Feedforward design for high-precision motion systems

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Abstract

High-precision motion systems are being pushed to the limit in terms of speed and accuracy. Although system designs are typically driven by rigidity, performance is deteriorated by the presence of relatively high eigenfrequencies. Philips Innovation Services invests in research how to cope with such system limitations. One of the research projects is called Xtreme Motion. This project aims at developing new methodologies driven by next-generation lithography equipment for 450 mm wafers.

A commonly used design procedure is to start with the hardware design using first principles or FEM modelling. As a second step, control strategies are chosen and performance is being evaluated. To obtain a balanced mechatronic design, most likely a number of design iterations will follow. Hence, the hardware designers get feedback how they should improve the hardware design such that better system performance can be obtained. This iterative process will continue until the performance requirements are met. As complexity of high-precision equipment increases, this design process tends to cost more time and effort.

For high-precision motion systems, feedforward control is considered to be one of the most important ways to improve servo performance. Therefore, many flavours of feedforward control exist in both theory and practice. As feedforward control and system’s dynamics are closely related, there is a two-way dependency in their designs. Therefore it makes sense to steer the system’s dynamics using knowledge about the applied control strategies. Besides the typically used eigenfrequency specification, also other specifications could be relevant: mass, stiffness, variation in dynamics, linearity, and actuator/sensor selection.

Within the Xtreme Motion project, one of the topics focuses on development of advanced control strategies for all types of positioning systems involved. Within this scope, one explored strategy is concerned with feedforward design [1] and will be presented here. Besides this work, another research project focuses on using system identification techniques to enhance feedforward tuning [2]. The latter work is being carried out in collaboration with the Control Systems Technology group of the Eindhoven University of Technology.

1. Feedforward Design for High-Precision Motion Systems

1.1. Servo Performance

Fig 1 shows a typical control scheme, with plant P, controller C, feedforward K_{ff}, and prefilter K_y which alters the original setpoint r into the actual setpoint r_y.

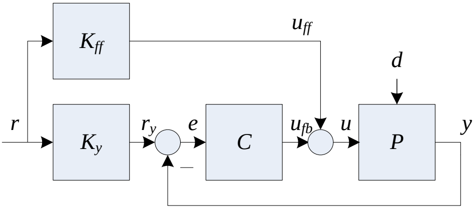

Fig 1. Generic control scheme

In the ideal case, feedforward control cancels all setpoint induced errors e, whereas feedback control attenuates disturbance d induced errors. In practice, feedback control also attenuates setpoint induced errors because of limited feedforward accuracy. The setpoint induced error can be computed using the reference sensitivity:

$$e = \underbrace{(I+PC)^{-1}}_{FB}\underbrace{(K_y - PK_{ff})}_{FF}\underbrace{r}_{IS} \qquad (1)$$

This error can be decomposed into 3 parts:

1. FB: Feedback decreases the error via the sensitivity function. Frequency content trade off while complying with Bode’s sensitivity integral.
2. FF: Feedforward is able to decrease the error by matching K_y and PK_{ff}. Matching both phase and magnitude is of importance.
3. IS: Input shaping can also help in decreasing the error. A smoother setpoint reduces frequency content typically results in a smaller error.

1.2 Performance Limitations

The ultimate goal is to obtain e=0. While the FB part is nonzero due to the Bode sensitivity integral and the setpoint is nonzero for a point-to-point motion application, the FF part is the only part that could render the error zero. $K_{ff} = P^{-1}$ and $K_y = I$ is often considered to provide this result. However, in practice, plant P can contain non-minimum phase zeros and can be strictly proper resulting in an unstable and/or improper K_{ff} filter. In practice this is often solved by restricting K_{ff} to a finite impulse response (FIR) filter and K_y to a delay filter at the cost of a nonzero error. By requiring a stiff mechanical design, this error is kept low.

2. Double-FIR Feedforward

2.1 Method

Common FF control techniques design K_{ff} as mass FF, mass/snap FF [3] (snap feedforward is proportional with the 4th derivative of the setpoint), or FIR FF [4], [1] while K_y is a delay compensation. In this work, double-FIR FF [1] is pursued where both K_{ff} and K_y are FIR filters.

The error due to setpoint induced errors can be rendered zero by satisfying:

$$P = K_y K_{ff}^{-1} \tag{2}$$

For single-input-single-output (SISO) systems K_{ff} contains the poles of P while K_y contains the zeros of P. To ensure no scaling of the setpoint, the DC-gain of K_y should be equal to 1. Furthermore, (2) is also valid for multi-input-multi-output (MIMO) systems where both K_y and K_{ff} become MIMO FIR filters.

2.2 Potential Benefit for Mechatronic Design

When enabling double-FIR FF for a motion control system, a rigid design is not strictly necessary anymore to obtain good settling performance. This enables the mechanical designer to consider alternative design options. To obtain good settling performance, linear and reproducible behaviour is sufficient. Dominant dynamical behaviour can be compensated with double-FIR FF. Of course, depending on the application, a stiff design can be desired for other purposes, e.g. a required high bandwidth in case of dominant (non-setpoint related) disturbances d. Feedback bandwidth is typically limited by system dynamics.

3. Experimental Example

The experimental setup under consideration is the “N-Forcer” as shown in Fig 2 [5]. The “N-Forcer” is a 6 DOF magnetic levitated positioning system with one long stroke of approximately 0.1 m. The stroke in the remaining directions is 0.2 mm/ 2 mrad. The position is measured using interferometry with a resolution of 0.6 nm.

Fig 2. Experimental setup: N-Forcer

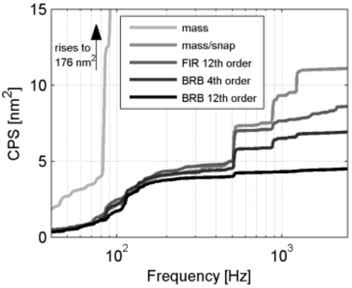

Fig 3. FF comparison, Cumulative power spectrum (CPS) of the error

Several FF methods are being compared on the N-Forcer setup as shown in Fig 3. Cable slab, actuator and suspension disturbances have been compensated for. A third order setpoint is used with an acceleration equal to 7 m/s^2 and a jerk equal to 1400 m/s^3. It can be seen that by employing double-FIR FF, the contribution of flexibilities is significantly less as compared to conventional mass and mass/snap FF techniques.

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