.

5. References

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Acknowledgments

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