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Input-output Response Based Simultaneous Tracking and Disturbance Attenuation Control for Helicopter Image Stabilizers*

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Abstract—**Image stabilizer is important for most unmanned helicopter system. Usually it should be able to drive the video sensor to track some targets precisely under heavy vibration due to the high speed rotation of the rotor. This is the so-called simultaneous tracking and disturbance attenuation control (STDA) problem. In this paper, a new 2DOF control strategy is proposed aiming at the STDA problem. The proposed control is composed of inner loop control, which is used to attenuate the disturbance due to helicopter's vibration, and a prefilter, which is outside the closed loop and used to ensure the transient performance of the whole system. One of the most absorbing advantages of the new proposed method is that the two parts are decoupled completely and thus can be designed separately. For inner loop control, an AFC enhanced PID control is proposed to realize disturbance suppression, while for the prefilter, a new parameter optimization algorithm is introduced to ensure optimal step tracking without influencing the disturbance attenuation performance. Furthermore, it should be pointed out that the whole controller is designed based on only input-output response independent on accurate model information of the system. Finally, experiments are conducted on a real image stabilizer with simulated vibration, and the results show the feasibility and validity of the proposed method.**

I. Introduction

Image and video collection is one of the most important applications of unmanned helicopter systems, while vibration due to the rotor's high speed rotation may greatly deteriorate the quality of the obtained images and videos. Thus in most real applications, an image stabilizer is usually equipped between the helicopter body and the image/video sensor so that (1) the high frequency vibration can be isolated and the influence of the carrier on the sensor can be alleviated; and (2) the pose of the sensor can be controlled as desired in order to realize persistent tracking and sensing with respect to the interesting targets. This results in the problem of simultaneously tracking and disturbance attenuation control (STDAC) problem.

There have published some work on the researches of STDAC problem. For example, in reference [4], an advanced PID control algorithm is designed, where the good rejection of load disturbances can be achieved. However, it is usually difficult to ensure the two different control performances simultaneously using a simple controller structure such as PID control. Thus, in recent years, two degree of freedom (2DOF) control strategy is proposed in many papers, among which there are several different kinds of 2DOF control schemes, including disturbance compensator based 2DOF control[1], inner model based 2DOF control[3], and prefilter based 2DOF control[2].

Comparatively, the prefilter based 2DOF (PF-2DOF) is prominent due to its basic structure being composed of two completely decoupling sub-structure, including the prefilter which is often used to ensure the performance of servo tracking, and the inner controller which is mainly used to attenuate the disturbances (vibration isolation). The most common referred to PF-2DOF includes time-delay (TD) PF-2DOF[5-14], low-pass (LP) PF-2DOF[15-18], and adaptive PF-2DOF[19], which are mainly distinguished from each other by the form of prefilter.

The TD method involves convolving the command input with a sequence of impulses known as input shaper. The convolution result is then used to drive the system. TD method has shown to be most effective for flexible plants. However, as the amplitude and time locations of the impulses of the input shaper are designed based on natural frequencies and damping ratios of the controlled system, TD is only suitable for simple target system of which natural frequencies and damping ratios can be obtained, such as open loop system[2]. The most important advantages of LP method is that it can help to avoid excitation of high frequency system modes that have not been accounted for in the filter design. Also, a LPF can help to reduce the possibility of saturation problems. The designing of a typical LPF is simple, and needs no modeling information. However, the vibration of low or middle frequency can't be eliminated by LPF. In reference [19], Y. Uchiyama introduces an adaptive filter for the 2DOF control system using μ-synthesis and get controller more robust against uncertainty. The drawback of adaptive filter is that large amount of calculation is needed, which can be vital for the control of platform, which requires the property of quick response. In summary, a common drawback of the above methods is that they are essential model based controller, i.e., their control performance depends heavily on the accuracy of the system models.

