Active Disturbance Rejection Control Based Feedback Control System for Quasi-Continuous-Wave Laser Beam Pointing Stabilization

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Abstract. Because of the significant nonlinearity of fast steering mirror (FSM), which is actuated by lead zirconate titanate (PZT) stacks, designing a high-performance laser beam pointing stabilization system is always a difficult work. This paper reports an active disturbance rejection control (ADRC) based feedback control system for laser beam pointing stabilization of a high-power quasi-continuous-wave (QCW) Nd:YAG slab laser with a repetition frequency of 160 Hz and an average output power of 1.5 kW. The simulation and experiment show that the ADRC is faster and smoother than traditional proportional-integral-differential (PID) control, and the ADRC can effectively reduce overshoot in the laser beam pointing stabilization process.

1. Introduction
High-power quasi-continuous-wave (QCW) lasers [1] have extensive scientific, commercial and industrial applications, such as astronomical observation, medical treatment and material processing. For successful implementation of many advanced techniques among these applications, such as the ignition of nuclear fusion [2], artificial laser guide star generated by QCW sodium beacon laser [3] and precision soft tissue surgery and lithotripsy in clinical application [4], a laser with excellent pointing stability is one of the essential factors. In addition to these operation scenarios, the QCW lasers are adopted to attain higher average power, such as incoherent sequence combination based on refraction displacement [5-7]. In many of the above situations, in order to reach the intended targets, the laser beam will inevitably travel a long path. Accordingly, it is possible that small pointing error leads to unpredictable damage to the optical elements or arriving at the wrong aims. In other words, the fluctuation of laser beam pointing is a critical factor for the high-power QCW laser. There exist three main factors that have impact on pointing stability: the disturbance of gas or liquid material (such as air, cloud and ocean) in the path of propagation, mechanical vibrations of optical components and the thermal effect. So as to reduce the influence of these factors, some approaches to evaluate and control the jitter of the laser beam are taken into account.

In the 1920’s, the proportional-integral-differential (PID) based automatic course controller was designed. With the invention and development of the laser, the PID controller was used as the major method to stabilize the laser beam pointing [8, 9]. Unfortunately, some uncertainties (such as the perturbations of laser parameters, random external disturbances and the nonlinearity of fast steering mirror (FSM)) make it difficult to maintain the laser beam pointing. After that, various new modern control methods (such as fuzzy control [8], predictive
control [10], etc.) were introduced to the laser beam pointing control. Although some progress was made by the usage of these methods, some drawbacks were also revealed. To the system applying the fuzzy control algorithm, the control principles, in general, are hard to determine and optimize. As for the predictive control, it is only limited to reduce the regular jitter of the laser beam. Furthermore, these advanced control algorithms are complex and difficult to regulate the parameters.

In recent years, a viable PID alternative control technology, which is called active disturbance rejection control (ADRC) [11], is articulated. It is developed from the classic PID algorithm and maintains the independence of the controlled target model. To deal with the perturbation in the high-power QCW laser and strong disturbance in the path of propagation, ADRC is an operative approach with a wide range of parameters, great operating convenience, good compatibility and satisfactory robustness.

A real-time feedback control system based on ADRC for the pointing stabilization of a high-power QCW Nd:YAG laser is expounded in this paper. For the time being, the QCW laser pointing stabilization feedback control system is based on the classic PID algorithm, a piezoelectrically actuated fast steering mirror and a far-field spot detection system. The system, which is designed and implemented in our work, uses ADRC algorithm, as ADRC is faster and anti-noise than the conventional PID. To the best of our knowledge, this is first reports on the high-power QCW laser pointing stabilization based on ADRC algorithm.

2. Experimental Setup

Figure 1 shows the configuration of the QCW Nd:YAG slab laser beam pointing stabilization with a feedback control system. The system is composed of a low-power master oscillator (MO) and a conduction-cooled, end-pumped slab (CCEPS) amplifier. The output from the laser diode arrays (LDA) with a wavelength of 808 nm, a pulse duration of 500 μs and a repetition frequency of 160 Hz, is shaped and injected into the slab. The average output power, which reaches up to 1.5 kW, of the Nd:YAG slab MOPA system is measured by thermopile power meter (PM, OPHIR NOVAlI/10K-W-V1). It is placed in the path of propagation after the Mirror, which is coated with high reflectivity (HR) films at 1064 nm (the reflectivity R>99.8%). The laser beam pointing stabilization system is comprised of FSM, a far-field spot detection system and a feedback control system based on ADRC algorithm. Maintaining the optical axis of laser beam at a specific point on a plane is the ultimate goal of this system.

![Figure 1. (Color online) Schematic arrangement of the QCW Nd:YAG laser beam pointing stabilization with a feedback control system. HVA, high-voltage amplifier; FSM: fast steering mirror; PM, power meter.](image)

2.1. Far-Field Spot Detection System
Normally, the position-sensing devices are position sensitive detector (PSD), quadrant photodiode (QD), charge-coupled device (CCD) and complementary metal oxide semiconductor (CMOS). As analog signal devices, PSD and QD have characteristics of quick response, high sensitivity, and their results are not related to laser spot size and shape. They have been applied to numerous laser beam pointing deviation detection systems. Nonetheless, due to these features, they are limited to measuring the barycenter of laser spot, and will not extract additional useful information such as the profile and intensity distribution of the far-field spot. Furthermore, the noise, including thermal agitation noise, shot noise and amplifier noise, is a main factor that has an impact on sensitivity and accuracy. The limitations of the PSD and QD are relieved by adopting a CCD or COMS camera.

