

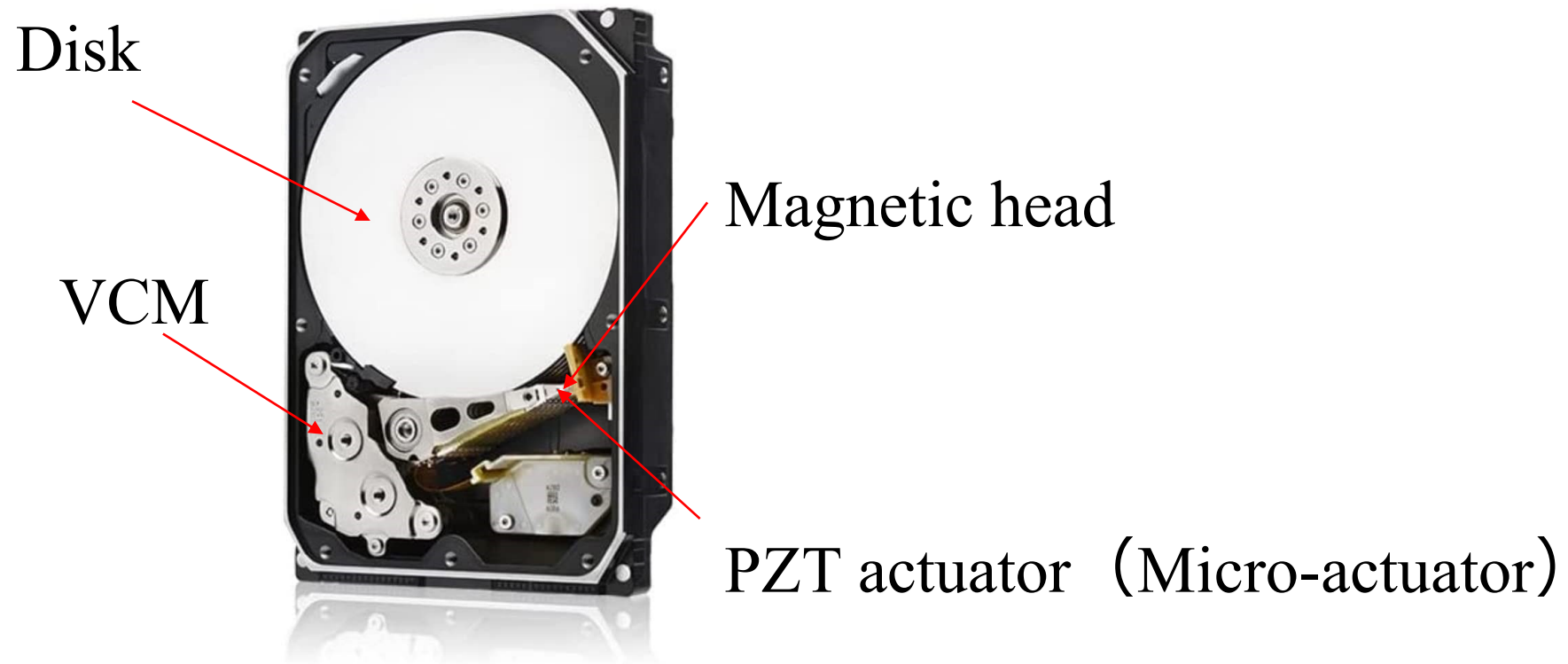
# Benchmark problem for magnetic-head positioning control in HDD

## User manual without MATLAB ver. (Windows PC)

Investigating R&D Committee on “Precision Servo Technology for High Value-Added Mechatronic System”  
The Institute of Electrical Engineers of Japan

# Magnetic-head positioning control system in the benchmark problem

- The control system has two actuators: VCM and PZT actuator.
- The control variable is the magnetic-head position.
- The PZT actuator has a stroke limitation (In this benchmark: 50 nm).
- We focus on the track-following control.



# The mechanical characteristics of the actuators and the example controllers are given in the following paper.

T. Atsumi and S. Yabui, “Quadruple-Stage Actuator System for Magnetic-Head Positioning System in HDDs,” The IEEE Transactions on Industrial Electronics, Vol. 67, No. 11, pp. 9184-9194, (2020-11)

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## Quadruple-Stage Actuator System for Magnetic-Head Positioning System in Hard Disk Drives

Takenori Atsumi , Member, IEEE, and Shota Yabui, Member, IEEE

**Abstract**—In this article, we present a magnetic-head positioning system in hard disk drives (HDDs) with a quadruple-stage actuator system. The quadruple-stage actuator system consists of a voice coil motor, a milliactuator with two piezoelectric (PZT) elements, a microactuator with two PZT elements, and a thermal actuator. The milliactuator is the first generation of a secondary actuator for a dual-stage actuator in the HDDs and moves a sway mode of a suspension in a head-stack assembly. The microactuator is the second generation of the secondary actuator for the dual-stage actuator in the HDDs and moves a yaw mode of the suspension. The thermal actuator is an actuator in a development phase for future HDDs. It consists of heaters embedded in the magnetic head and moves read/write elements a few nanometers in a horizontal direction with thermal expansion. The achievable disturbance-rejection performance of the proposed quadruple-stage-actuator system is higher than that of the conventional triple-stage actuator system because the proposed system can decrease a negative impact caused by the stroke limitation of the thermal actuator. As a result, the magnetic-head positioning system with the quadruple-stage-actuator system enables us to improve the positioning accuracy under the external vibrations by about 48% from that with the triple-stage-actuator system.

**Index Terms**—Hard disks, microactuators, positioning control, servo systems.

### I. INTRODUCTION

TO INCREASE the data capacity of hard disk drives (HDDs), we have to improve the positioning accuracy of magnetic heads in the HDDs so that the size of bits for information stored on a disk decreases [1]–[3].

In the magnetic-head positioning system, one of the most critical issues is positioning errors caused by external vibrations of file servers used in data centers. Most of the positioning errors are below 2 kHz [4]. Thus, to compensate for the

negative impacts of the external vibrations, we have to increase a servo bandwidth of the control system in the magnetic-head positioning system. However, the mechanical characteristics limit the servo bandwidth [5], [6]. Therefore, the magnetic-head positioning system should be fabricated with multiple actuators so that the servo bandwidth can be increased [7].

In current HDDs, a dual-stage-actuator system has been employed for the magnetic-head positioning systems. In the dual-stage-actuator system, the first actuator is a voice coil motor (VCM), and the second actuator is a piezoelectric (PZT) actuator [8]–[18]. Since 2016, we have had two kinds of PZT actuators in shipped HDDs. The first one is “milliactuator” which moves a sway mode of a suspension to control the magnetic-head position. The second one is “microactuator” which moves a yaw mode of the suspension. The frequency of the primary mechanical resonance of the microactuator is much higher than that of the milliactuator [19], [20].

For the magnetic-head positioning system, we have reported that a triple-stage actuator system was dramatically able to improve the positioning accuracy during a track-following control from the dual-stage actuator systems [21]–[23]. Since 2015, other research groups have also reported advantages of the triple-stage actuator system [24]–[26]. In the triple-stage actuator system, magnetic heads have a heater located in a horizontal direction of read/write elements in order to control the position of the read/write elements with thermal expansion induced by the heater with an electric current. However, in the triple-stage actuator system, a bottleneck of the servo bandwidth is not its mechanical resonances, but its stroke limitation.

In this article, to overcome the negative impact caused by the stroke limitation of the thermal actuator, we present a magnetic-head positioning system in an HDD with a quadruple-stage actuator system. The first stage is the VCM for moving a head-stack assembly (HSA), the second stage is the milliactuator for moving a sway mode of a suspension, the third stage is the microactuator for moving a yaw mode of a suspension, and the fourth stage is the thermal actuator. The proposed approach is verified by simulations based on measured controlled objects and a disturbance source.

### II. QUADRUPLE-STAGE ACTUATOR SYSTEM FOR HDD

A current shipped HDD is comprised of a cover, a base, a VCM, several PZT actuators, several magnetic heads, several

## Frequency response of VCM

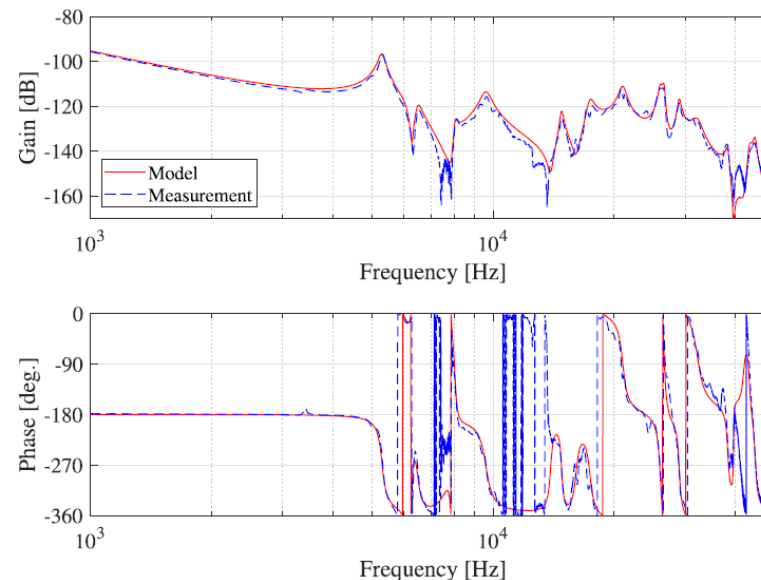


Fig. 5. Frequency response of  $P_{\text{vcm}}$ .

## Frequency response of PZT actuator

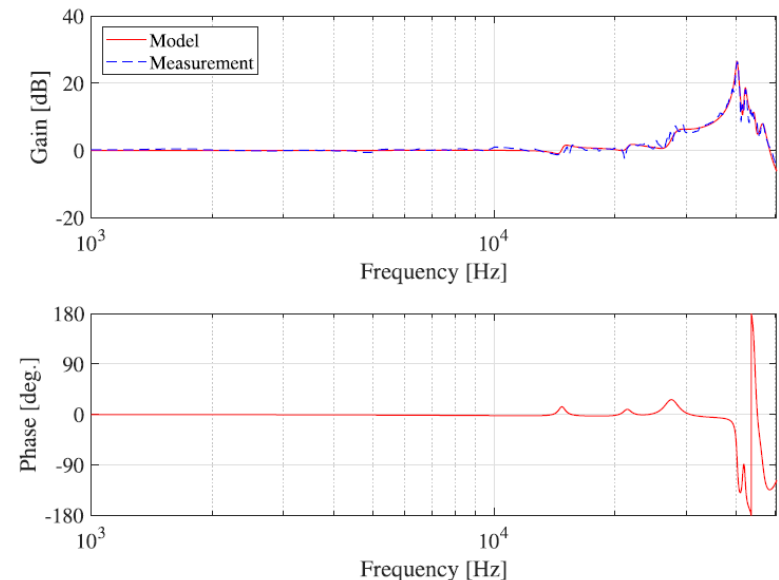


Fig. 7. Frequency response of  $P_{\text{mic}}$ .

