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Optical Laser Jitter Suppression using Feedback and Adaptive Control Methods

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Abstract

In this paper, the problem of precise laser pointing and jitter suppression using feedback and adaptive methods is considered. A unique laser jitter control test bed developed at Naval Postgraduate School is used to demonstrate the effects of optical jitter and the performance of feedback and adaptive control algorithms in suppressing the optical jitter. In this test bed, disturbance is injected through a fast steering mirror and the control algorithm is implemented using another fast steering mirror and xPC target. The control commands are generated using improved feedback techniques and Least Mean Square algorithms. It is shown that efficient broadband jitter suppression can be attained using feedback algorithms whereas narrowband or sinusoidal disturbances are better suppressed by the adaptive methods. Experimental results are presented to validate the performance of the proposed algorithms.

INTRODUCTION

Optical beam pointing and jitter control have become important research topics in recent years due to their growing applications ranging widely from laser communications to space missions. The narrow band jitter is generally created in a spacecraft by rotating devices such as reaction wheels, control moment gyros, cryo-coolers and motion of flexible structures, such as solar arrays. The atmosphere adds a broadband disturbance to a laser beam. The control of jitter is also a challenging problem for current programs such as the James Webb Space Telescope, Air Borne Laser, and imaging spacecraft. In order to achieve efficient jitter control, several control techniques have been propose including the modified Linear Quadratic Regulator (LQR) algorithm and adaptive control systems such as the Least Mean Square (LMS). In order to study the effects of various disturbances and to develop and test efficient disturbance attenuation and pointing control techniques, a unique test bed is developed at Naval Postgraduate School (NPS) in Monterey, CA.

The control of disturbance or noise has its origin in the areas of acoustics and structures. Adaptive noise control algorithms have recently been successfully applied to reduce noise in many acoustic systems. Adaptive filters and their applications have been widely studied by many researchers in the past [1], [2]. Adaptive filters are designed by minimizing an error function and can be realized as FIR (Finite Impulse Response) or IIR (Infinite Impulse Response) filters [3]. The most commonly applied adaptive filter is the LMS (least mean square) algorithm. Even though the adaptive algorithms have many advantages such as large stability bounds, the main disadvantage in using them is that they require a coherent reference signal, which may be very difficult to obtain for certain applications. Other noise or vibration control techniques include feedback and feedforward methods. A feedback algorithm for the duct noise problem was proposed by Olson and May in [4]. This algorithm uses a high loop gain achieved by the error feedback that is implemented through an amplifier in order to reduce the undesired sound. A vibration attenuation strategy for spaceborne optical interferometers by combining a stochastic model of the primary disturbance source with the measurements from an experimental test bed is proposed in [5]. LQG and $\mathcal{H}_\infty$ controllers for the narrow band disturbance rejection and active vibration control are developed in [6]. The scope of this paper is to modify the feedback and adaptive algorithms and test them experimentally. The standard LQR is modified by introducing an additional feedback, which provides an additional degree of freedom to carry out the design so that required jitter attenuation is achieved. The standard LMS algorithm is modified by incorporating an adaptive bias filter (ABF).

This paper is organized as follows. The detailed description about the system being studied is given in Section 2. In Section 3, disturbance rejection technique based on Linear Quadratic Regulator (LQR) is presented. In Section 4, a modified LQR algorithm is explained. Section 5 is devoted to the discussion on adaptive jitter control methods. In Section 6, experiments performed on the optical laser test bed are summarized and the results are analyzed. Conclusions are drawn in Section 7.

SYSTEM DESCRIPTION

The optical laser test bed being studied in this project is shown in Figures 1 and 2. The test bed consists of a Disturbance Injection Fast Steering Mirror (DFSM), a Control Fast Steering Mirror (CFSM), three On-Trak position sensing devices namely OT1, OT2 and OT3, two 80/20 beam splitters, three optical folding mirrors, a shaker, an accelerometer and a laser source. Folding mirror 1 is used to divert the laser beam to the DFSM, which injects the user-defined disturbance to the laser beam. The corrupted laser beam then travels through a 80/20 beam splitter, which splits the laser beam into two separate beams: one is sent through the control Mirror CFSM while the other is reflected on Folding Mirror 2, which directs the beam to Sensor OT1 where the position of the laser beam is measured. The control mirror CFSM, which receives the control commands from a PC through Real Time Workshop and xPC target provides the corrective actions to the laser beam while it is being passed through.