In the experimental setup, a high-resolution, high signal to noise ratio (SNR) CMOS camera (PHOTON FOCUS, MV1-D1312IE-160-CL-12) with near infrared (NIR) sensitivity enhanced is applied to track the position of the high-power QCW laser beam. To catch the position of the laser spot without omitting one single pulse, the camera is in sync with the QCW slab laser trigger signal. For the sake of reducing the spot intensity to the acceptable range of the CMOS chip, absorptive type neutral density filters are placed in front of the CMOS camera. The Camera is located at the focus of the Lens whose focal length is 1000 mm and the far-field spot alights upon the apt region of interest (ROI) of the CMOS chip. With the pixel size of 8 μm × 8 μm, the sensitivity of the detection system is better than 8 μrad.

The images of the laser spot are transferred from the CMOS camera to the frame grabber via CameraLink interface with a frequency of 160 Hz. Utilizing the Microsoft Foundation Classes (MFC) in the Microsoft Visual Studio software, a program is developed to calculate the centroid of laser spot captured by the CMOS camera. After subtracting the background noise, the pixel coordinates of the spot centroid in the X and Y direction are computed from the image data. The origin coordinates (0, 0) are situated at the upper left corner of the ROI. Based on these processed data, the program generates the feedback control signal with the usage of ADRC algorithm. Furthermore, the program has the capacity for handling some common errors, such as the transmission error from the camera to the frame grabber.

2.2. Fast Steering Mirror

![Figure 2. (Color online) Simplified structure of FSM; PZT, lead zirconate titanate; CM, compliant mechanism.](image)

Figure 2 shows the simplified structure of FSM. It is composed of the PZT stacks, the compliant mechanisms and a mirror coated with HR films at 1064 nm (the reflectivity R>99.8%). The PZT stacks are the foremost component in FSM system which can drive FSM to compensate the pointing deviation within ±3 mrad via compliant mechanism. Moreover, the actuating mechanisms of X and Y direction are designed according to the same principle due to the independence of each other. Besides, a high-voltage amplifier is applied to amplify the control signal to drive the PZT actuator. To analyze the piezoelectric driven mirror, the second-order mechanical resonance model can be adopted. More exactly, the FSM system can be considered as mass-spring-damper system [6]:

\[
G(s) = \frac{K \omega_n^2}{s^2 + 2 \zeta \omega_n s + \omega_n^2}
\]  

(1)
Where the model parameters $K$, $\omega_n$ and $\zeta$ are the gain of model, resonant frequency and damping ratio, respectively. Based on the experimental frequency response data, these unknown parameters can be decided. The frequency response results of the FSM system used to design the controller are shown in figure 3. The dynamics are characterized by an approximate 15-degree phase lag at low frequencies, a suspension mode resonance at 540 Hz, and a rapidly-decaying phase profile at frequencies greater than 200 Hz. Hence, the parameters of transfer function are obtained by analyzing these experimental data, where $K = 0.97$, $\omega_n = 650$ and $\zeta = 0.43$.

![Figure 3](image_url)  
**Figure 3.** (Color online) Analytical and experimental frequency response of the FSM system.

2.3. ADRC System

![Figure 4](image_url)  
**Figure 4.** (Color online) Architecture of the ADRC system; TD, tracking differentiator; ESO, extended state observer; NLSEF, nonlinear state error feedback; FSM, fast steering mirror.

Due to the lack of specific mathematical model of the device, an operative method for high-capability control of the FSM system, which is the ADRC algorithm, is introduced. The disturbance of air in the path of propagation and the unpredictable jitter of high-power laser beam are evaluated and compensated in real time. Architecture of the ADRC system for FSM is shown in figure 4. Owing to the hysteresis of FSM and the time-varying perturbation of the laser beam, the FSM system description can be form of:

$$
\begin{align*}
\dot{x}_2(t) &= f(x_1(t), x_2(t), \omega(t, x), t) + bu(t) \\
\dot{x}_1(t) &= x_2(t) \\
y(t) &= x_1(t)
\end{align*}
$$

(2)
Where \( u(t) \) is the input of the FSM system, \( \omega(t, x) \) is unknown exogenous factor, \( f(x(t), x_2(t), \omega(t, x), t) \) is a pending function including unmodelled variables, \( y(t) \) is the output, and \( b \) is the gain of the FSM. Then, \( x_1(t) \) and \( x_2(t) \) are the state parameters of FSM system, respectively.

