Settling Time Shortening Method Using Final State Control for High-precision Stage with Decouplable Structure of Fine and Coarse Parts

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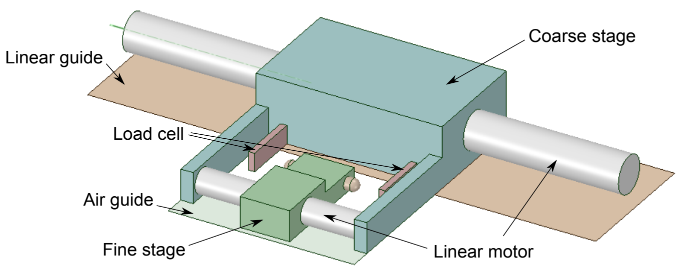
***Abstract*—High-precision stages require high-speed and high-precision control to improve their production throughput and quality. However, it is expected that their motion speed and accuracy will reach a limit in the near future if the structure of the conventional high-precision stage is used. Therefore, the authors designed and fabricated a stage called the catapult stage which has a decouplable structure consisting of a fine stage and a coarse stage. This stage is different from conventional dual stages in which the fine stage would be disturbed by the coarse stage since they contact with each other. This paper proposes a novel control system design for the catapult stage, and a settling time shortening control method using final-state control (FSC). So far, FSC is mainly applied to the applications such as hard disk drives whose initial states are the zero. However, it is important to consider the initial states for the catapult stage since the initial position, velocity and acceleration of the catapult stage are not equal to zero. Simulations and experimental results demonstrate the effectiveness of the proposed methods.**

***Index Terms*—Precise Positioning, High Precision Stage, Dual Stage, Settling Time Shortening, Final State Control**

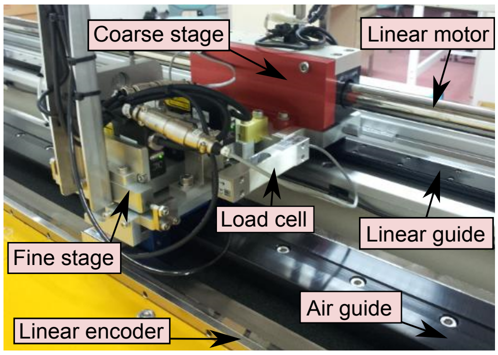
I. Introduction

High-precision stages are essential industrial equipments to produce semiconductors and liquid crystal displays. These stages demand high precision and high throughput since these productions require a low price and high-density. To achieve higher throughput, these stages have to be larger and faster. On the other hand, a high-precision motion control requires a feed back (FB) loop with high bandwidth to achieve nanoscale positioning. However, the larger these stages are, the heavier these stages would be. As a result, it is becoming difficult to make the bandwidth of a FB loop higher due to a lower resonant frequency. Consequently, to increase in size and speed is conflicting request in high-precision stages.

Dual-servo stages which have a coarse component and a fine component have been used to achieve high precision and high throughput in high-precision stages [1]–[3], such as optical disks [4] and hard disk drives (HDD) [5]. The dual-servo stage makes the fine stage simple and light-weight. The coarse stage has a low bandwidth with a large stroke, while the fine stage has a high bandwidth with a small stroke [6]. The fine stage and the coarse stage, however, need to be driven at the same acceleration because they are driven to avoid contacting with each other. Thus the fine stage also needs to have a motor with



(a) Schematic of the catapult stage.



(b) Experimental stage

Fig. 1. Structure of the catapult stage.

TABLE I
THE CATAPULT STAGE PARAMETERS

Maximum thrust force of the fine stage	$F_{f\max}$	40.0	N
Maximum thrust force of the coarse stage	$F_{c\max}$	218	N
Mass of the fine stage	M_f	6.0	kg
Mass of the coarse stage	M_c	11	kg
Coefficient of viscosity of the coarse stage	D_c	101.7	N·s/m
Gap	X_{off1}	1.0	mm
Gap	X_{off2}	1.0	mm

large thrust and mass, which limits the potential to achieve a higher FB bandwidth. For this reason, a high-precision stage with a new structure which is compatible with increasing in size and acceleration is required. Our research group designed and fabricated an experimental high-precision stage called the catapult stage. The stage allows contact and separation between a fine part and a coarse part. Fig. 1 shows the structure of the catapult stage. The coarse stage is guided by a linear guide and driven by a linear motor. The motor possesses a large thrust for acceleration and deceleration. The fine stage is guided by an air guide and driven by a linear motor with small thrust. The fine part can be controlled precisely during constant velocity motion.