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Color versions of one or more of the figures in this article are available online at <http://ieeexplore.ieee.org>.  
Digital Object Identifier 10.1109/TIE.2019.2955432

# Block diagram of magnetic-head positioning control system

$P_{cv}$ : VCM in continuous-time system,  $P_{cp}$ : PZT actuator in continuous-time system

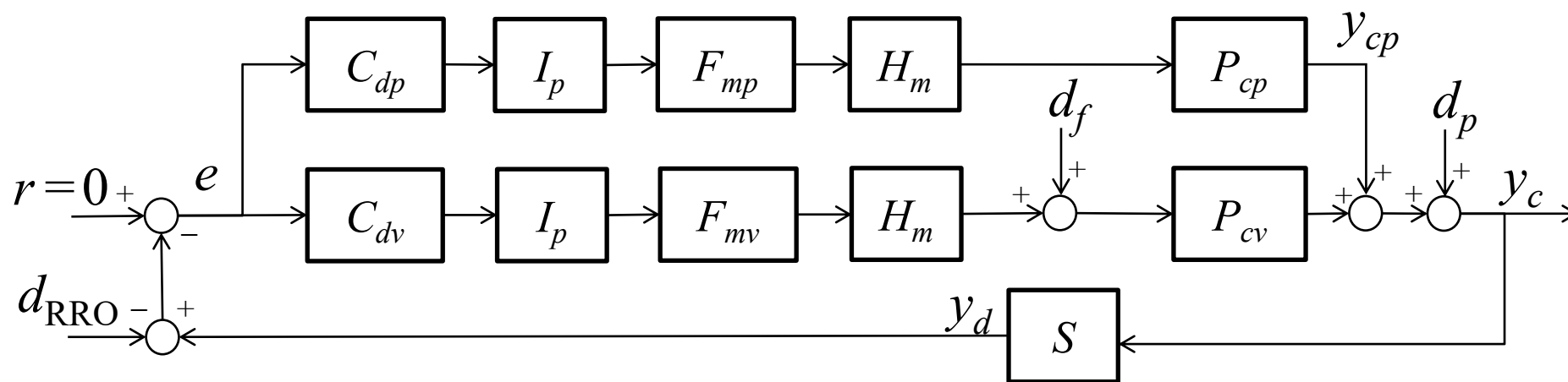
$C_{dv}$ : Feedback controller for VCM,  $C_{dp}$ : Feedback controller for PZT actuator

$F_{mv}$ : Multi-rate filter for VCM,  $F_{mp}$ : Multi-rate filter for PZT actuator

$I_p$ : Interpolator,  $H_m$ : Multi-rate zero-order hold,  $S$ : Sampler

$d_p$ : Fan-induced vibration,  $d_f$ : Rotational vibration (RV),  $d_{RRO}$ : Repeatable Run-Out (RRO)

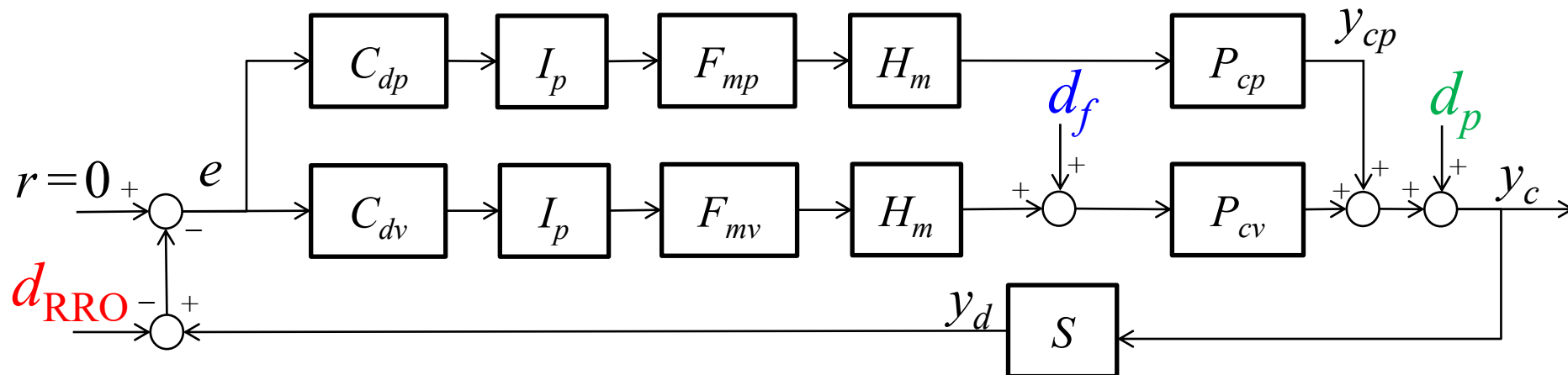
$y_c$ : Head position in continuous time,  $y_d$ : Head position in discrete time,  $y_{cp}$ : Displacement of PZT actuator



The control system is MISO sampled-data control system with multi-rate filters.

# Disturbances in the benchmark problem

- $d_{\text{RRO}}$  : RRO (Repeatable Run-Out)  
Oscillation of target tracks written on the disk. Note that it is regarded as noise.
- $d_f$  : RV (Rotational vibration)  
External vibration caused by other HDDs in a storage box.
- $d_p$  : Fan-induced vibration  
External vibration caused by cooling fans in a storage box.



- Control system in the benchmark problem
- How to use the benchmark problem
- Example

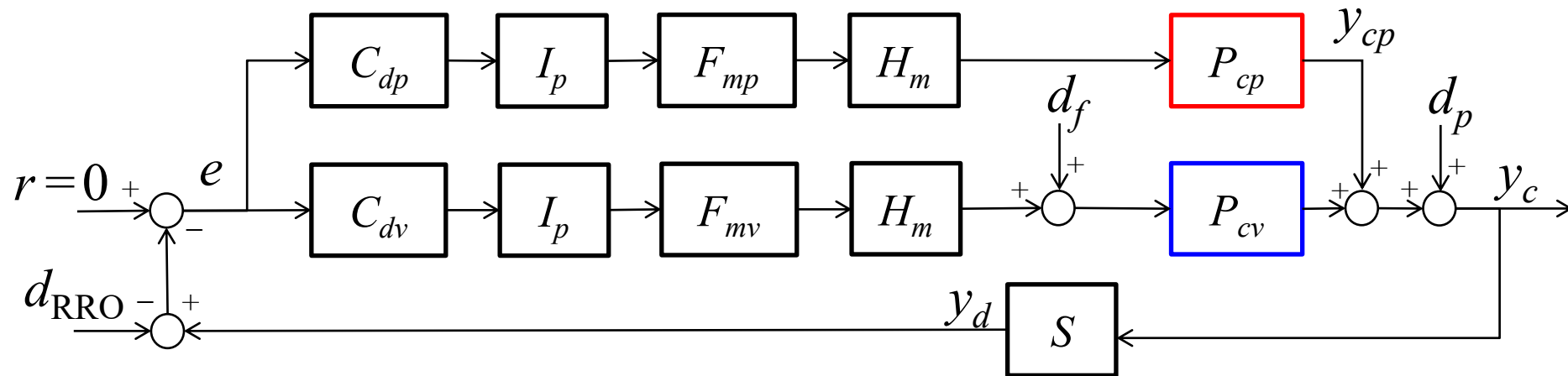
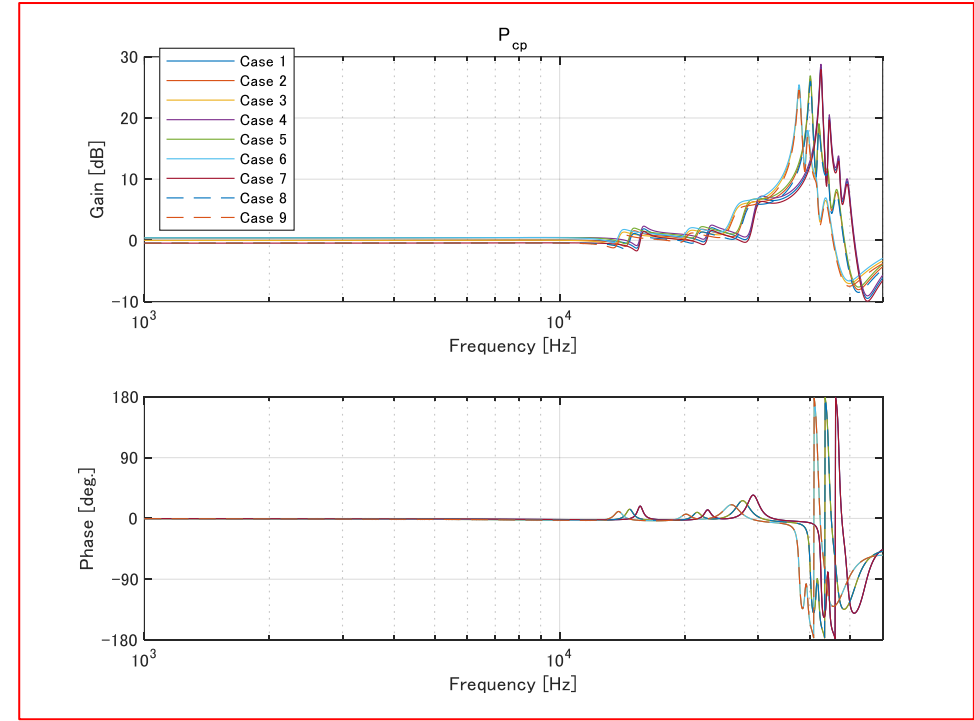
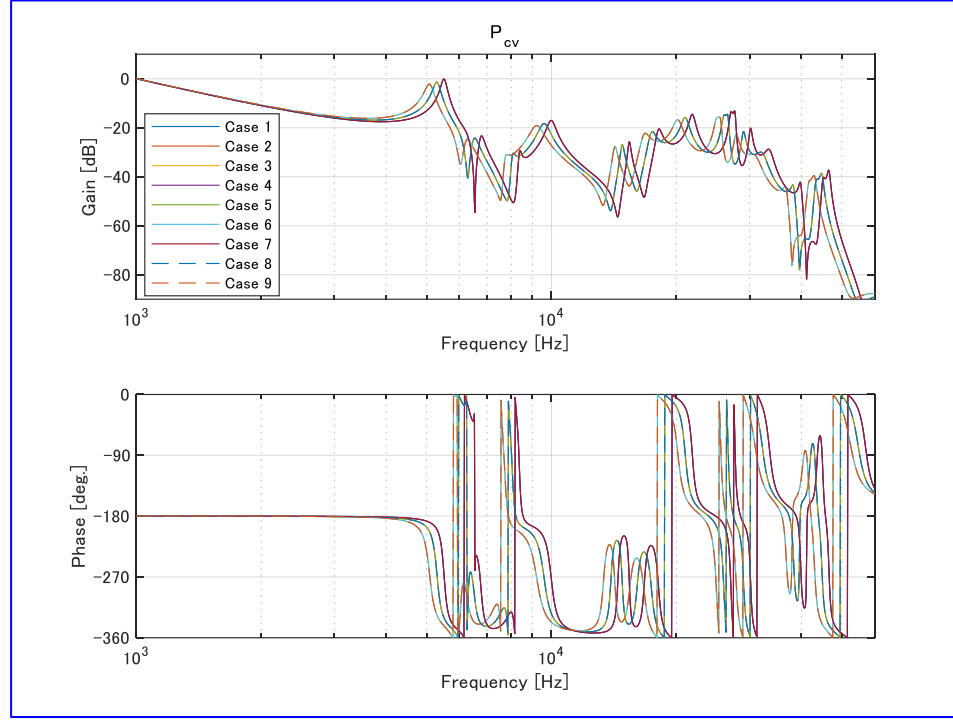
- Control system in the benchmark problem
- How to use the benchmark problem
- Example