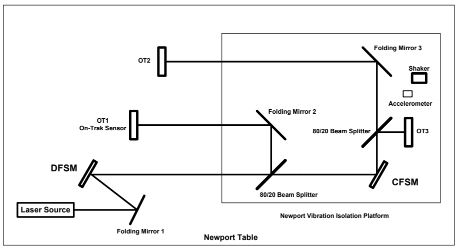

Figure 1: Optical Laser Test bed

Figure 2: Picture of the Test Bed

The laser beam is then sent through the second 80/20 beam splitter. One part of the beam is measured by Sensor OT3 and the other part is diverted by Folding Mirror 3 to another sensor OT2 where the X and Y positions of the laser beam are measured again. Using the input-output data obtained experimentally, X and Y axes models with the laser beam position on Sensor OT2 in X and Y directions (x_p and y_p respectively) as outputs are derived as follows. The X-axis model is,

$$x_p(s) = k_x\theta_x(s) + \nu_x = k_x\frac{\omega_x^2}{s^2 + 2\zeta_x\omega_x s + \omega_x^2}V_x(s) + \nu_x = k_x\, G_x(s)V_x(s) + \nu_x \qquad (1)$$

where
θ_x - Angular movement of the control mirror in X direction
V_x - Input voltage to the Control Mirror CFSM X-axis
ν_x - Disturbance (Broadband Disturbance and Constant Bias) to Laser Beam in x direction
ω_x = 3708.4 rad/sec, ζ_x =0.95, k_x =4.95. Similarly, the laser position in Y direction on Sensor OT2 y_p is related to the input voltage to the control mirror in Y direction V_y by

$$y_p(s) = k_y\theta_y(s) + \nu_y = k_y\frac{\omega_y^2}{s^2 + 2\zeta_y\omega_y s + \omega_y^2}V_y(s) + \nu_y = k_y G_y(s)V_y(s) + \nu_y \qquad (2)$$

where ω_y = 3261.5 rad/sec, ζ_y =0.95, k_y =6.76.

JITTER SUPPRESSION USING FEEDBACK METHODS

In this section, standard LQR design for the X-axis is considered and the difficulties in getting the desired disturbance attenuation are discussed. A similar analysis can also be done for the Y-axis. To avoid the repetition of similar material, the Y-axis analysis is not included. Consider the state space model of the X-axis,

$$\begin{aligned} \begin{pmatrix}\dot{x}_1\\ \dot{x}_2\end{pmatrix} &= \begin{pmatrix}0 & 1\\ -\omega_x^2 & -2\zeta_x\omega_x\end{pmatrix}\begin{pmatrix}x_1\\ x_2\end{pmatrix} + \begin{pmatrix}0\\ \omega_x^2\end{pmatrix}u \\ y_x &= \begin{pmatrix}k_x & 0\end{pmatrix}\begin{bmatrix}x_1 & x_2\end{bmatrix}^T + \nu. \end{aligned}$$

The subscript x in above expressions is used to denote that the current design process is carried out for the X-axis. Referring to Equation 1, note that $y_x = x_p$ and $\nu = \nu_x$. It is necessary to add an integrator in order to guarantee a good tracking performance. The addition of an integrator will introduce an additional state to the system, which is $\dot{x}_3 = r - y_x = r - k_x x_1 - \nu$. We now design a controller of the form $u = -\begin{pmatrix} k_1 & k_2 & k_3 \end{pmatrix} \begin{bmatrix} x_1 & x_2 & x_3 \end{bmatrix}^T = -K_{cx}\ x$ by minimizing the standard LQR cost functional $J = \int_0^\infty (x^T Q_x x + u^T R_x u)\ dt$. With this controller, the transfer functions relating the output y_x with the set point r and the broadband disturbance ν can be obtained as follows.

$$\begin{aligned} Y_x(s) \quad = \quad & \frac{-k_x k_3 {\omega_x}^2}{s^3 + (k_2 {\omega_x}^2 + 2\zeta_x \omega_x)s^2 + {\omega_x}^2(1+k_1)s - k_x k_3 {\omega_x}^2} R(s) + \\ & \frac{s(s^2 + (k_2 {\omega_x}^2 + 2\zeta_x \omega_x)s + {\omega_x}^2(1+k_1))}{s^3 + (k_2 {\omega_x}^2 + 2\zeta_x \omega_x)s^2 + {\omega_x}^2(1+k_1)s - k_x k_3 {\omega_x}^2} \nu(s) \end{aligned} \tag{3}$$