Thus, in this paper, a new prefilter based 2DOF scheme is proposed. The most absorbing advantage of this new method is that it requires only the system input-output responses

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instead of any other accurate system model information such as natural frequency and damping ratio. The new controller is composed of three parts, a high gain acceleration feedback control (AFC) and an ordinary model-free PID inner loop control which formulate the inner DOF of the control and mainly used to attenuate the disturbances due to helicopter's vibration; the outer loop is a new prefilter which is also designed based only on the input-output responses. Subsequently, the control method is tested on a new-designed image stabilizer system to verify the feasibility and validity of it. Finally, conclusion is listed out in section V.

The rest of this paper is organized as follows. Section II introduces the basic structure of the new proposed controller. Then, in section III and section IV, the main idea of the disturbance suppression inner control and the prefilter are given, which is followed by section V where experiments are carried out and the results are analyzed in detail. Finally, conclusion and future's work are listed out in section VI.

II. Basic Control Structure

In order to simultaneously ensure the performance of vibration isolation and tracking control, a new 2DOF control structure is proposed in this paper. The basic structure of the new 2DOF controller is shown as Fig.1. The inner part, which is composed of a PID controller and an AFC controller, is the first control DOF for the purpose of disturbance attenuation; and the outer part is a prefilter, which is mainly used as a regulator to improve the tracking control performance.

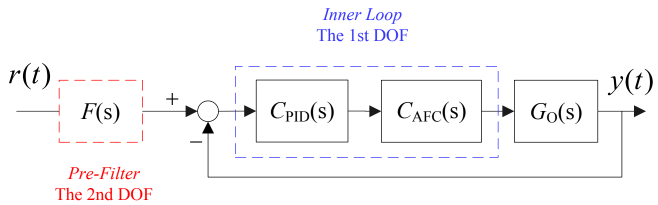


Figure 1. Basic structure of the new proposed 2DOF control

In this paper, the PID control is used to control the rotating speed and its parameters are regulated using Ziegler-Nichols scheme. It has been shown in reference [20] that Ziegler-Nichols method is able to obtain a group of PID parameters with good performance of disturbance attenuation. Furthermore, in order to suppress the high frequency disturbance, an AFC inner loop is proposed after PID controller (see Fig. 1). Acceleration signals can directly reflect the influence of some high frequency disturbance on a mechatronic system in broad frequency band and thus has been extensively used to improvement the robustness of a controlled system[21]-[24].

While for the outer part, a new design method aiming at the prefilter is given in this paper. Unlike the prefilters designed by TD method and LP method, where the prefilters may slow down the transient response of the controlled system, the new prefilter synthesis scheme can obtain a group of optimized parameters so that the tracking performance can be improved greatly based on only input-output response.

In the next two sections, the three parts of the proposed control structure will be introduced in detail.

III. Disturbance Suppression Inner Loop

A. *High gain acceleration feedback control*

Spong et al. proposed acceleration as the input to the system where the actuator produces directly commanded acceleration instead of torque [25]. In this way the external disturbances and dynamic couplings no longer impair the tracking performance of each individual axis and consequently need not to be taken into account. In this paper, we use AFC as the inner loop to suppress high frequency vibration from helicopter body.

1) *The principle of acceleration feedback control*

Generally, the dynamics of a mechatronic system can be described as,

$$J\ddot{\theta} = \tau_a - \tau_n \qquad (1)$$

where J is the inertia parameter of the system, $\ddot{\theta}$ is the acceleration, τ_a is the torque generated by the actuator and τ_n is the total disturbing torque acted on the system. An acceleration feedback control can be designed as following equation,

$$\tau_a = k_a(a_{cmd} - \ddot{\theta}) \qquad (2)$$

where k_a is a constant, and a_{cmd} is the acceleration command.