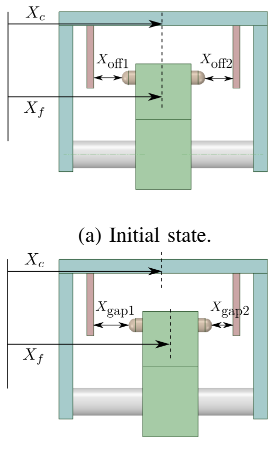
The characteristic of the catapult stage is to allow contact between the fine and coarse stages in the acceleration and deceleration regions. Thus a new control system for the catapult stage is required.

The purpose of this paper is to show the validity of the catapult stage. In section II, the structure and characteristics of the catapult stage are depicted. In section III, a novel control system design for the catapult stage is proposed. The control system takes into account the characteristic of the catapult stage which allows contact between the fine and coarse stages. In section IV, a settling-time shortening control based on FSC is proposed. The control can reduce the settling time in the constant velocity region where the fine stage requires a precision control. In section V and VI, simulations and experimental results demonstrate that the remarkable performance obtained.

II. Structure of the Catapult Stage

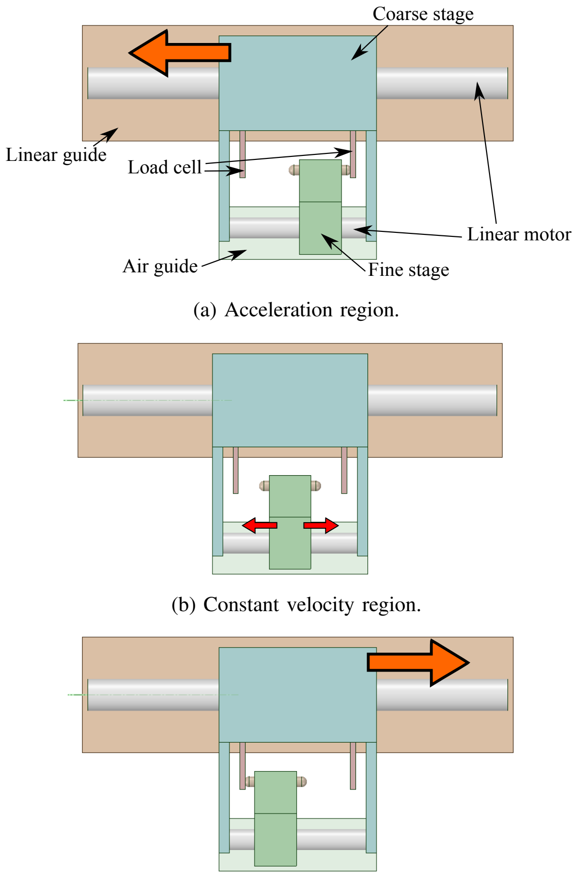
In this section, a structure and characteristics of the catapult stage are explained. Fig. 1(a) shows the overview of the catapult stage and Fig. 2 shows the top view of the connection mechanism between the fine stage and the coarse stage. Load cells are mounted on the coarse stage and protrusions are attached on the fine stage. The coarse stage transmits its thrust to the fine stage via load cells and protrusions.

Fig. 3 demonstrates the motion of the catapult stage. In the acceleration region, the coarse stage contacts with the fine stage and pushes the fine stage to accelerate. As a result, the motor driving the fine stage can be small and light-weight because it s not used in this region. In the constant velocity region, the fine stage is separated from the coarse stage and each stage is controlled independently. In addition, the fine stage is controlled not to be affected by the disturbance from the air guide. The fine stage requires high positioning accuracy in this region. In the deceleration region, the coarse stage contacts with the fine stage again and brakes the fine stage to decelerate and stop. TABLE. I shows the parameters of the catapult stage.



(b) During driving.

Fig. 2. Structure of the catapult stage (link).



(a) Acceleration region.

(b) Constant velocity region.

(c) Deceleration region.

Fig. 3. Movement of the catapult stage.

III. Model and Control System of the Catapult Stage

In section III-A, a stage model and an impact force model of the catapult stage which is proposed in previous research [7] is introduced. In section III-B and III-C, a novel control system which takes into account characteristics of the catapult stage is proposed. The sub script "f" means the fine stage and "c" means the coarse stage.

A. Modelling of the catapult stage [7]

1) Stage model: In this section, models of the catapult stage is defined. Plants of the fine and coarse stages are given by

$$X_f = P_f(s)\,(u_f - F_{if}),\ X_c = P_c(s)\,(u_c - F_{ic}), \qquad (1)$$

where u is the control input, F_i is the reaction force from the other stage and X is the position. The resultant force is given by the motor force and the interaction force. In this paper, plant models $P_f(s)$ and $P_c(s)$ are defined as the rigid body models shown in (2).