# Model of the controlled object

- Parameters of the nominal controlled object are shown in the following paper.  
T. Atsumi and S. Yabui, “Quadruple-Stage Actuator System for Magnetic-Head Positioning System in HDDs,”  
The IEEE Transactions on Industrial Electronics, Vol. 67, No. 11, pp. 9184-9194, (2020-11)
- Sampling time:  $1/(7200/60)/420 \approx 1.9841 \times 10^{-6}$  (7200rpm, 420 sector)
- Number of multi rate: 2
- Track pitch : 482 kTPI (52.7 nm)
- Controlled object has variations
  - Temperature dependencies of mechanical resonant frequencies
    - LT(Low temp.) : VCM: +4 % from nominal model, PZT actuator: +6 % from nominal model
    - RT(Room temp.) : Same as nominal models
    - HT(High temp.) : VCM: −4% from nominal model, PZT actuator: −6% from nominal model
  - Temperature dependencies of damping ratios
    - LT(Low temp.) : VCM: -20 % from nominal model, PZT actuator: -20 % from nominal model
    - RT(Room temp.) : Same as nominal models
    - HT(High temp.) : VCM: +20% from nominal model, PZT actuator: +20% from nominal mode
  - PZT actuator’s gain
    - $\pm 5\%$
- The number of cases for controlled objects: 9

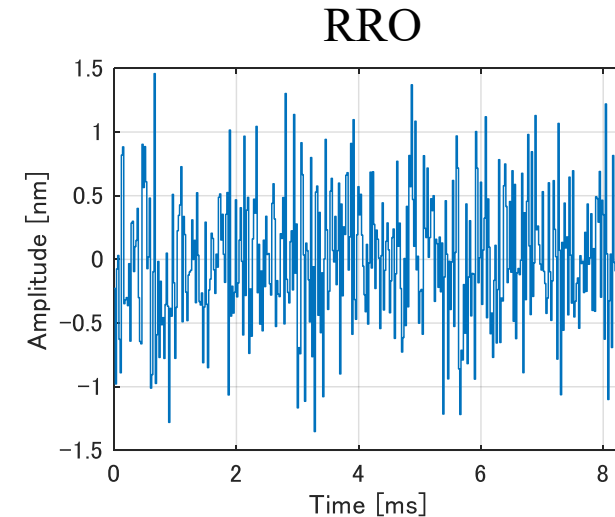
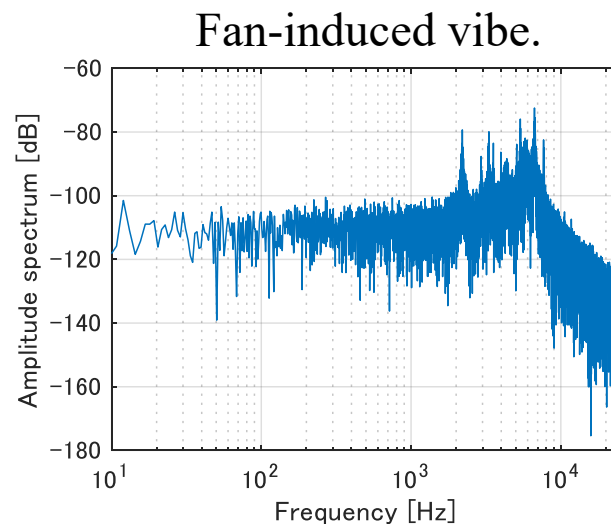
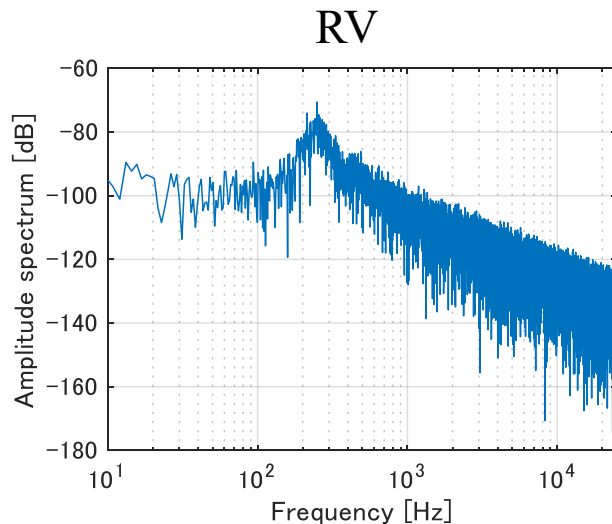
| Case No. | 1       | 2       | 3       | 4           | 5           | 6           | 7           | 8           | 9           |
|----------|---------|---------|---------|-------------|-------------|-------------|-------------|-------------|-------------|
| Temp.    | LT      | RT      | HT      | LT          | RT          | HT          | LT          | RT          | HT          |
| PZT gain | Nominal | Nominal | Nominal | Nominal +5% | Nominal +5% | Nominal +5% | Nominal −5% | Nominal −5% | Nominal −5% |

# Frequency responses of the controlled object for all cases



# Disturbances in the benchmark problem

- RV: Reproduced by the disturbance shown in the following paper  
T. Atsumi and S. Yabui, "Quadruple-Stage Actuator System for Magnetic-Head Positioning System in HDDs," The IEEE Transactions on Industrial Electronics, Vol. 67, No. 11, pp. 9184-9194, (2020-11)
- Fan-induced vibration: : Reproduced by the disturbance shown in the following paper  
T. Eguchi, Y. Asai, K. Ichikawa, and M. Takada: ``Airborne and Structure-Borne Transmission of High Frequency Fan Vibration in a Storage Box", Proceedings of the ASME 2017 Conference on Information Storage and Processing Systems, Paper No. 5406 (2017)
- RRO: Time-domain signal which has same amplitude for all frequencies except 0 Hz.



- Control system in the benchmark problem
- **How to use the benchmark problem**
- Example

# Setting

Step 1. Download and install the Windows version of the MATLAB Runtime for R2022a from the following link on the MathWorks website:

<https://www.mathworks.com/products/compiler/mcr/index.html>

Step 2. Download the EXE files from the following website:

[http://www2.iee.or.jp/~dmec/committee/DMEC1005/dsa\\_HDD\\_bench\\_e.html](http://www2.iee.or.jp/~dmec/committee/DMEC1005/dsa_HDD_bench_e.html)

Step 3. Unzip the “HDDBenchmarkProblem.zip”.

# Usage

Step 1. Define the state-space matrixes of your designed controllers as follows.

- $C_{dv}$ : A\_Cd\_vcm.txt, B\_Cd\_vcm.txt, C\_Cd\_vcm.txt, D\_Cd\_vcm.txt
- $C_{dp}$ : A\_Cd\_pzt.txt, B\_Cd\_pzt.txt, C\_Cd\_pzt.txt, D\_Cd\_pzt.txt
- $F_{mv}$ : A\_Fm\_vcm.txt, B\_Fm\_vcm.txt, C\_Fm\_vcm.txt, D\_Fm\_vcm.txt
- $F_{mp}$ : A\_Fm\_pzt.txt, B\_Fm\_pzt.txt, C\_Fm\_pzt.txt, D\_Fm\_pzt.txt

Step 2. Execute “Simulation\_trackfollow” which shows simulation results of the control system.

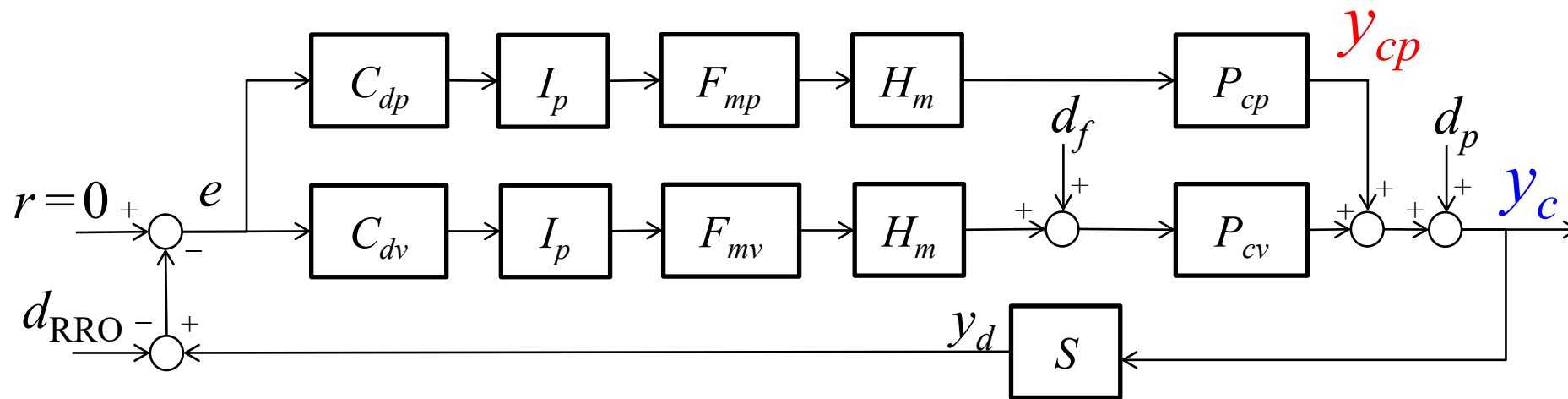
Step 3. Execute “Plot\_control\_system” which shows frequency responses of the control system.