It is clear that in order to reduce the effects of disturbance ν, the sensitivity function S_x (transfer function relating Y_x and ν) must be made small within the frequency band of ν. Assuming that the frequency band of ν is Ω and the desired level of disturbance attenuation is L, this idea is illustrated in Figure 3. The smaller the sensitivity function gain within the band Ω, the better the disturbance attenuation. It may not be always possible to shape the

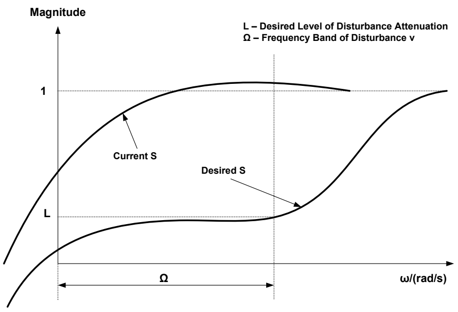

Figure 3: Sensitivity Function

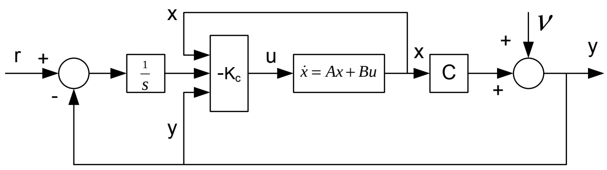

Figure 4: State and Output Feedback

sensitivity function as desired without violating the stability constraints. In other words, the exhaustive tuning of the weighting parameters may not necessarily yield the controller that can provide the desired sensitivity function. The sensitivity function S_x is made up of three poles and three zeros with one zero being at zero. This means that $\lim_{\omega \to 0} S_x(j\omega) = 0$ & $\lim_{\omega \to \infty} S_x(j\omega) = 1$. One way to attain the desired disturbance level L as shown in Figure 3 is to design a controller such that the sensitivity function S_x has at least one pole whose cut-off frequency point in the bode plot is in the low frequency region and all the zeros whose cut off frequency points in the bode plot are greater than Ω. If it is not possible to move the cut off frequency points of all the zeros greater than Ω, an additional pole is required to cancel the effect of the zero. Furthermore, the sensitivity function gain must be kept as low as possible at low frequencies. For low frequencies, the sensitivity function S_x can be approximated by $S_x(j\omega) \approx j\omega \frac{1+k_1}{-k_x k_3}$. Therefore, in order to get the desired disturbance attenuation, it is best to keep the value of k_1 low and the value of $-k_3$ high. However, if $-k_3$ or/and k_2 are increased, it will increase the lower bound of k_1 forcing us to increase k_1 to avoid instability. The fact that k_1 cannot be reduced independently has a serious impact on the sensitivity function shaping. An optimal compromise between the variables may not be always made in practice.

STATE AND DISTURBANCE FEEDBACK

It can be shown that an additional degree of freedom for the control system design can be obtained by introducing the output feedback to the traditional state feedback formulation. The modified setup is shown in Figure 4. This setup shown may seem redundant at first because in the standard state feedback setup, the output y is simply related to the state vector x by $y = Cx = k_x x_1$. However, in the optical laser test bed, Cx and y are quite different. Due to constant bias and the broadband disturbance ν, the output of the control mirror Cx and the actual laser position on the On-Trak sensor y are at least a few thousand microns apart in general depending on the constant bias and disturbance. The output y and the state x are still related by $y = Cx + \nu$. This means that by using the output feedback, we are in fact employing a disturbance feedback, more importantly, without even directly measuring it. Let us next discuss what impact this new feedback has on the controller design and the sensitivity function shaping. Again, we will consider the control design for the X-axis only. With state and output feedback, the controller will be,

$$u = -\begin{pmatrix} k_1 & k_2 & k_3 & k_4 \end{pmatrix} \begin{bmatrix} x_1 & x_2 & x_3 & y \end{bmatrix}^T = \begin{pmatrix} k_o & k_2 & k_3 \end{pmatrix} \begin{bmatrix} x_1 & x_2 & x_3 \end{bmatrix}^T + k_4 \nu \quad (4)$$

where $k_o = k_1 + k_4 k_x$. As done earlier, we can obtain the transfer functions relating y with r and ν as follows.

$$\begin{aligned} Y_x(s) &= \frac{-k_x k_3 {\omega_x}^2}{s^3 + (k_2 {\omega_x}^2 + 2\zeta_x \omega_x)s^2 + {\omega_x}^2(1 + k_1 + k_4 k_x)s - k_x k_3 {\omega_x}^2} R(s) \\ &+ \frac{s(s^2 + (k_2 {\omega_x}^2 + 2\zeta_x \omega_x)s + {\omega_x}^2(1 + k_1))}{s^3 + (k_2 {\omega_x}^2 + 2\zeta_x \omega_x)s^2 + {\omega_x}^2(1 + k_1 + k_4 k_x)s - k_x k_3 {\omega_x}^2} \nu(s) \end{aligned} \quad (5)$$