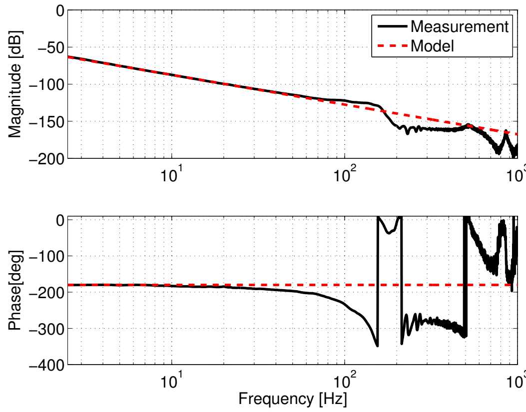
$$P_f(s) = \frac{1}{M_f s^2},\ P_c(s) = \frac{1}{M_c s^2 + D_c s}. \qquad (2)$$

Here, M is the mass and D is the coefficient of viscosity. Fig. 4(a) and Fig. 4(b) show the frequency responses of the fine stage and the coarse stage in measurements and models which fitted by 2nd-order transfer functions. In addition, Fig. 4(c) shows a viscosity measurement by using a velocity control. From these results, the stage parameters M_f, M_c, D_c are identified as TABLE. I.

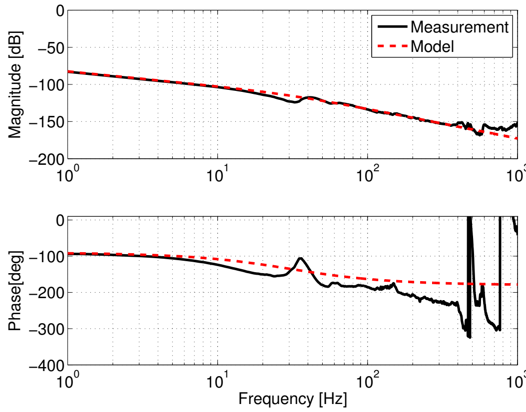
2) Impact force model: The impact force F_i occurs when the fine stage contacts with the coarse stage. By Hertz contact theory [8], the impact force F_{if}, F_{ic} is given by

Require: X_{gap1}, X_{gap2}, $\dot{X}_f$, $\dot{X}_c$
Ensure: F_{if}, F_{ic}
if $X_{\text{gap1}} < 0$ **then**
  $X = -X_{\text{gap1}}$
  $\dot{X} = -(\dot{X}_f - \dot{X}_c)$
  $F_i = -KX^{\frac{3}{2}} - \alpha\sqrt{|X|}\dot{X}$
  $F_{if} = F_i$
  $F_{ic} = -F_i$
else if $X_{\text{gap2}} < 0$ **then**
  $X = -X_{\text{gap2}}$
  $\dot{X} = \dot{X}_f - \dot{X}_c$
  $F_i = -KX^{\frac{3}{2}} - \alpha\sqrt{|X|}\dot{X}$
  $F_{if} = -F_i$
  $F_{ic} = F_i$
else
  $F_{if} = 0$
  $F_{ic} = 0$
end if

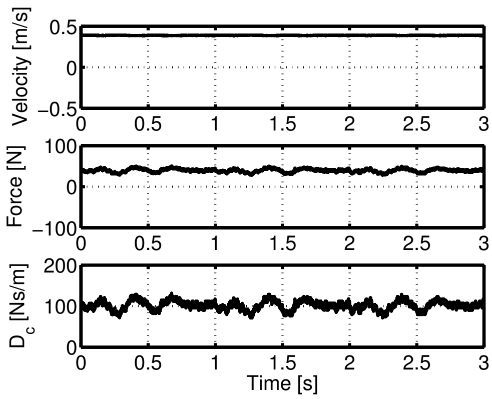
where K is the non-linear spring coefficient, α is the non-linear damper coefficient, X is the deformation of the load cell, $\dot{X}$ is the relative velocity between the fine and coarse stages.



(a) Frequency response of the fine stage.



(b) Frequency response of the coarse stage.

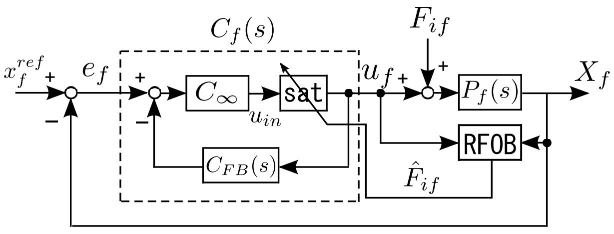


(c) Viscosity measurement by velocity control.