Substituting Eq. (2) into Eq. (1) yields:

$$\ddot{\theta} = \frac{k_a}{J + k_a} a_{cmd} - \frac{1}{J + k_a} \tau_n \qquad (3)$$

When the acceleration feedback gain k_a is chosen as,

$$k_a \gg max(\Delta J, \tau_a) \qquad (4)$$

Eq. (3) becomes

$$\ddot{\theta} \approx \frac{k_a}{k_a + J} a_{cmd} \qquad (5)$$

which implies that by a large enough gain the acceleration feedback control can suppress the disturbances perfectly. In real applications, the high gain feedback can be combined to some low-pass filter to formulate an AFC control loop so that the high frequency disturbances can be suppressed.

2) *The Kalman Filter estimator of acceleration*

In order to use the AFC scheme, a first problem is the mounting of accelerometers on the image stabilizer. A further problem is the couplings among the measurements of rotation accelerations of the image stabilizer and the helicopter. To decouple the measurement couplings requires accurate kinematic parameters which presents the AFC in many real applications. Consequently, estimating the acceleration from velocity or angle measurements has been proposed [21][26][27]. An obvious advantage of it is the fact that most of mechatronic systems are instrumented with encoders and/or tachometers and no further hardware is thus required for acceleration estimation. Thus, in the paper, an Kalman filter based acceleration estimator will be used to obtain acceleration signals of the image stabilizer. The acceleration estimator has been tested in a rotating machine in reference and the details of the algorithm can be referred to in reference [21].

The acceleration estimation can be expressed in a state space model,

$$\begin{cases} \mathbf{x}_k = A\mathbf{x}_{k-1} + \omega_k \\ z_k = H\mathbf{x}_k + \nu_k \\ y_k = C\mathbf{x}_k \end{cases} \tag{6}$$

$$\begin{gathered} A = \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix}, H = \begin{bmatrix} 1 & 0 \end{bmatrix}, C = \begin{bmatrix} 0 & 1 \end{bmatrix}^T \\ Q = E(\omega_k \omega_k^T) \approx \begin{bmatrix} 0 & 0 \\ 0 & q \end{bmatrix}, r = E(\nu_k^2) \end{gathered} \tag{7}$$

where *A, H,* and *C* are the system matrix, the measurement matrix, and the output matrix, respectively; $x_k = [\xi_k, \alpha_k]^T$ is the state vector, where ξ_k is the velocity signal, and α_k is the acceleration signal; y_k is the estimated acceleration; ω_k and ν_k are the process and measurement noises, respectively, which are assumed to be independent of each other, Q the covariance matrix of the process noise, and *r* the covariance of the measurement noise.

Let a priori and a post-priori estimation errors be

$$\begin{cases} \mathbf{e}_k^- = \mathbf{x}_k - \hat{\mathbf{x}}_k^- \\ \mathbf{e}_k = \mathbf{x}_k - \hat{\mathbf{x}}_k \end{cases} \tag{8}$$

The Kalman Filter based acceleration estimation can be expressed as,

$$\begin{cases} \mathbf{x}_k^- = A\hat{\mathbf{x}}_{k-1} \\ P_k^- = AP_{k-1}A^T + Q \\ \hat{\mathbf{x}}_k = \mathbf{x}_k^- + P_k^- H^T (HP_k^- H^T + r)^{-1}(z_k - H\mathbf{x}_k^-) \\ P_k = (I - P_k^- H^T (HP_k^- H^T + r)^{-1} H)P_k^- \end{cases} \tag{9}$$

where

$$\begin{cases} P_k^- = E(\mathbf{e}_k^- \mathbf{e}_k^{-T}) \\ P_k = E(\mathbf{e}_k \mathbf{e}_k^T) \end{cases} \tag{10}$$

By properly designing the parameters *q* and *r*, or even by adding the Newton Predictor, the rotating acceleration signals can be estimated with acceptable precision.

B. Ziegler-Nichols PID controller

Usually, AFC can only be used to improve the robustness of a nominal controller, thus in this paper a Ziegler-Nichols PID controller is used to ensure the basic control performance of the rotating speed of the image stabilizer. The Ziegler-Nichols is also a model free control scheme, which is proposed based on large number experimental results. The idea is that parameters of the controller are tuned based on some dynamic characteristics, step response or frequency response, of controlled object. Firstly, step response curve can be obtained through step response experiment. Then PID parameters can be calculated based on the curve. The reference [20] introduce the algorithm to calculate the PID parameters.