As an example, the unzipped folder includes controllers in the following paper (Dual: VCM + Micro.).

T. Atsumi and S. Yabui, “Quadruple-Stage Actuator System for Magnetic-Head Positioning System in HDDs”, The IEEE Transactions on Industrial Electronics, Vol. 67, No. 11, pp. 9184-9194, (2020-11)

# Validation of control system

- We evaluate the worst case of  $3\sigma$  (three times of STD) value of  $y_c$  in steady state response for one second.
- Maximum value of  $|y_{cp}|$  must be smaller than 50 nm.



- Control system in the benchmark problem
- How to use the benchmark problem
- **Example**

# Results of “Simulation\_trackfollow” with the example controller

Figure 1: Amplitude spectrum of  $d_f$

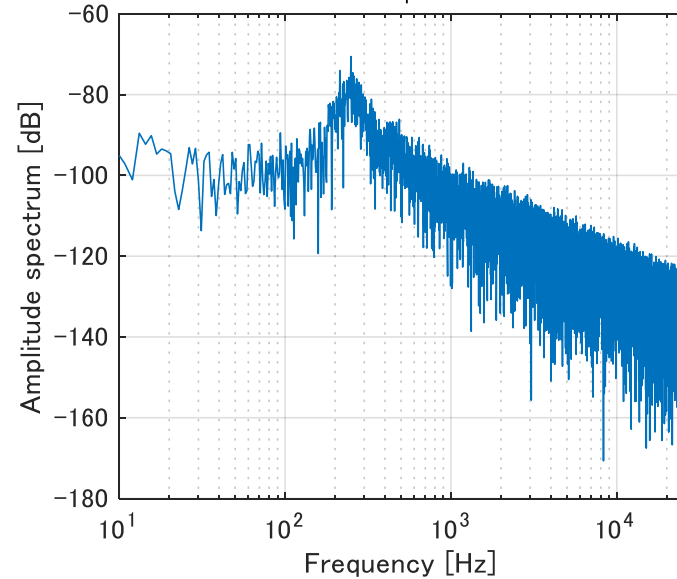


Figure 2: Amplitude spectrum of  $d_p$

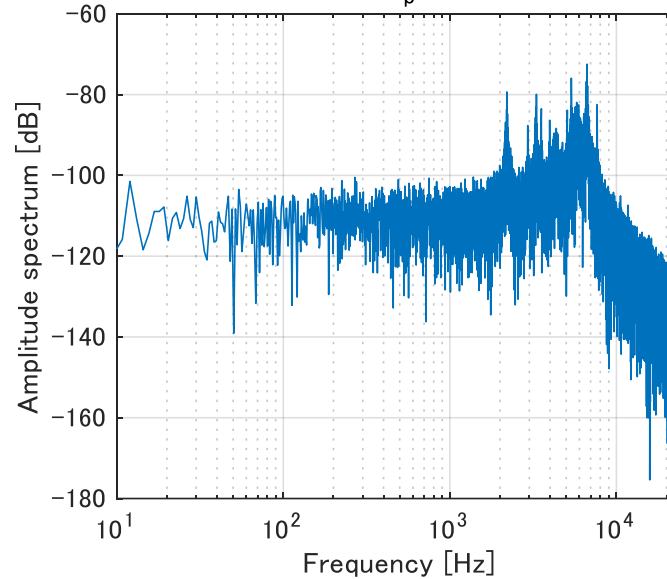
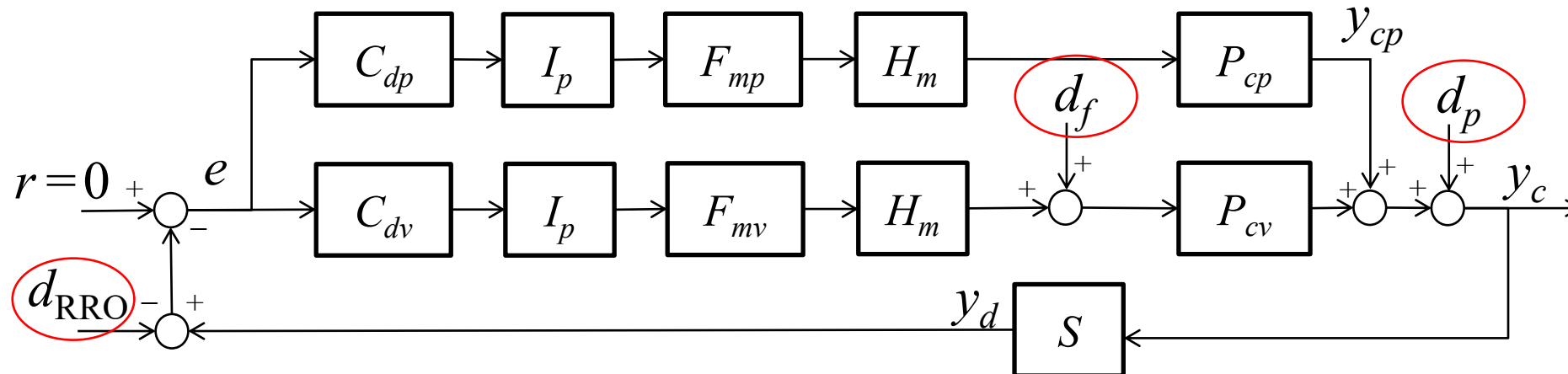
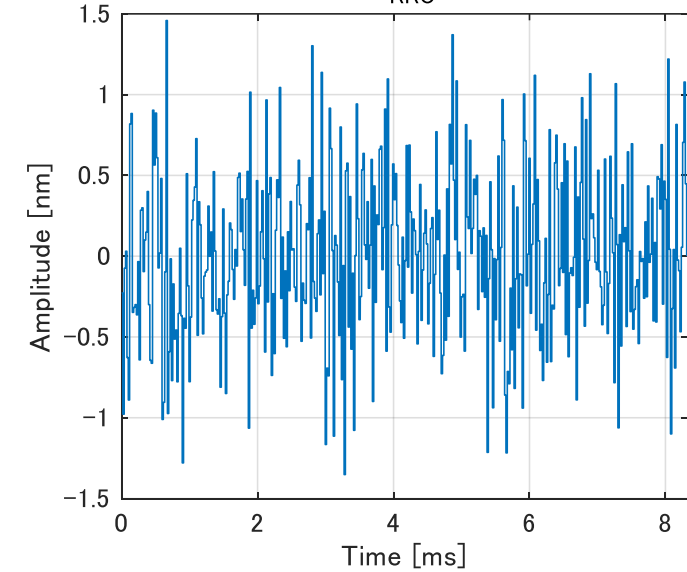


Figure 3:  $d_{RRO}$



# Results of “Simulation\_trackfollow” with the example controller (Cont.)

Figure 4:  $y_{cp}$

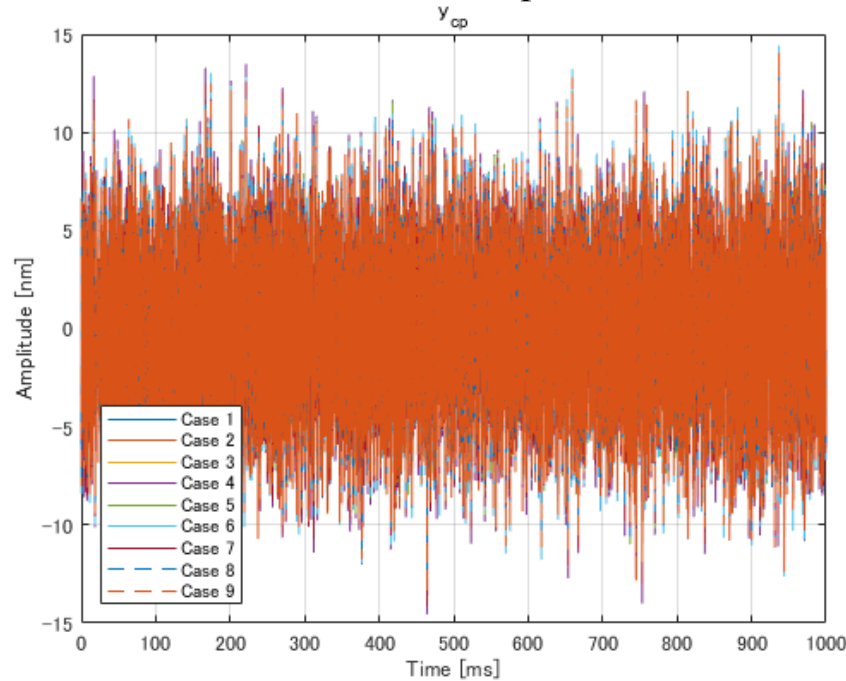
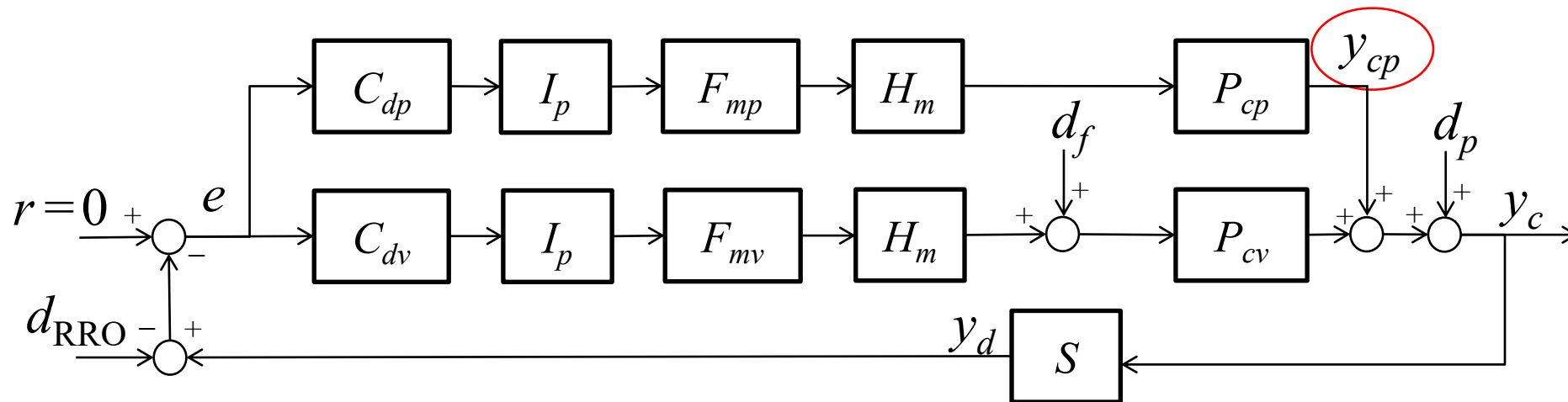
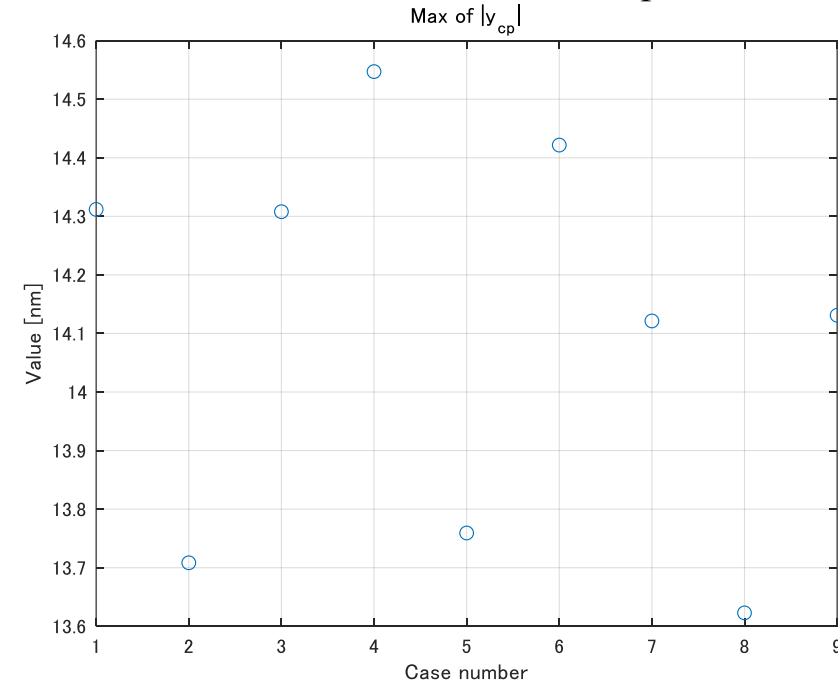