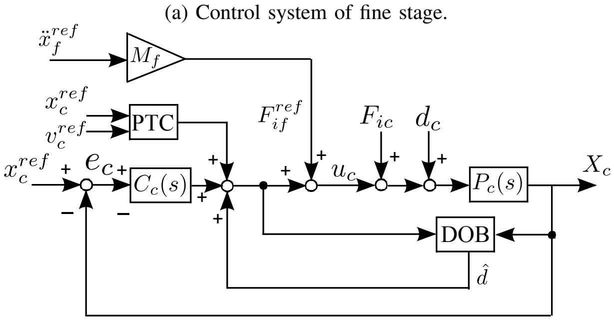
Fig. 4. Parameter identification of the catapult stage.

B. Control system of the fine stage

Fig. 5(a) shows the proposed control system of the fine stage. x_f^{ref} is position reference of the fine stage. The FB controller $C_f(s)$ for the plant $P_f(s)$ is designed in advance considering the robustness and stability. Furthermore, a reaction force observer (RFOB) is designed to estimate the reaction force from the coarse stage [9]. RFOB is a disturbance observer (DOB) which regards the reaction force F_{if} as the disturbance. In the beginning of the constant speed region, the fine stage needs an anti-windup controller because the tracking



(a) Control system of fine stage.



(b) Control system of coarse stage.

Fig. 5. Control system design of the catapult stage.

error of the fine stage may cause the thrust saturation of the fine stage. $C_f(s)$ is an anti-windup controller based on C_∞ and $C_{FB}(s)$ in (3) [10]. The "sat" is a saturation function.

$$C_f(s) = \frac{C_\infty}{1 + C_{FB}(s)C_\infty} \tag{3}$$

In addition, a control switching and a trigger to switch control are required because the fine stage is controlled only in the constant velocity region. Therefore, this paper proposed the control switching algorithm using the saturation function "sat" and the estimated reaction force $\hat{F}_{if}$. The thrust limit u_{sat} is given by

$$u_{sat} = \begin{cases} 0, & |\hat{F}_{if}| > F_{if}^{thr} \\ u_{lim} & \text{otherwise}, \end{cases} \tag{4}$$

where a distinction between contact and noncontact with the fine and coarse stages is based on the estimated reaction force $\hat{F}_{if}$ and a threshold F_{if}^{thr}. Moreover, the threshold F_{if}^{thr} is sufficiently larger than the estimated reaction force $\hat{F}_{if}$ at the noncontact region. The input u_f is given by

$$u_f = \begin{cases} u_{sat}, & u_{in} > u_{sat} \\ -u_{sat}, & u_{in} < -u_{sat} \\ u_{in}, & \text{otherwise}. \end{cases} \tag{5}$$

C. Control system of the coarse stage

Fig. 5(b) shows the proposed control system of the coarse stage. x_f^{ref}, x_c^{ref} and v_c^{ref} are the position reference value of the fine and coarse stages and the velocity reference value of the fine stage, respectively. The FB controller $C_c(s)$ for the plant $P_c(s)$ is designed in advance considering the robustness and stability. The control system of the coarse stage is a two-degree-of-freedom control system which consists of a feedforward (FF) controller by using perfect tracking control (PTC)

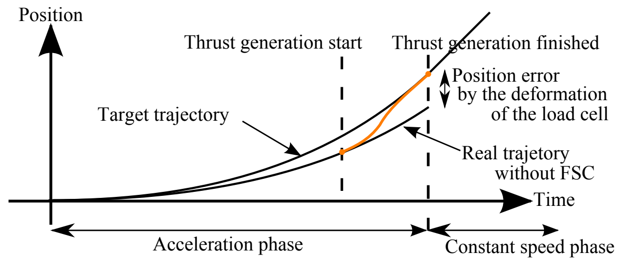


Fig. 6. Concept of thrust generation at acceleration region.

and a feedback controller $C_c(s)$ to track the target trajectory ideally [11]. Additionally, DOB is designed based on (1). DOB suppresses disturbance

$$d_{allc} = F_{if}^{ref} + F_{ic} + d_c, \tag{6}$$

where F_{ic} is the reaction force from the fine stage and d_c is the input disturbance excited by the linear guide. Furthermore, F_{if}^{ref} is the reference thrust to drive the fine stage in the acceleration and deceleration regions. It is given by

$$F_{if}^{ref} = M_f \ddot{x}_f^{ref}. \tag{7}$$

Therefore, the coarse stage gives the fine stage the reaction force to drive it ideal if the input disturbance d_c and the disturbance d_{allc} are the zero.