IV. Input Shaping Prefilter

If the controlled system, *G*(*s*), is a linear system with *l* under-damped modes, and the desired closed system *M*(*s*) is also a multi-mode linear system denoted as,

$$M(s) = K_m \prod_{j=1}^{l} \frac{\omega_{mj}^2}{s^2 + 2\zeta_{mj}\omega_{mj}s + \omega_{mj}^2} \tag{11}$$

where K_m , ω_{mj}, and ζ_{mj} are some pre-defined parameters.

Correspondingly, we can suppose the following input shaping prefilter,

$$F(s) = \frac{a_n s^n + a_{n-1}s^{n-1} + \cdots + a_0}{\prod_{j=1}^{l}(s^2 + 2\zeta_{mj}\omega_{mj}s + \omega_{mj}^2)} \tag{12}$$

where *n=2l*, and $a_n, a_{n-1}, \cdots, a_0$ are to be designed.

The input shaping prefilter *F*(*s*) given in (12) can be further rewritten as the following form,

$$F(s) = \frac{a_n s^n + a_{n-1}s^{n-1} + \cdots + a_0}{F_d(s)} \tag{13}$$

where

$$F_d(s) = \prod_{j=1}^{l}(s^2 + 2\zeta_{mj}\omega_{mj}s + \omega_{mj}^2) \tag{14}$$

If we define

$$H(s) = F(s)G(s),\ f_i(s) = \frac{s^i}{F_d(s)},\ h_i(s) = \frac{s^i}{F_d(s)}G(s)$$

for all $i = 0, 1, 2, \cdots, n$, then we have

$$F(s) = \sum_{i=0}^{n} a_i \cdot f_i(s) \tag{15}$$

$$H(s) = \sum_{i=0}^{n} a_i \cdot h_i(s) \tag{16}$$

Define the unit step response of *G*(*s*), *M*(*s*), *F*(*s*)*G*(*s*) and $h_i(s)$ are *g*(*t*), $y_r(t)$, *y*(*t*) and $y_i(t)$, respectively. Generally, *g*(*t*) can be directly obtained through unit step response experiment, and thus $y_i(t)$ can be computed based on the pre-defined $F_d(s)$. After that, $y(t)$ can be computed using $y_i(t)$ as follows,

$$y_i(\mathrm{t}) = \int_0^t (\mathscr{L}^{-1}(\frac{s^i}{F_d(\mathrm{s})}) - \tau)\,\mathrm{g}(\tau)d\tau$$
$$y(t) = \sum_{i=0}^{n} a_i \cdot y_i(t) \qquad (17)$$

That is, for a linear system with the input shaping prefilter as Eq. (12), the unit step response of the system can be predicted through Eq. (17). The corresponding weighting coefficients are the nominator coefficients of *F(s)* to be designed.

In order to ensure the system approach the desired transfer function $M(s)$, the following cost function should be small as far as possible,

$$E = \int_0^\infty (y(t) - y_r(t))dt \qquad (18)$$

Thus, the design of the prefilter can be formulated as a problem that obtaining a group of optimal values of $\{a_0, \cdots, a_n\}$ that minimize the cost function E.

The integration range of the cost function given in (15) is from $t = 0$ to $t = \infty$, which is unrealistic. In fact, this integration range can be selected as a finite period of time:

$$E = \int_0^T (y(t) - y_r(t))^2 \cdot dt \qquad (19)$$

because the inner loop control will make both $y(t)$ and $y_r(t)$ convergent to the steady state in a limited time interval, if T is selected long enough, the difference between $y(t)$ and $y_r(t)$ when $t>T$ will be ignorable.

