Closed-Loop Identification and Structural Modeling of Power Assist Control System

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***Abstract*—To address vibration issues in electric arm-type power assist systems caused by low rigidity and feedback delays, this study develops a reliable mathematical model for control design. First, experimental system identification was conducted using the CL-MOESP method to capture the device's frequency characteristics. Second, equivalent joint stiffness constants were derived from arm deflection measurements via motion capture and the least squares method. Finally, a mathematical model incorporating these constants was developed and validated through numerical simulations. Comparison with actual system identification results confirms the proposed model's effectiveness in accurately reproducing the system's complex dynamic behavior.**

Keywords—power assist system, system identification, CL-MOESP method, joint stiffness, structural modeling

I. Introduction

Power assist devices reduce physical workload, but low rigidity and feedback delays often cause problematic vibrations. This study aims to improve the operability of an electric robotic arm-type system by developing a reliable mathematical model for control design. Instead of a simple black-box model, we physically formulate multi-inertia characteristics as equivalent joint stiffness. First, the Closed-Loop Multivariable Output-Error State Space (CL-MOESP) method is used for system identification, which is necessary due to safety and control intervention constraints. Next, a structural model is developed using stiffness constants derived from actual deflection measurements. Finally, the model's validity is verified by comparing its Bode diagrams with experimental identification results to ensure structural reproducibility.

II. System Configuration

The electric power assist system (Fig. 1)[1], manufactured by Aikoku Alpha Co., Ltd., features a 50 kg load capacity. For sensing, a six-axis force sensor and a rotary encoder monitor manual force and angular displacement. Actuation includes vertical assistance via an AC motor and ball screw, and swivel assistance via a pneumatic cylinder and friction wheel. A PC-integrated DSP system enables real-time control by processing sensor signals to command the AC motor. While this configuration ensures precision, the link arm's low rigidity remains a critical factor in the system's dynamic behavior.

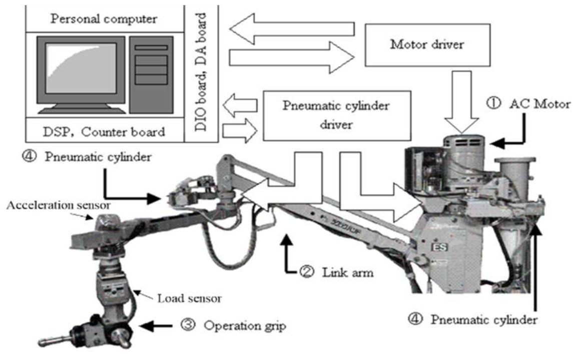

Fig.1 Overview of the power assist system

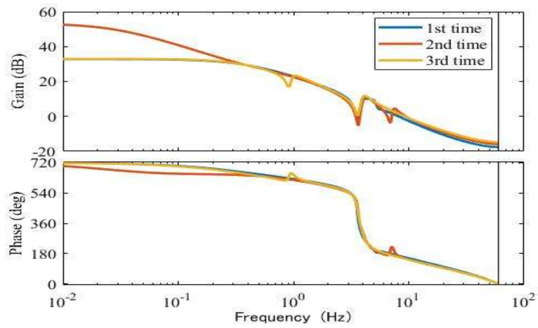

Fig.2 Identification results with an order of 8

III. System Identification via CL-MOESP Method

For the power assist device under study, open-loop identification is difficult to implement due to safety requirements and the continuous intervention of the control system. Therefore, the Closed-Loop Multivariable Output-Error State Space (CL-MOESP) method[2] was adopted as a practical closed-loop identification technique. To apply this method, an M-sequence signal with an amplitude of ±0.0005 was added to the output of the PID controller as an external excitation. Data acquisition was performed with a sampling period of 0.00833 s, consistent with the device's control cycle.

The model order was determined by observing the decay of singular values to capture the dominant system dynamics. An 8th-order model was selected because it clearly identified resonance points and captured a broader range of frequency components compared to lower-order models. The identification results for this 8th-order model are presented in Fig. 2. The Bode diagram reveals resonance and anti-resonance points near 0.9 Hz, 3.6 Hz, and 6.9 Hz. These characteristics strongly suggest that the device is not a simple rigid body but a multi-inertia system containing elastic elements. This finding necessitates the development of a structural model that incorporates the rigidity deficiencies of the arm.