IV. Settling Time Shorten Control of the Fine Stage in Acceleration Region

The characteristic of the catapult stage, referred in section II, is that the fine stage is controlled when the motion enters into the constant velocity region. However, it is impossible to avoid the position errors due to the deformation of the load cell, shown in section V later, even if the coarse stage is controlled ideally.

For this reason, this paper proposed a method to begin giving the fine stage thrust when it can be activated in the acceleration region. Fig. 6 shows its conceptual diagram. This study applies final-state control (FSC) to the fine stage in the acceleration region. In section IV-A, FSC is introduced. In section IV-B, the condition to apply FSC to the catapult stage is considered.

A. Final State Control [12]

FSC is a control system which takes an initial state to a final state in finite time by applying feedforward inputs.

A state-space model of a discrete-time system is defined as follows.

$$\boldsymbol{x}[k+1] = \boldsymbol{A}\boldsymbol{x}[k] + \boldsymbol{B}u[k] \tag{8}$$

Let us consider to obtain the feedforward input $u[k]$ that drives an initial state $x[0]$ to a final state $x[N]$ by N steps control inputs. A performance index is set as follows.

$$\begin{aligned} J &= \boldsymbol{U}^{\mathrm{T}}\boldsymbol{Q}\boldsymbol{U}, \ \boldsymbol{Q} > 0 \\ \boldsymbol{U} &= [u[0] \ u[1] \ \cdots \ u[N-1]]^{\mathrm{T}} \end{aligned} \tag{9}$$

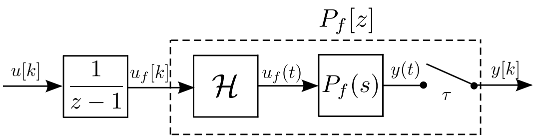


Fig. 7. Augmented system with an integrator.

$\boldsymbol{Q}$ is an weighting matrix. The feedforward inputs minimizing (9) are given as follows.

$$\begin{aligned}\boldsymbol{U} &= \boldsymbol{Q}^{-1}\boldsymbol{\Sigma}^{\mathrm{T}}(\boldsymbol{\Sigma}\boldsymbol{Q}^{-1}\boldsymbol{\Sigma}^{\mathrm{T}})^{-1}(\boldsymbol{x}[N]-\boldsymbol{A}^N\boldsymbol{x}[0]) \\ \Sigma &= [\boldsymbol{A}^{N-1}\boldsymbol{B}\ \boldsymbol{A}^{N-2}\boldsymbol{B}\ \cdots\ \boldsymbol{B}]\end{aligned} \tag{10}$$

An initial state can be taken to a desired final state in finite time by using these feedforward inputs.

B. Applying FSC to the catapult stage

In this section, the condition to apply FSC to the catapult stage is stated. First, let us consider when the fine stage starts to control. The fine stage can not separate from the coarse stage when the inertial force is larger than the maximum thrust of the fine stage. Therefore, it is necessary to deal with the position, velocity and thrust of the fine stage to consider the influence of the inertial force. For this reason, an augmented system with an integrator is needed to add the thrust element to state variables. Fig. 7 shows a system where the control input $u_c[k]$ is augmented by a discrete-time integrator $1/(z-1)$. $P_f(s)$ is a continuous-time model defined by a continuous time state-space equation

$$\begin{aligned}\dot{\boldsymbol{x}}_{fc}(t) &= \boldsymbol{A}_{fc}\boldsymbol{x}_{fc}(t)+\boldsymbol{B}_{fc}u_c(t) \\ y(t) &= \boldsymbol{C}_{fc}\boldsymbol{x}_{fc}(t).\end{aligned} \tag{11}$$

$P_f[z]$ is a discrete-time model of $P_f(s)$ with zero-order hold. The state-space equation is given by

$$\begin{aligned}\dot{\boldsymbol{x}}_{fd}[k+1] &= \boldsymbol{A}_{fd}\boldsymbol{x}_{fd}[k]+\boldsymbol{B}_{fd}u_c[k] \\ y[k] &= \boldsymbol{C}_{fd}\boldsymbol{x}_{fd}[k],\end{aligned} \tag{12}$$

where $\boldsymbol{A}_{fd} = e^{A_{fc}T_s}$, $\boldsymbol{B}_{fd} = \int_0^{T_s} e^{\boldsymbol{A}_{fc}\tau}\boldsymbol{B}_{fc}d\tau$, $\boldsymbol{C}_{fd} = \boldsymbol{C}_{fc}$ and T_s is the sampling-period. The state-space equation of the augmented system $P[z]$ is given by

$$P[z] = \left[\begin{array}{c|c}\boldsymbol{A} & \boldsymbol{B} \\ \hline \boldsymbol{C} & 0\end{array}\right] = \left[\begin{array}{cc|c}\boldsymbol{A}_{fd} & \boldsymbol{B}_{fd} & 0 \\ 0 & 1 & 1 \\ \hline \boldsymbol{C}_{fd} & 0 & 0\end{array}\right], \tag{13}$$