For low frequencies, the sensitivity function can be approximated by $S(j\omega) \approx j\omega \frac{1+k_1}{-k_x k_3}$. It is interesting to note that the additional output feedback does not change the zeros of the sensitivity function, but, provides an additional degree of freedom (additional control parameter k_4) in selecting the locations of the poles. The control parameters k_1, k_2, k_3 & k_4 can be designed using many methods. Referring to Equation (4), one practical approach would be to use the LQR algorithm to find the parameters k_o, k_2 & k_3 first and choose k_1 and k_4 that satisfy the relationship $k_o = k_1 + k_4 k_x$ next. The best choice for k_1 is -1, which lowers the sensitivity gain drastically at low frequencies thus giving a better disturbance attenuation. It is noted that this flexibility is not present in the standard LQR setup.

JITTER SUPPRESSION USING ADAPTIVE ALGORITHMS

In this section, it is explained how the standard Least Mean Square can be used for narrowband disturbance rejection. In any practical laser targeting or relay station, there is a secondary path through which the output of the LMS filter must go. One may use Fast Steering Mirrors (FSM) to correct the beam. This secondary path must be modeled in the control algorithm in order to take into account the delays and other effects that occur to the control signal. In order to properly make use of the LMS algorithm, a copy of the secondary plant transfer function is placed in the path to the updating algorithm for the weight vector. This is known as the Filtered-X LMS (FXLMS) algorithm and is derived in [7]. The block diagram of this setup is shown in Figure 5. Using a one or two weight LMS filter, the bias in the reference signal is adjusted to remove the DC component of the error signal. An estimate of C' is used as the reference signal to the ABF. The error signal in this case is the mean error, which stops the adaptation once the signal is centered on the target. This is shown in Figure 6.

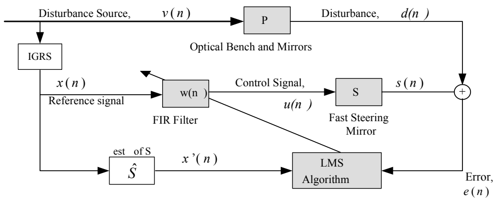

Figure 5: Block Diagram of the FXLMS

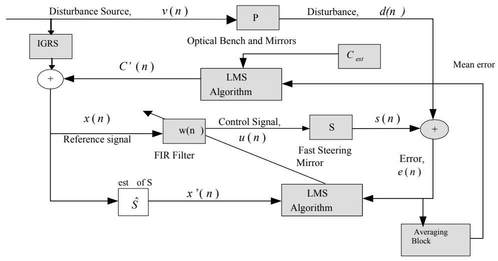

Figure 6: Block diagram of ABF

EXPERIMENTS

With State and Output Feedback Controller

This section summarizes the experimental results obtained by implementing the modified state and output feedback controller on the optical laser test bed. The examples presented in this paper design the controllers only for the X-axis. The controllers for the Y-axis can also be designed similarly. The control laws for the X and Y axes are designed to be

$$\begin{aligned} u_x &= -\begin{pmatrix} -1 & 0.0006 & -0.3 & 0.3 \end{pmatrix} \begin{bmatrix} x_1 & x_2 & x_3 & y_x \end{bmatrix}^T \\ u_y &= -\begin{pmatrix} -1 & 0.0006 & -0.4 & 0.25 \end{pmatrix} \begin{bmatrix} z_1 & z_2 & z_3 & z_y \end{bmatrix}^T \end{aligned} \quad (6)$$

where z_1, z_2, z_3 are states of the Y axis and z_y is the corresponding output.