Substituting (17) into (19) obtains

$$E = \int_0^T (\sum_{i=0}^{n} a_i \cdot y_i(t) - y_r(t))^2 \cdot dt \qquad (20)$$

According to the optimization theory, the necessary and sufficient condition for achieving the minimum value of E is

$$\frac{\partial E}{\partial a_k} = 0 \qquad k = 0,1,2,\cdots,n \qquad (21)$$

Substituting (20) into (21), we have

$$\int_0^T y_k(t) \cdot (\sum_{i=0}^{n} a_i \cdot y_i(t) - y_r(t)) \cdot dt = 0 \quad k = 0,1,2,\cdots,n \quad (22)$$

Define,

$$S_{\alpha,\beta} = \int_0^T y_\alpha(t) \cdot y_\beta(t)) \cdot dt$$
$$\alpha = 0,1,2,\cdots,n \qquad (23)$$
$$\beta = 0,1,2,\cdots,n$$

and

$$S_{\alpha,r} = \int_0^T y_\alpha(t) \cdot y_r(t)) \cdot dt$$
$$S_{\alpha,r} = \int_0^T y_\alpha(t) \cdot y_r(t)) \cdot dt \qquad (24)$$
$$\alpha = 0,1,2,\cdots,n$$

Using (24), (22) can be rewritten as,

$$\sum_{i=0}^{n} a_k \cdot S_{k,i} - S_{k,r} = 0$$
$$k = 0,1,2,\cdots,n \qquad (25)$$

Thus the values of $a_0, a_1, a_2, \cdots, a_n$ can be obtained from the $n+1$ equations given in (25).

In actual application, discrete forms of (22) and (24) are more convenient for the designs of input shaping prefilters,

$$S_{\alpha,\beta} = \sum_{j=0}^{N} (y_\alpha(j \cdot \Delta t) \cdot y_\beta(j \cdot \Delta t))$$
$$\alpha = 0,1,2,\cdots,n \qquad (26)$$
$$\beta = 0,1,2,\cdots,n$$

$$S_{\alpha,r} = \sum_{j=0}^{N} (y_\alpha(j \cdot \Delta t) \cdot y_r(j \cdot \Delta t))$$
$$\alpha = 0,1,2,\cdots,n \qquad (27)$$

where Δt is the sample period and $N=T/\Delta t$.

For most controlled systems, the static gain K can be easily identified, thus a_0 can be calculated as: $a_0=K_m/K$. In this case, (21) can be rewritten as

$$\frac{\partial E}{\partial a_k} = 0 \qquad k = 1,2,\cdots,n \qquad (28)$$

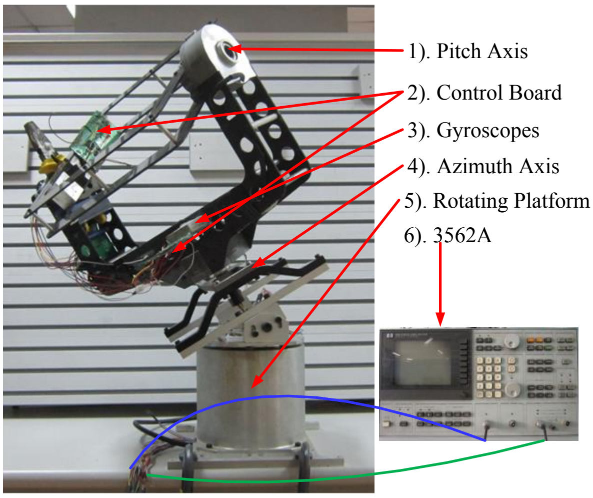
Accordingly, there are n equations in (24), and $S_{0,0}$ and $S_{0,r}$ do not need to be calculated.

Up to now, we have introduced a method on how to obtain an optimal input shaping prefilter to obtain a good input-output response. This, combined to the inner control loop given in the last section, completes the design of the new 2DOF control.