where $\boldsymbol{x}_{fd}[k]$ is a state variable of $P_{fd}[z]$ and $\boldsymbol{x}[k] := [\boldsymbol{x}_{fd}^{\mathrm{T}}[k]\, u_c[k]]^{\mathrm{T}}$ is a state variable of the argument system. In this paper, the fine stage starts to control when its acceleration becomes $1.0\ \mathrm{m/s^2}$ which is equal to about 70 percent of the maximum acceleration required to drive the fine stage. It is hoped that this criterion will be smaller in further studies.

Second, let us consider the necessary condition to generate FF input by applying FSC to the fine stage control. So far, FSC is mainly applied to systems such as hard disk drives whose initial state is the zero. However, it is important to consider the initial state when FSC is applied to the catapult stage because the initial states of it are not the zero. The initial states and the final states of the position, velocity and thrust are needed to apply FSC to the fine stage because (2) is a second order rigid model. The final states of the position, velocity and thrust are already known, however, the initial states of these need to be measured because they are unknown. In this paper, the position is measured by a linear encoder, the velocity is obtained by backward difference of the position and the thrust is estimated by RFOB. Thereby, the FF input taking account of the initial position, velocity and thrust of the fine stage can be generated. Fig. 8 shows the fine stage control system with FSC.

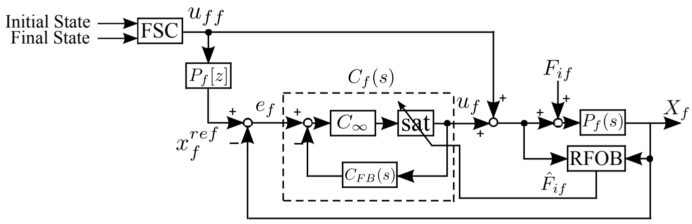


Fig. 8. Control system of fine stage with FSC.

V. Simulation

In section V, simulations show that position errors at the beginning of the constant velocity region can be small by applying FSC to the fine stage in the acceleration region. Fig. 10(a) shows the target position, velocity and acceleration trajectories. The target position trajectory is based on 5th-order polynomials. The distance of movement is $600\,\mathrm{mm}$, the maximum velocity is $400\,\mathrm{mm/s}$ and the average acceleration $800\,\mathrm{mm/s^2}$. These trajectories during 0.0 s to 0.5 s is in the acceleration region. These trajectories during 0.5 s to 1.5 s is in the constant velocity region. The target trajectory of the coarse stage is shifted by gap lengths $X_{\text{off1}}, X_{\text{off2}}$ in the acceleration region and deceleration regions compared with the target trajectory of the fine stage to avoid the impact force between the fine stage and the coarse stage. The control period is $200\,\mu$s. A PID position controller is designed for the fine and coarse stages, so that the closed-loop bandwidth of the position loop can be 20 Hz and 20 Hz, respectively. The cut-off frequency of DOB is $40\,\mathrm{Hz}$.

The "Conventional" control system uses the PID controller to the coarse stage and the fine stage. The "Proposed 1" control system uses PTC and DOB to the coarse stage and the PID controller to the fine stage which is shown in Fig. 5(a). The "Proposed 2" control system uses the PID controller to the coarse stage and FF input generation in the acceleration region to the fine stage which is shown in Fig. 8.

Fig. 10 shows the simulation results. It is defined that settling time is the time from the beginning of the constant velocity region to that the position error of the fine stage is smaller than $1\ \mu\mathrm{m}$. The settling time of "Conventional", "Proposed 1" and "Proposed 2" are 55 ms, $55\,\mathrm{ms}$ and $0.00\,\mathrm{ms}$, respectively. Fig. 10 shows that it is impossible to avoid the position error due to the deformation of the load cell even if the coarse stage is controlled ideally if the fine stage is driven only in the constant velocity region. From these results, it is

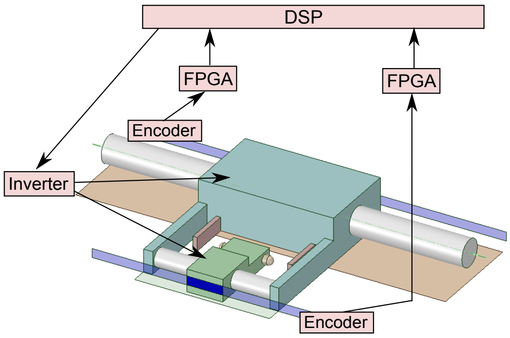


Fig. 9. Signal processing system of the catapult stage.