To evaluate the performance of the above control laws, several experiments were carried out on the optical laser test bed. The objective of these experiments is to test how well the controller drives the laser beam to a specified target and increases its intensity by rejecting or reducing the disturbances. The center of the On-Trak sensor (OT2) with the coordinates (0,0) is selected as the target. Referring to Figure 1, a 200 Hz broadband disturbance and a random bias are injected through the DFSM in order to "disturb" the laser beam. Experiments were performed in real time for 35 seconds. The random bias is injected at zeroth second and the broadband disturbance is injected at 12^{th} sec. The control laws given by Equation (6) are implemented on the control mirror CFSM through Real Time Workshop and xPC Target. The control mirror is set to send its commands at 20^{th} sec. The experimental results obtained with traditional LQR controller and the modified LQR controller are summarized in Table 1. The standard deviation ans mean of the laser beam with respect to X position before and after being controlled and the percent of disturbance attenuation are compared in Table 1. Note that the standard deviation and mean values are given in micrometer (μm). The mean values clearly indicate the tracking performance and the standard deviation values indicate disturbance attenuation ability of the control laws. A simple comparison of these results clearly demonstrates the superior performance of the modified LQR algorithm.

Table 1: Summary of Results

	Std. Dev. /(μm)		Mean/(μ m)		% Attenuation
	Before Control	After Control	Before Control	After Control	
Modified	33.55	11.27	2299	-0.0107	33
Standard	33.21	31.89	2236	-1.456	86

Experiments with Adaptive Algorithms

In this experiment, a disturbance of frequencies 50 and 87 Hz is injected through the DFSM. In addition, the DFSM is used to inject a random component of 200 Hz band-limited white noise, to simulate the effect of atmospheric turbulence on the uplink laser beam for a simulated relay station. Since the LMS controller uses an Internally Generated Reference Signal (IGRS) consisting of the two disturbance frequencies, the controller will not remove the random component. However, by combining the LMS controller with the LQR, control of the random component as well as the frequencies added by the inertial actuator may be realized. Additionally, by adding the ABF modification and removing the integrator from the LQR, a faster response to the bias error may also be achieved. A comparison of three experiments using the different control methods is shown in Figures 7 and 8. It can be seen from these plots that the use of the LMS/ABF + LQR controller results in the best response. The random component is removed and the narrowband frequencies are attenuated. The time constant for the system is drastically improved over the LMS/ABF or LQR controller alone.

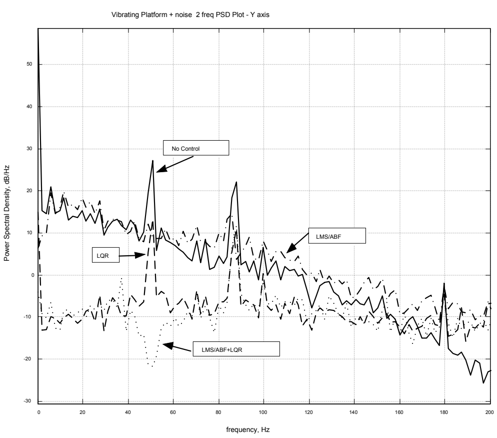

Figure 7: Y axis PSD plot

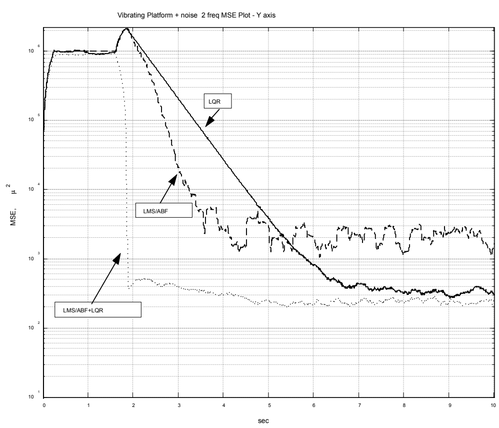

Figure 8: Y axis MSE plot

CONCLUSIONS

The jitter attenuation problem for an optical laser test bed located at Naval Postgraduate School is considered and the possibility of using the standard state feedback method is investigated. After showing that the standard state feedback does not provide the required degree of freedom to achieve good broadband disturbance attenuation and precise pointing control, the standard setup is modified by introducing an additional output feedback. After showing the effectiveness of the modified LQR algorithm for broadband jitter suppression, narrowband or sinusoidal jitter problem is considered using adaptive algorithms. It is shown that for the case of a vibrating support structure for the control system with a random fluctuating optical beam, a combination of FXLMS/ABF and LQR control could remove the random as well as narrowband components in the disturbed beam. Additionally, the combination LQR+LMS/ABF controller reaches the final value for the Mean Square Error of the LQR controller a full 5 seconds faster than the LQR controller. In conclusion, the experimental results demonstrated that the addition of ABS filter to LMS significantly increased the converging rate of the jitter. In order to achieve the reduction of both sinusoidal and random jitter, a combination of ABF/LMS and LQR is most effective. The ABF/LMS control is most effective for a sinusoidal jitter and the LQR control for a random or broadband jitter.

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