Figure 5: Max of  $|y_{cp}|$



# Results of “Simulation\_trackfollow” with the example controller (Cont.)

Figure 6:  $y_c$

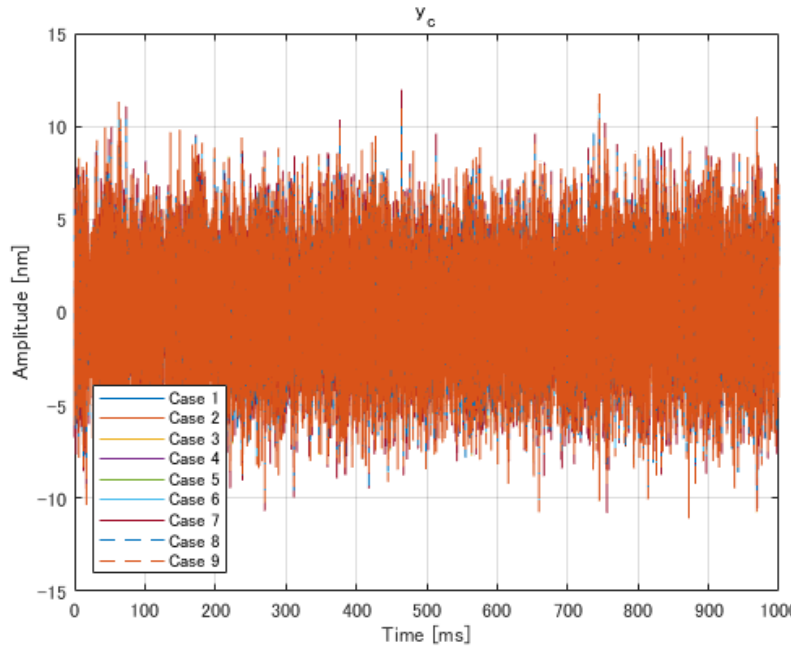


Figure 7: Amplitude spectrum of  $y_c$

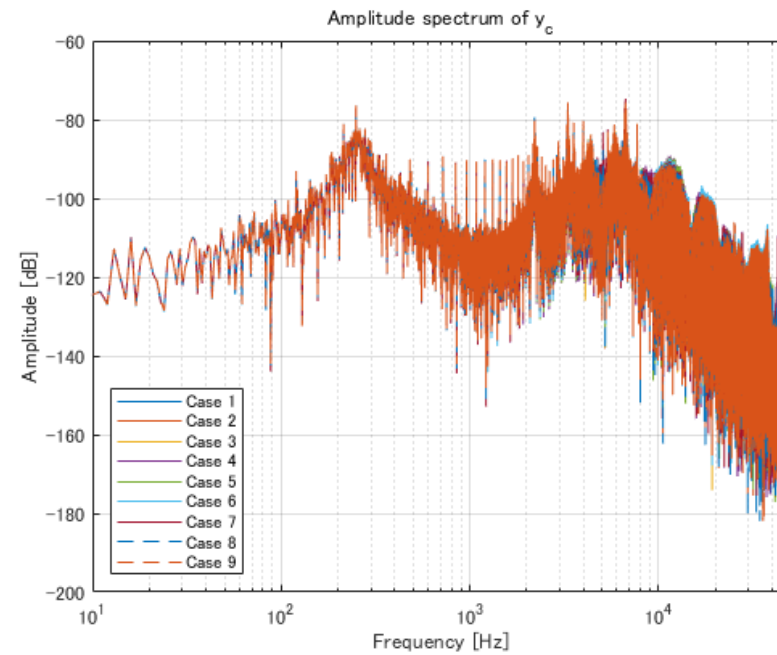
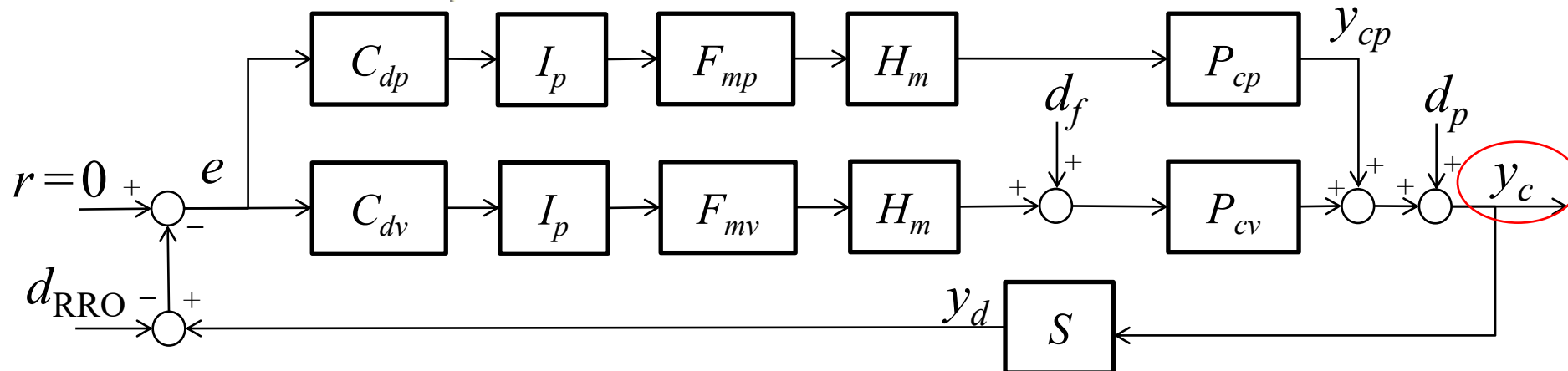
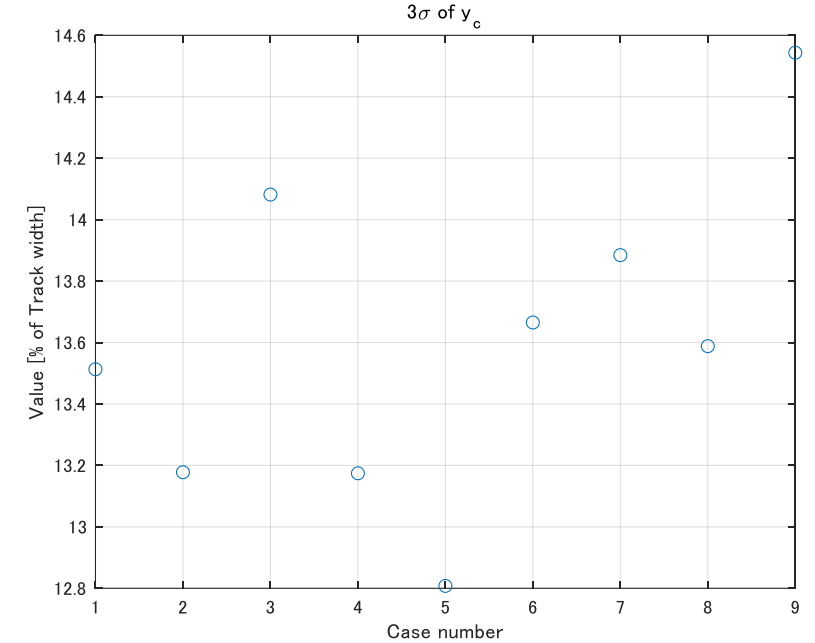


Figure 8:  $3\sigma$  values of  $y_c$  [% of Track width]