IV. Construction of a Mathematical Model Considering Joint Deflection

To physically represent the multi-inertia characteristics identified through experimental identification, a structural model incorporating measured joint stiffness was constructed. First, arm deflection was measured using a motion capture system under loads ranging from 0 to 30 kg. Significant elastic deformation was identified at three primary locations: between the base and Arm 1, between Arm 1 and the Mid section, and between the Top and Ope sections.

Equivalent joint stiffness constants were calculated using the least squares method based on the relationship between the measured deflection and distance. A comparison between the measured and calculated deflection is shown in Fig. 3, where the profiles match closely, confirming the accuracy of the estimated spring constants in representing static arm deformation. Subsequently, equations of motion were derived by applying Lagrange's equations to the physical link model illustrated in Fig. 4, which accounts for the deformation induced by the load.

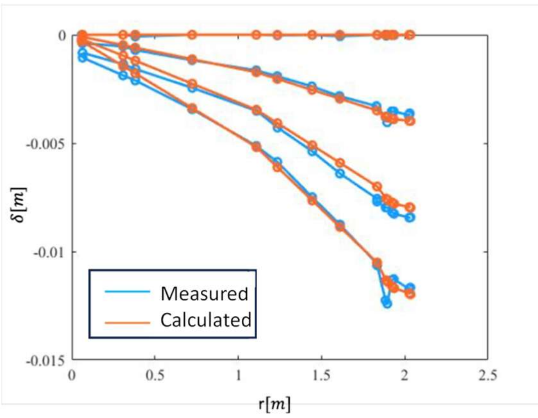

Fig.3 Comparison between measured and calculated deflection

To verify the structural validity of the model, the derived equations were replicated in a numerical simulation, and the CL-MOESP method was applied to the acquired data. Fig. 5 compares the Bode diagrams of the proposed mathematical model and the actual system. The experimental data exhibit anti-resonance and resonance points near 3.5 Hz and 6.9 Hz, respectively, while the mathematical model shows these points near 3.5 Hz and 7.7 Hz. Although a discrepancy in absolute gain exists due to uncertainties in mass and damping coefficients, the model successfully reproduces the multi-inertia characteristics. These results demonstrate that the physical framework established in this study is sufficiently valid for the design of future vibration suppression control systems.

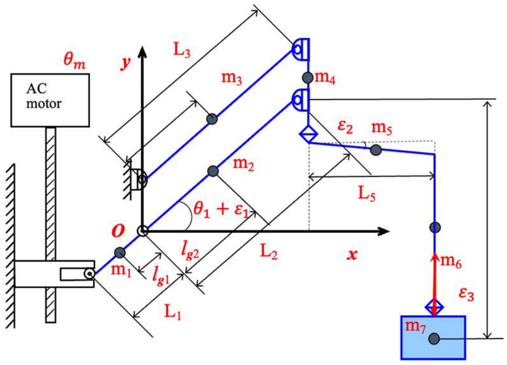

Fig.4 Link model considering the load

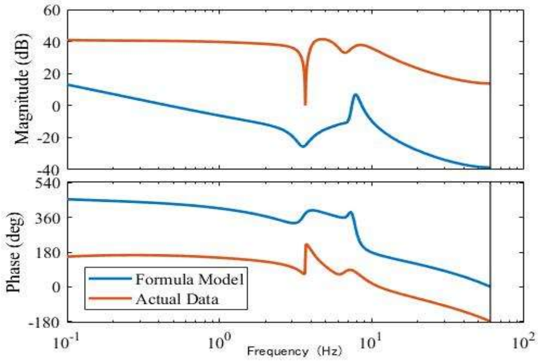

Fig.5 Bode diagram of formula model and actual data

V. Conclusion

To develop a linear model for an arm-type power assist device, this study combined CL-MOESP experimental identification with deflection-based joint stiffness estimation. The identification revealed a multi-inertia system, leading to a mathematical model that successfully reproduced resonance peaks at 3.5 Hz and 7.7 Hz, closely matching the actual system. These results confirm that accounting for joint deflection effectively captures the system's dynamic characteristics. While specific control designs were not yet implemented, future research will utilize this linear model to develop vibration suppression controls, such as notch filters or state feedback. We aim to quantitatively verify operability improvements and ultimately resolve vibration issues caused by low structural rigidity.

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