TABLE II
SIMULATION RESULT

	Fine	Coarse	Settling Time	Maximum Thrust
Conventional	PID	PID	55 ms	40 N
Proposed 1	PID	PTC+DOB	55 ms	40 N
Proposed 2	PID+FSC	PID	0.00 ms	4.4 N

more important to consider the control method of the fine stage than to improve the control performance of the coarse stage.

VI. EXPERIMENT

In section VI, experimental results show that position errors at the beginning of the constant velocity region can be small by applying FSC to the fine stage in the acceleration region. We do not experiment ”Proposed 1” because the precision of the coarse stage is not important referred in section V. The conditions of the experiments are same with those of the simulations. Fig. 9 shows a signal processing system of the catapult stage. The positions of the fine stage and the coarse stage are measured by linear encoders with resolution of $1\ \mathrm{nm}$. Fig. 11 shows the experimental results. Fig. 11 compares the results of “Conventional” and “Proposed 2”. The settling time of “Conventional” and “Proposed 2” are $56\,\mathrm{ms}$ and $0.00\,\mathrm{ms}$. In addition, the required thrust of the fine stage by using “Proposed 2” is much smaller than that by using “Conventional”. As a result, the motor with the fine stage can be smaller and lighter by using “Proposed 2”.

VII. CONCLUSION

This paper proposed a novel control system using an anti-windup compensation and a control switching algorithm to take into account the characteristics of the catapult stage which allows contact between the fine stage and the coarse stage (Proposed 1). Simulation results prove its effectiveness of “Proposed 1”.

However, it was found that, with “Proposed 1”, the fine stage can not avoid position errors due to the deformation of the load cell at the beginning of the constant velocity region. For this reason, this paper proposed a method to begin generating a new trajectory of the fine stage when it can be activated in the acceleration region. In this study, final state control (FSC) is applied to the fine stage in the acceleration region (Proposed 2). Furthermore, the effectiveness of “Proposed 2” is verified by the simulation results and experimental results.

Further study of the optimized solution of FF control taking into account the rated thrust of the motor should be conducted. The findings would contribute to the design of the catapult stage.

TABLE III
EXPERIMENTAL RESULT

	Fine	Coarse	Settling Time	Maximum Thrust
Conventional	PID	PID	56 ms	40 N
Proposed2	PID+FSC	PID	0.00 ms	6.3 N

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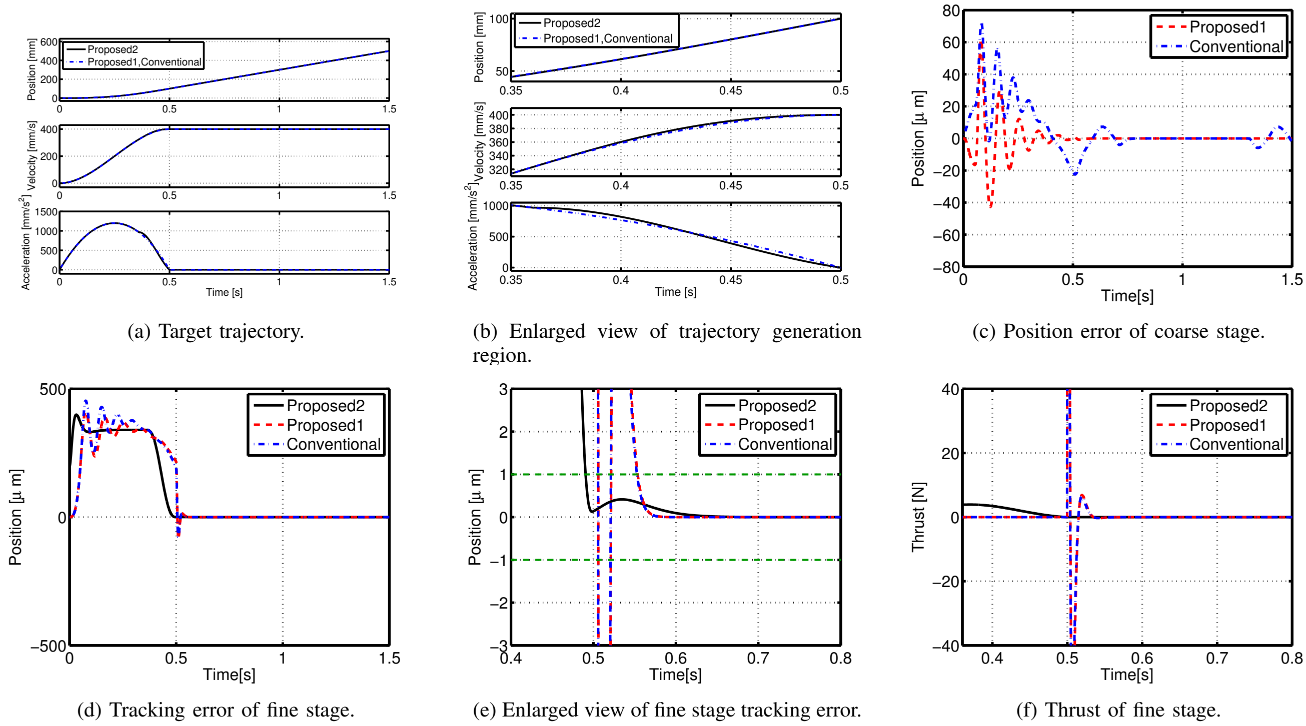