# Results of “Plot\_control\_system” with the example controller

Figure 9:  $P_{cv}$

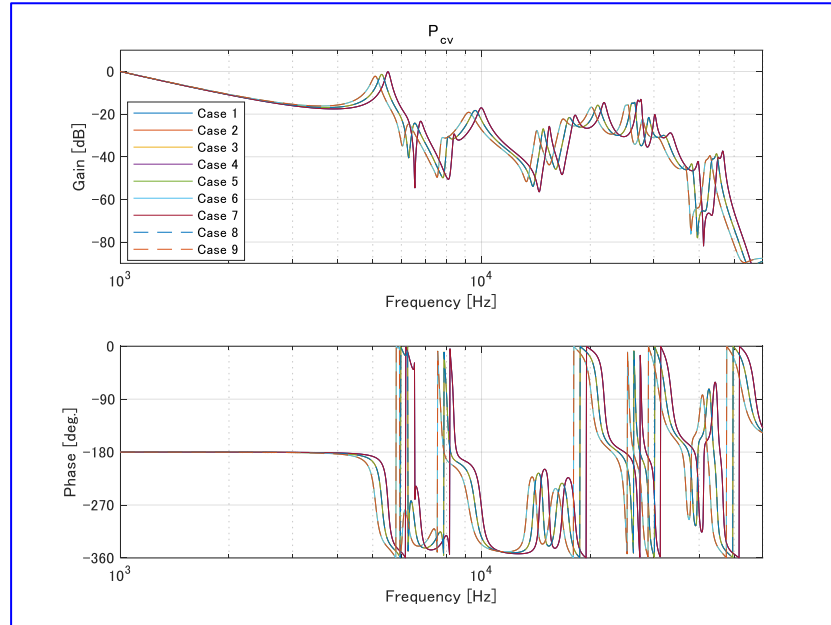
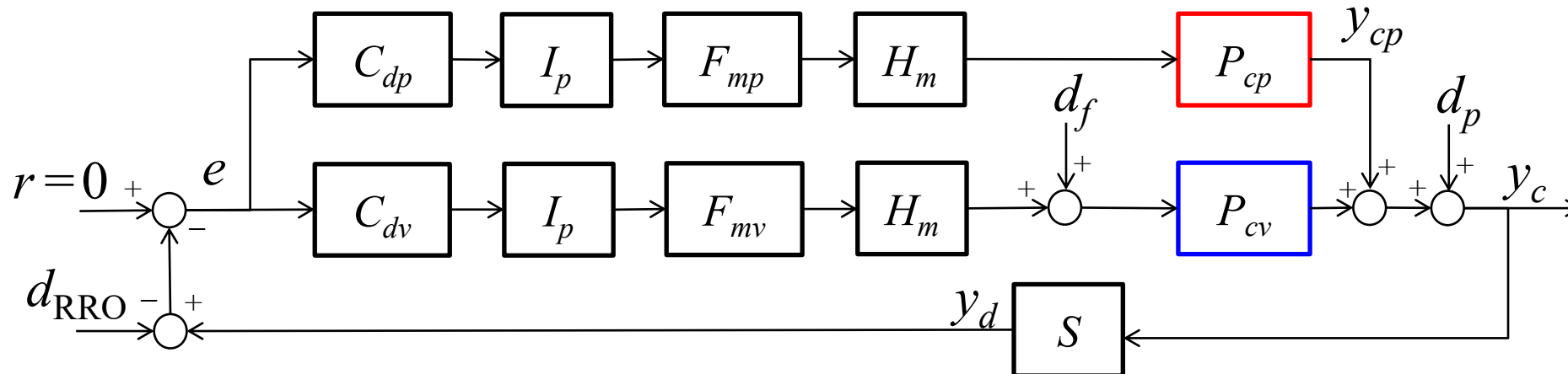
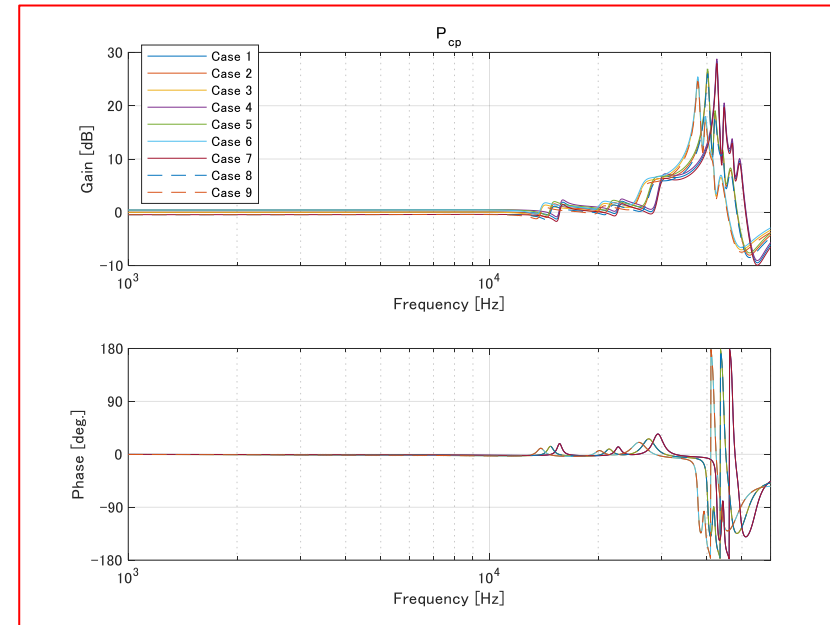
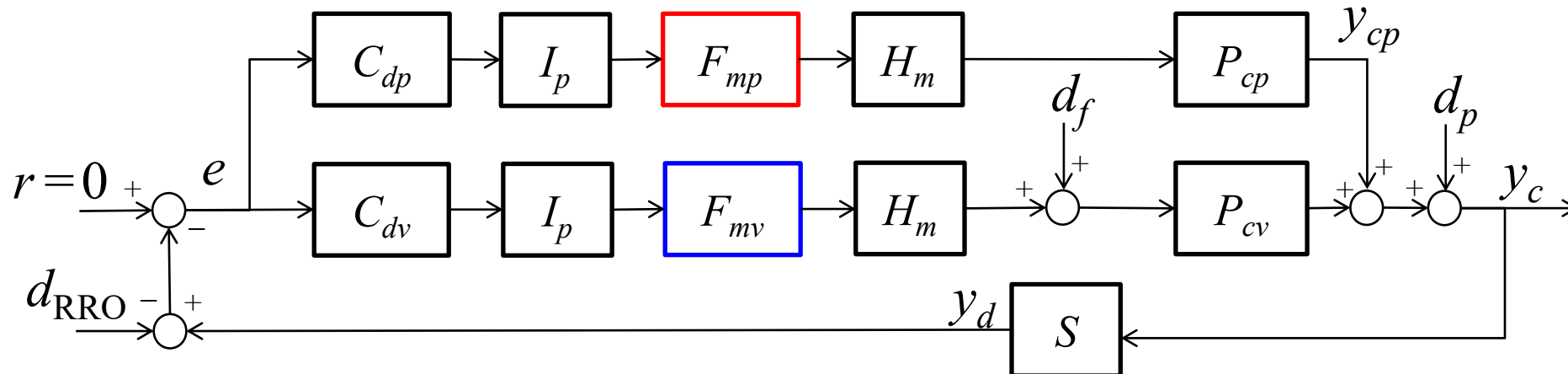
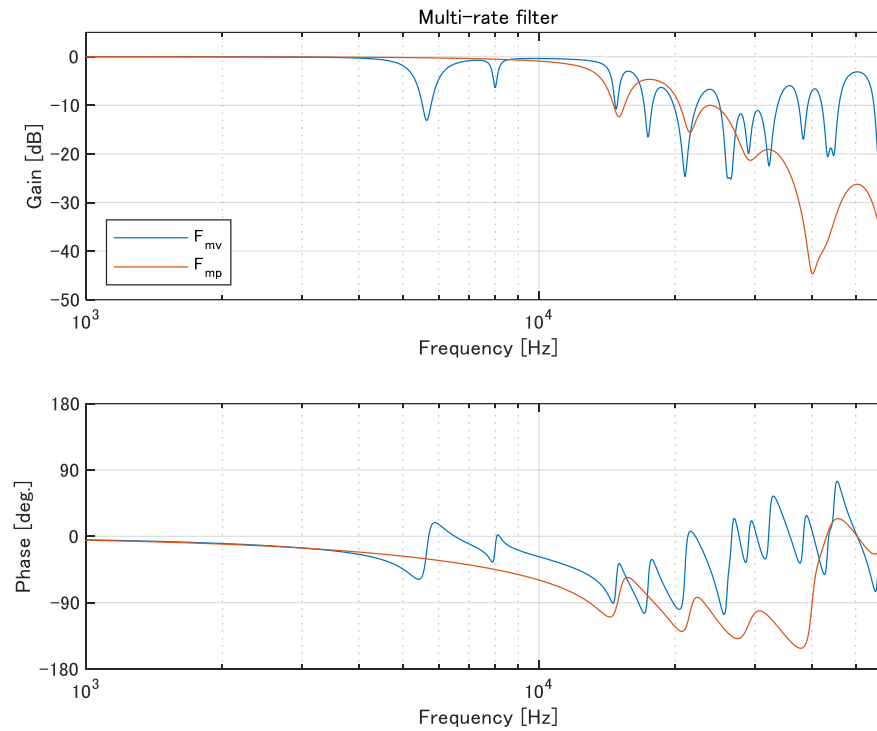