V. Experiments and Results Analysis

A. Experimental setup

In this section, experiments are conducted on an image stabilizer designed in Shenyang Institute of Automation. In order to simulate the vibration of a helicopter, the stabilizer is equipped on another rotating platform as shown in Fig.4. the rotating platform can produce some vibration with pre-defined frequency through connected to a dynamical signal analyzer 3562A which can produce a swept sinusoid signal. Two high-precision gyroscopes are installed in two axis of the image stabilizer, respectively, so that the rotating speed can be measured in real time and speed control can be implemented.



Figu re 2. Experimental setup

B. Experimental results for disturbance attenuation

To testify the disturbance attenuation performance of inner loop controller, the frequency response property for both open loop and closed loop are tested using 3562A, i.e.,

$$\frac{u(j\omega)}{v_i(j\omega)}$$

where $u(j\omega)$ is the swept sinusoid signals produced by 3562A and used to drive the rotating platform, and $v(j\omega)$ is the measured rotating speed of the stabilizer and the subscript i(azimuth or pitch) denoted different axis. The vibration frequency of our real helicopter system is usually from 3Hz to 5Hz, thus in our experiments the swept sinusoid signals are set from 1Hz to 10Hz. The results for azimuth axis and pitch axis are shown as Fig. 3 and Fig. 4, respectively. From this figure, it can be seen that the disturbance can be attenuated greatly using the given controller. Specifically, for the azimuth axis, the influence of the vibration is suppressed by 3.1 times at 3Hz (from -26.3dB to -36.1dB) and 3.9 times at 5Hz (from -32.4dB to -43.2dB); while for the azimuth axis, the influence of the vibration is suppressed by 3.3 times at 3Hz (from -21.2dB to -31.5dB) and 5.0 times at 5Hz (from -26.1dB to -40.1dB).

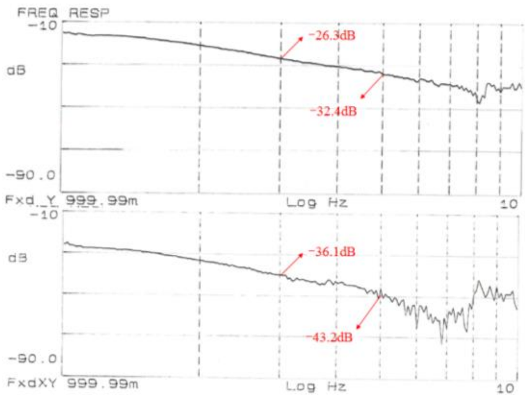


Figure 3. Frequency response property of azimuth axis (*upper: result for open loop; lower: result for closed loop*)

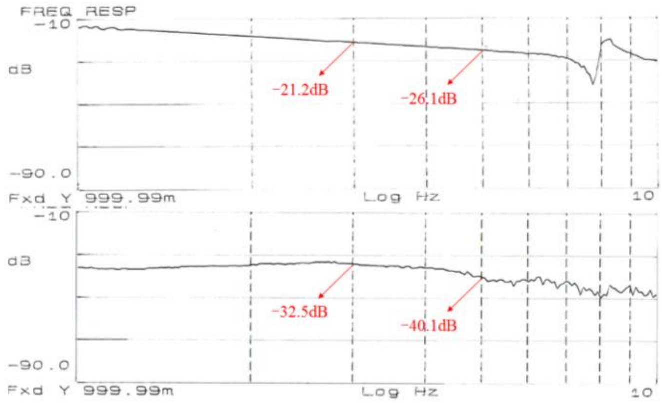


Figure 4. Frequency response property of pitch axis (*upper: result for open loop; lower: result for closed loop*)

Fig. 5 and Fig. 6 show the time response of the system with and without controller, where Fig. 5 is the result of azimuth axis at 3Hz, and Fig. 6 is the result of pitch axis at 5Hz. From these figures, similar results from frequency domain analysis can be obtained.

