Integrated Design Methodology for High-Precision/Speed Servomechanisms

Min-Seok Kim and Sung-Chong Chung

HYbrid Systems Design and Control LABoratory
School of Mechanical Engineering
Hanyang University, SungdongGu, Seoul 133-791, Korea

Abstract
An integrated design methodology is proposed to ensure the required high-speed and high-precision specifications in servomechanisms, where the interactions between mechanical and electrical subsystems will have to be considered simultaneously. Both the geometric errors referring to Abbe offset and the contour errors referring to circular motions are minimized through the design procedure satisfying allowable structural deformation errors, the relative stability and so on. The validity of the integrated design methodology is confirmed through design results.

Keywords: Abbe error, contouring error, high-precision/speed servomechanism, integrated design, nonlinear constrained optimization, stability

1. Introduction
High-precision/speed servomechanisms have been widely used in the manufacturing and semiconductor industries [1~2]. These specifications significantly exceed the axis motion capabilities of conventional ones. Therefore, it is necessary to devise special design concept to achieve this level of performance for high-precision/speed servomechanism.

In order to ensure the desired specifications in the servomechanism, an integrated design methodology is proposed [3~5], where the interactions between mechanical and electrical subsystems will have to be considered simultaneously during the design process.

In the first step of the integrated design process, it is necessary to focus on the strict modeling and analysis of those subsystems, individually. In addition to the modeling of subsystems, an accurate identification process of the mechanical subsystem is conducted. In the next step, the focus is on integrating subsystems to evaluate the desired performance of the servomechanism. For this purpose, we formulate the optimization problem that includes the relevant parameters of the servomechanism. Finally, simulations and numerical case studies are presented to demonstrate the effectiveness of the proposed design method.

2. Modeling of servomechanism
The mechanical characteristics of servomechanisms such as an equivalent inertia and stiffness have significant effects on the design optimization.

The free-body diagram of servomechanism to look for dynamic behaviors is shown in Fig. 1. The mathematical model of the mechanical subsystem is constructed by developing the equation of dynamic motion between the motor and mechanical components of servomechanisms. The transfer function between a motor torque \( \tau \) and rotational motor speed \( \omega \) is described as Eq. (1).

\[
G_p(s) = \frac{\omega(s)}{\tau(s)} = \frac{s^2 + b_1}{J_m s^3 + a_3 s^2 + a_2 s + a_1},
\]

\[
a_1 = \left( k_c K_{emf} + 1 \right) / J_m, \quad a_2 = \left( J_m K_{emf} \eta + R^2 M_i K_{eq} \right) / J_m M_i \eta, \quad a_3 = \left( k_c K_{emf} + 1 \right) K_{eq} / J_m M_i, \quad b_1 = \left( R^2 + K_{eq} / M_i \right) R = \frac{p}{2\pi}
\]

where, \( M_i \) is mass of table and workpiece, \( K_c \) is a torque constant, \( K_{emf} \) is a back-emf constant, \( \eta \) is the efficiency of driving mechanism, \( p \) is a ball-screw pitch, and \( K_{eq}, J_{eq} \) is an equivalent stiffness and inertia.

![Fig. 1 Free-body diagram of mechanical subsystem.](image-url)