Figure 10:  $P_{cp}$



# Results of “Plot\_control\_system” with the example controller (Cont.)

Figure 11: Multi-rate filters



# Results of “Plot\_control\_system” with the example controller (Cont.)

Figure 12: Bode plot for  $u_{dv} \rightarrow y_d$

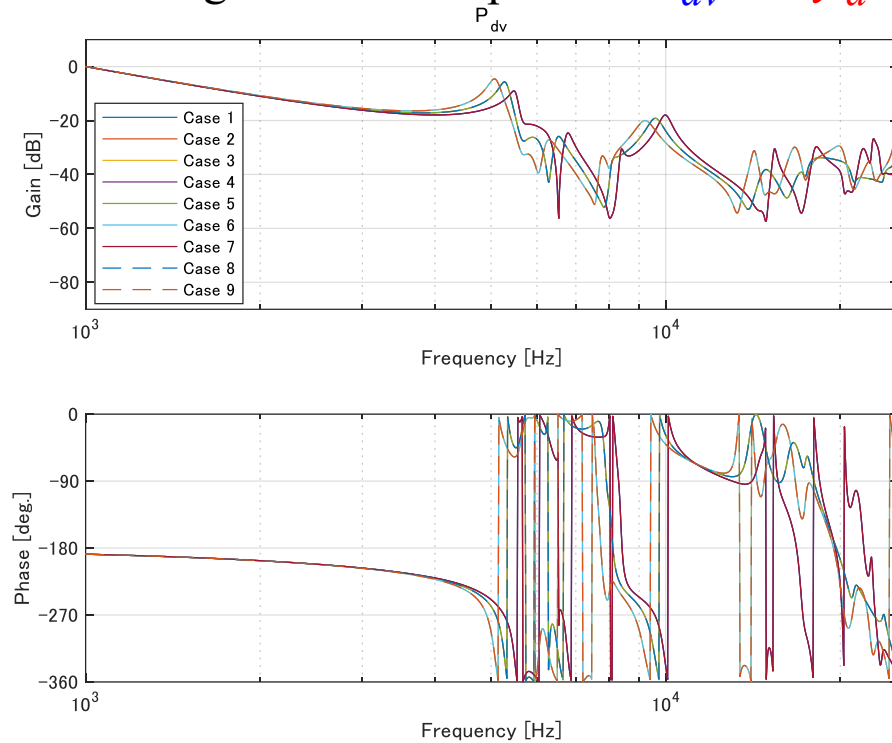
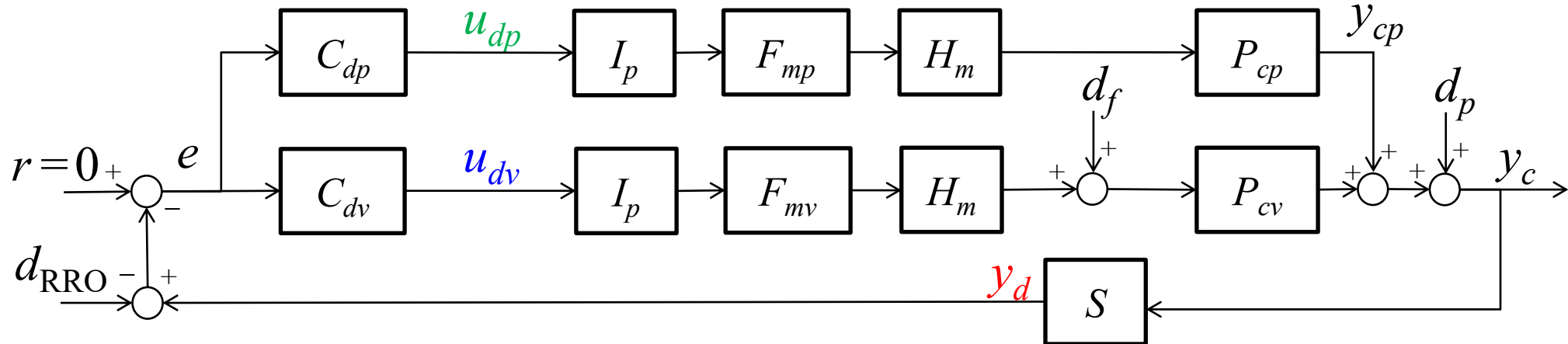
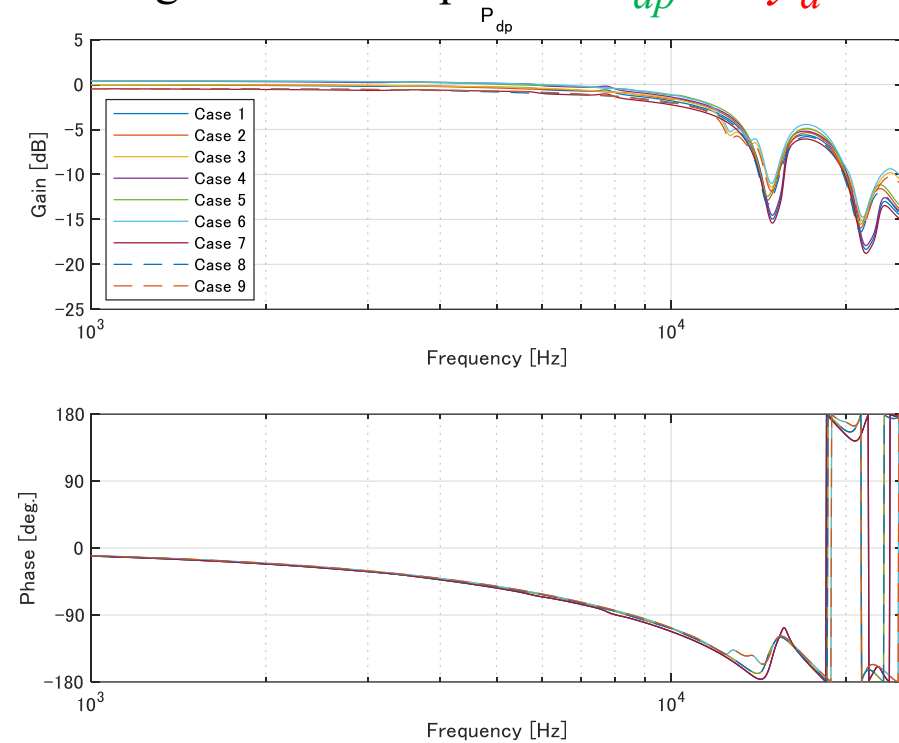


Figure 13: Bode plot for  $u_{dp} \rightarrow y_d$



# Results of “Plot\_control\_system” with the example controller (Cont.)

Figure 14 : Feedback controller for VCM

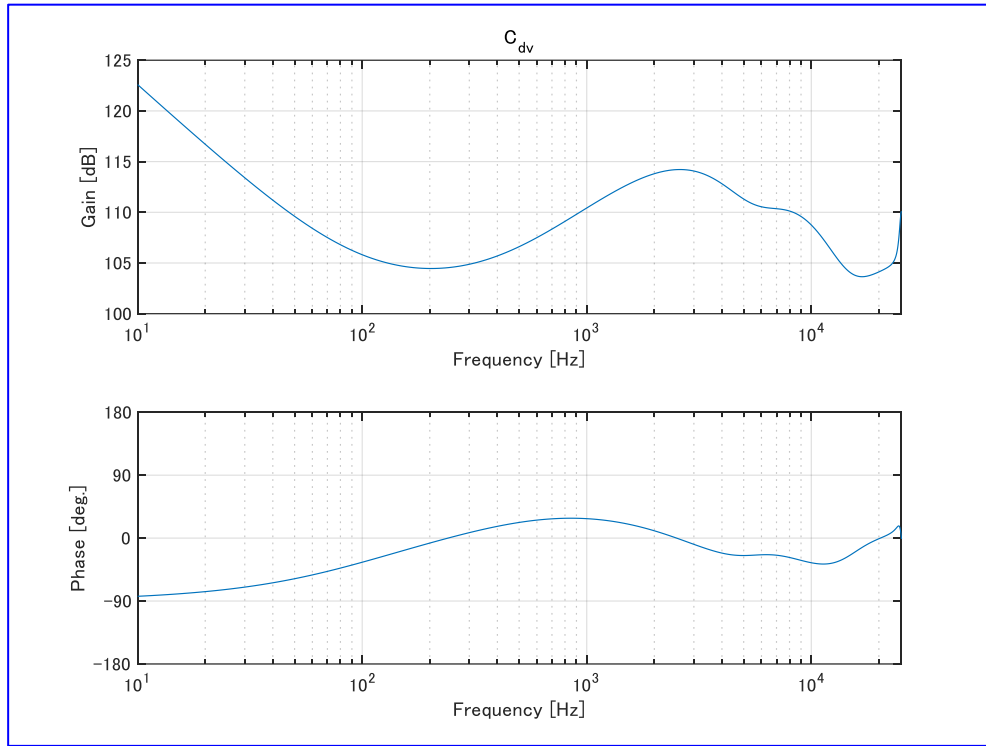
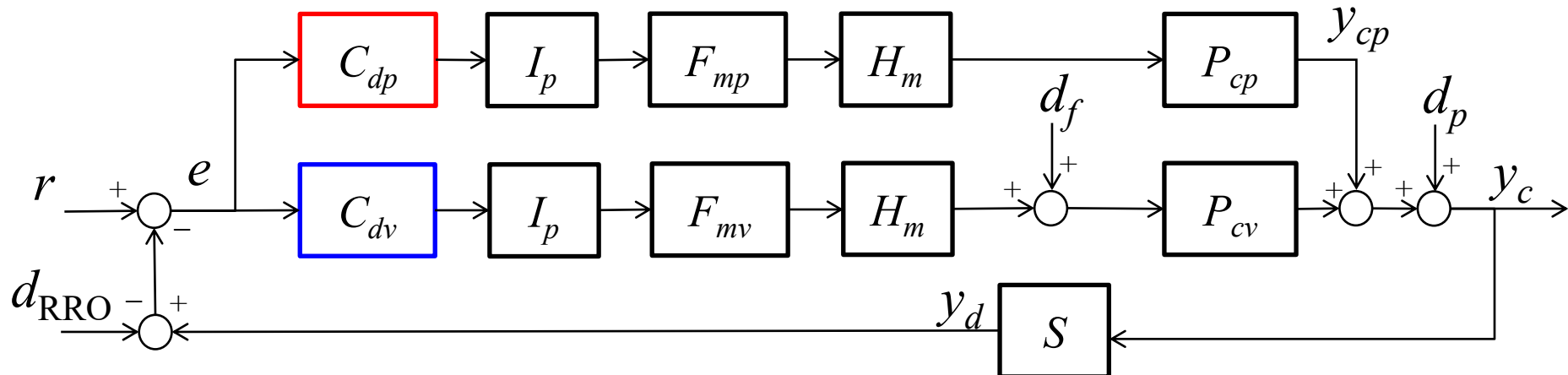
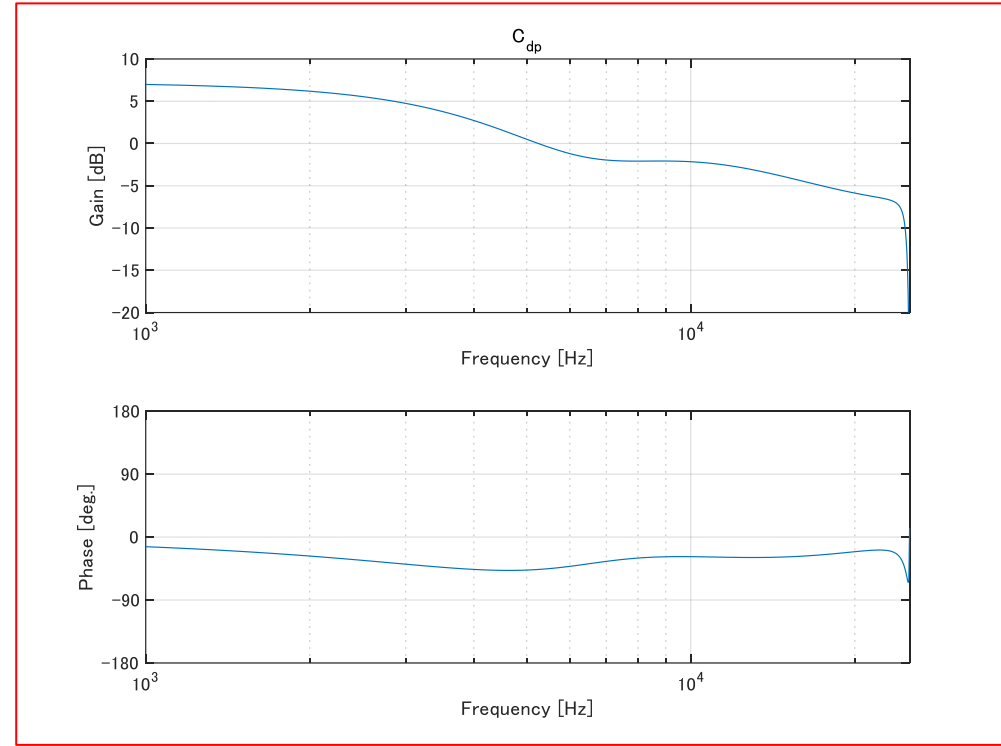