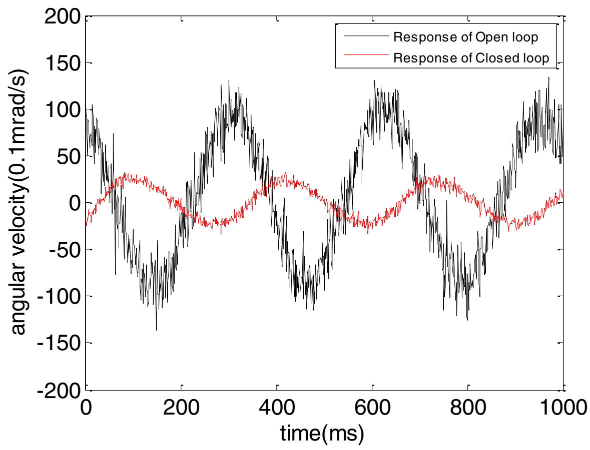


Figure 5. Azimuth velocity output curve at 3Hz with and without inner controller

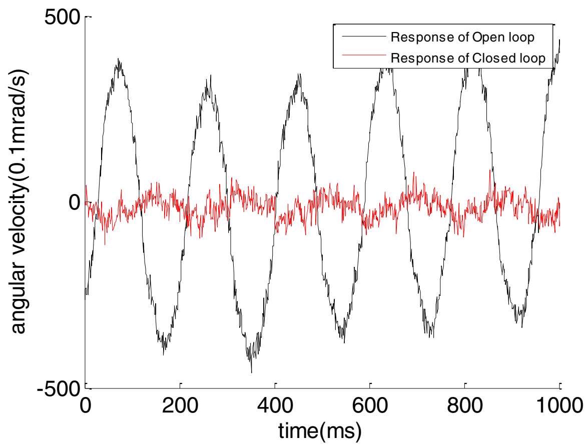


Figure 6. Pitch velocity output curve at 5Hz with and without inner controller

C. Experimental results of tracking control

In the second step, we need to design a prefilter to improve the transient performance. Fig.7 shows the step response of azimuth axis and pitch axis with only inner controller. After that, using method introduced in section IV. Fig.8 gives out the step response of the two axis with optimal prefilter. From Fig. 8, it can be directly seen that the transient performance is improved greatly.

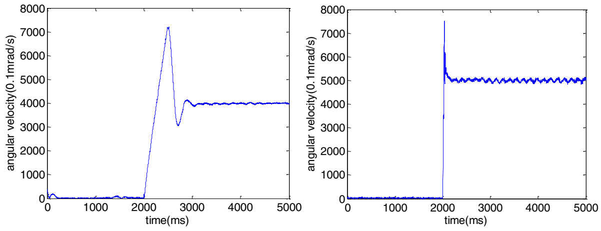


Figure 7. Velocity step response curve of azimuth axis (*left*) and pitch axis (*right*) without prefilter

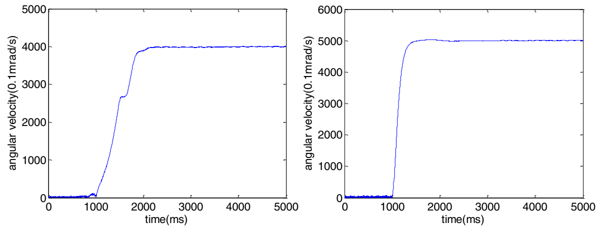


Figure 8. Velocity step response curve of azimuth axis (*left*) and pitch axis (*right*) with optimal prefilter

VI. CONCLUSION AND FUTURE'S WORK

In this paper, simultaneous tracking and disturbance attenuation control problem of helicopter image stabilizers is researched, and a new 2DOF control method based on only input-output responses is proposed. The main contributions of this work are as the following three aspects, (1) the whole control structure combining AFC and PID inner loop to a prefilter is original and the design process requires only input-output response instead of accurate mathematical model of the controlled system; (2) a new prefilter parameter optimization method is introduced to improve the transient tracking performance; (3) Extensive experiments are conducted on a real image stabilizer and the results show the validity and feasibility of the new proposed algorithm. In near future, the whole system and algorithms will be equipped on a real unmanned helicopter system and a flight test will be conducted.

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