Considering the characteristic of this second order Newton system, the ADRC system is principally composed of tracking differentiator (TD), extended state observer (ESO) and nonlinear state error feedback (NLSEF). In three parts of the ADRC system, TD is the most apparent part derived from PID directly. The TD is adopted to provide a transition process for setpoint and extract differential part of the input signal. The TD for FSM system can be described as follows:

\[
\begin{align*}
e &= s_1 - s_0 \\
\dot{e} &= v_1 \\
v_1 &= f(t) \\
f(t) &= \text{ft}(e, v_1, r, h)
\end{align*}
\] (3)

Where \( s_0 \) is ideal input signal of the system, which is the setpoint of laser beam pointing, \( s_1 \) is the variable we want to control, which is the present position, and \( v_1 \) is the differential of \( e \). \( r \) and \( h \) are the adjustable tuning parameters. And the optimal control function \( \text{ft}(e, v_1, r, h) \) is defined as:

\[
\text{ft}(e, v_1, r, h) = \begin{cases} 
\text{rs}
& |e| > d \\
\text{a}
& r \frac{a}{d}, & |a| \leq d 
\end{cases}
\] (4)

Where \( a \) and \( d \) are defined as:

\[
a = \begin{cases}
v_1 + \frac{(a_0 - d)}{2} \text{sgn}(y), & |y| > d_0 \\
v_1 + \frac{y}{h}, & |y| \leq d_0 
\end{cases}
\] (5)

\[
d = rh \\
d_0 = dh \\
y = e + s_0 + hv_1 \\
a_0 = \sqrt{d^2 + 8r |y|}
\] (6)

As mentioned above, the second part of the ADRC system is the ESO. The ESO is a breakthrough of state observer, since not only the states but also total disturbance is estimated in real time. According to the characteristics of the FSM system, a third order ESO is introduced as follows:

\[
\begin{align*}
e_1 &= z_1 - y \\
\dot{z}_1 &= z_2 - \beta_1 e_1 \\
\dot{z}_2 &= z_3 - \beta_2 g_1(e_1) + bu \\
\dot{z}_3 &= -\beta_3 g_2(e_1)
\end{align*}
\] (7)

Where \( z_1, z_2 \) and \( z_3 \) are the estimates of \( s_1, v_1 \) and \( \omega(t, x) \), respectively. \( \beta_1, \beta_2 \) and \( \beta_3 \) are adjustable parameters. And, function \( g \) can be parametrized by utilizing tuning parameter \( a \) and adjustable threshold value \( \delta \):
The last but not the least, the NSLEF, the third part of ADRC, is adopted to obtain \( u_0 \) according to the difference between values from TD \( s_1, v_1 \) and estimated values \( z_1, z_2 \). The general NSLEF is described as follows:

\[
\begin{cases}
    e_1 = s_1 - z_1 \\
    e_2 = v_1 - z_2 \\
    u_0 = \beta_{01} e_1 + \beta_{02} e_2
\end{cases}
\]

Where \( \beta_{01} \) and \( \beta_{02} \) are the adjustable parameters, so the synthesis of control volume is:

\[
u = u_0 - \frac{z_3}{b}\]

3. Results and Discussion
The simulation results to a feedback control of the FSM system by MATLAB are shown in figure 5. It is obvious that the FSM system with ADRC based feedback control system yields less overshoot compared with the system, which is controlled by the traditional PID algorithm. As a good tradeoff value for a robust controller, the parameter values of ADRC are taken as follow, where \( h=0.004, \ r=10900, \ \beta_1=400, \ \beta_2=4000, \ \beta_3=20000, \ \beta_{01}=5000, \ \beta_{02}=100 \) and \( b=1 \).

Figure 5. (Color online) Simulation results of the feedback control of the FSM system by MATLAB.

The performance of FSM system is tested with the QCW slab laser beam, whose average output power is 1.5 kW, repetition frequency is 160 Hz and propagation distance is 15 meters. Normally, the camera is situated at the focal point of the Lens where the spot falls near the reference point \((655, 540)\) in the pixel coordinates for this camera). The centroid of the Nd:YAG slab laser spot is computed on a high-performance workstation. The experimental results of the FSM system (X axis) applying PID and ADRC algorithm respectively are demonstrated in figure 6. The results show that the FSM system works well. On application of the feedback close-loop control, the centroid of the laser beam is moving from 648 pixel to 655 pixel (the setpoint), and the pointing fluctuations of the laser beam are less than 5 μrad with the usage of focusing lens. As is shown in the figure, it is noticeable that the ADRC based feedback control system has better performance over traditional PID.
control system in tracking precision and response time. In summary, the ADRC based feedback control is faster and smoother with less overshoot.

Figure 6. (Color online) The experimental results of FSM system (X axis) applying PID and ADRC algorithm.

4. Conclusion
This paper introduces an ADRC based feedback control system for QCW laser beam pointing stabilization, which enables an appropriate tradeoff between robustness and performance. It is discussed and experimentally verified in a high-power QCW slab laser with a repetition frequency of 160 Hz and an average output power of 1.5 kW. Compared with traditional PID control, the ADRC control is faster and smoother with less overshoot for nonlinear FSM system based on PZT stacks. We believe that higher processing speed and better robustness can be accomplished by optimizing the ADRC controller parameters and upgrading the hardware like Field Programmable Gate Array (FPGA) and digital signal processor (DSP).

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