Figure 15 : Feedback controller for PZT actuator



# Results of “Plot\_control\_system” with the example controller (Cont.)

Figure 16: Bode plot for  $e \rightarrow y_d$

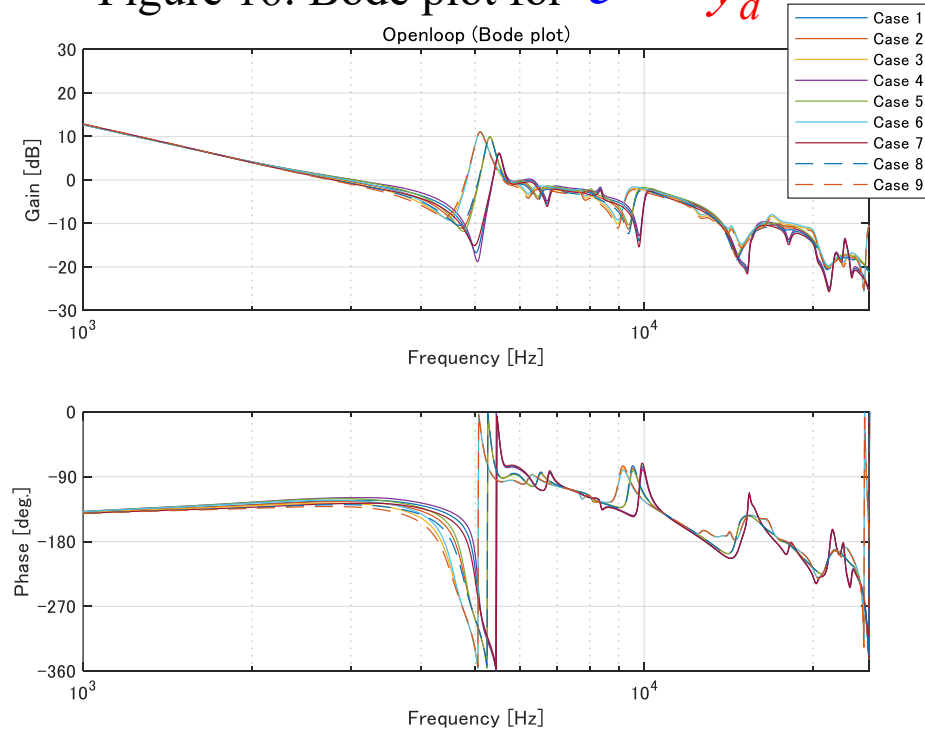
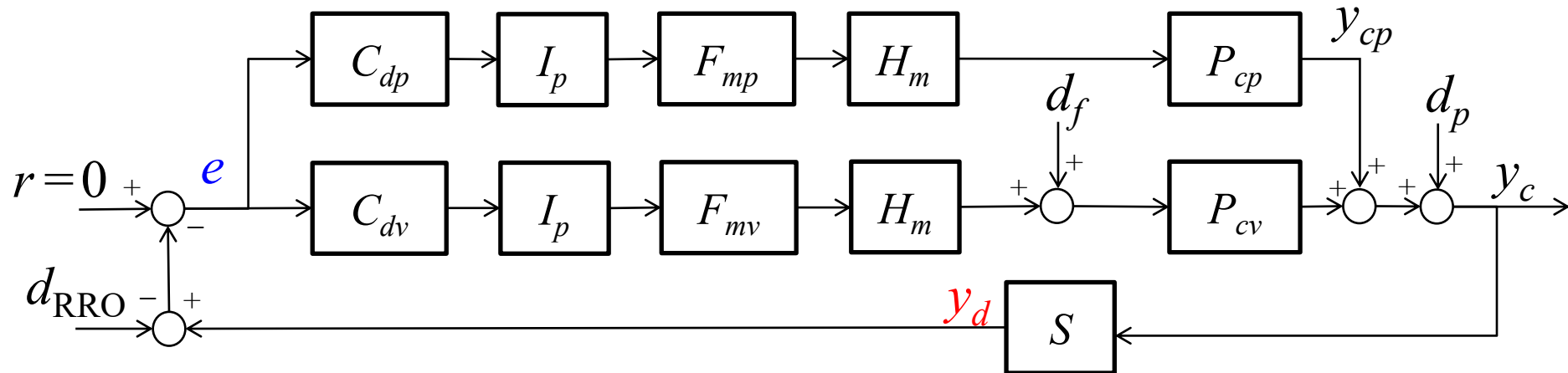
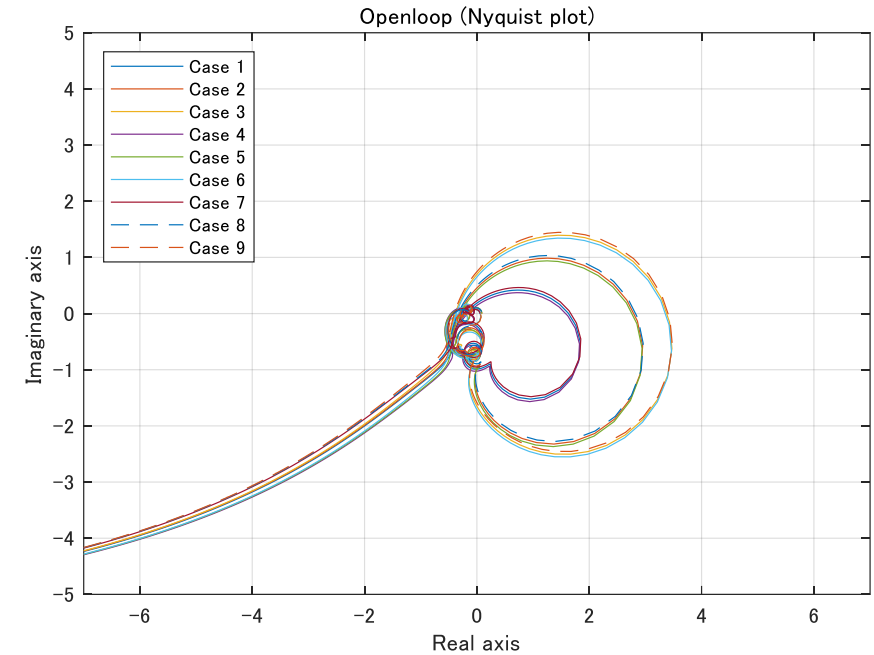
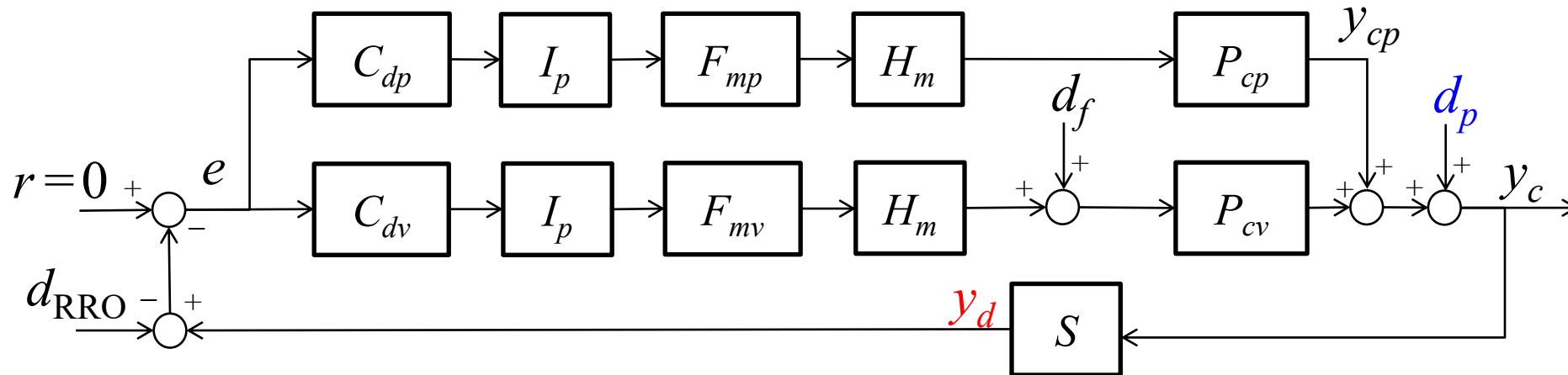
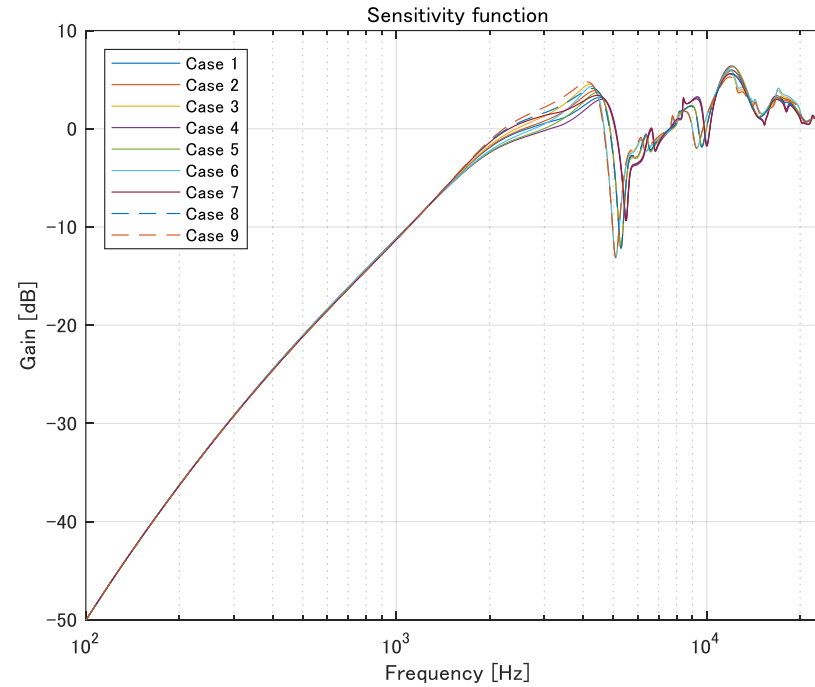


Figure 17: Nyquist plot for  $e \rightarrow y_d$



# Results of “Plot\_control\_system” with the example controller (Cont.)

Figure 18: Gain Bode plot for  $d_p \rightarrow y_d$



# END

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