(a) Target trajectory.

(b) Enlarged view of trajectory generation region.

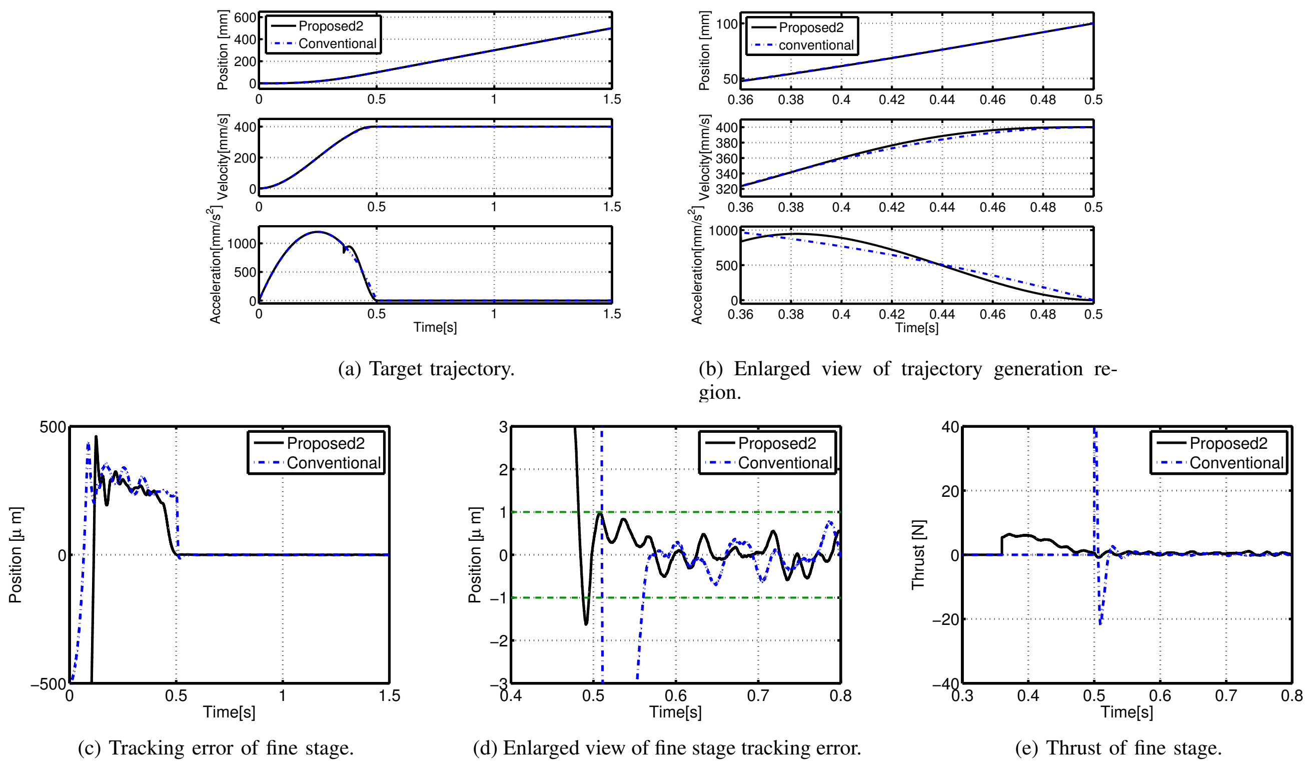
(c) Position error of coarse stage.

(d) Tracking error of fine stage.

(e) Enlarged view of fine stage tracking error.

(f) Thrust of fine stage.

Fig. 10. Simulation results.



(a) Target trajectory.

(b) Enlarged view of trajectory generation region.

(c) Tracking error of fine stage.

(d) Enlarged view of fine stage tracking error.

(e) Thrust of fine stage.

Fig. 11. Experimental results.