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学 位 の 種 類	博士（工学）
学 位 記 番 号	博第1238号
学位授与の日付	2022年3月31日
学位授与の条件	学位規則第４条第１項該当　課程博士
学 位 論 文 題 目	Controller Design for Positioning of Lightweight Two-Link Robot with Elastic Joints Aiming at Fast and Precise Response （高速・高精度応答を目指した弾性関節を有する軽量2リンクロボットの位置決め制御設計）
論 文 審 査 委 員	主 査　教授　岩崎　誠 教授　森田　良文 教授　小坂　卓 教授　大石　潔（長岡技術科学大学）

論文内容の要旨

Nowadays, industrial robots are extensively applied in numerous fields to eliminate dangerous and demanding tasks. In order to improve work efficiency and productivity of production lines, fast and precise positioning is a prerequisite for motion control of industrial manipulators. Furthermore, there has recently been a strong demand for human collaborative robots with soft, compact, and flexible mechanisms to ensure safety, reduce costs, and lower energy consumption. However, mechanical resonance vibrations associated with the low-rigidity mechanisms impair the control accuracy, especially when the robots move at high speeds. Therefore, controller designs have been continuously developed to improve the positioning systems of flexible robots.

This thesis aims to propose frequency domain-based controller designs that can realize high-speed high-precision responses for the positioning system of a serial two-link elastic-joint lightweight-link manipulator in which each joint can be modeled as a three-mass (3M) system. Aiming at the fast positioning, the two-degree-of-freedom (2-DOF) control framework consisting of both feedforward (FF) and feedback (FB) components is employed for each joint, where the FF filters are designed according to the coprime factorization (CpF) method, whereas the FB controllers are conventionally synthesized using P-PI control. However, the performance with the conventional 2-DOF control design is severely degraded if the influence of the coupling torques generated in a concurrent movement of the robot joints becomes significant. Hence, four compensation schemes are proposed in this study to address the coupling effect.

The first proposal is an application of H_∞ control theory to synthesize the FB controllers. An H_∞ synthesis is applied to shape the closed-loop transfer functions from the coupling torque to the controlled output besides the sensitivity and complementary sensitivity functions. Experimental verification proves that the H_∞ controller outperforms the conventional P-PI controller, especially residual vibration suppression capability. However, the expected control targets are not satisfied due to a high overshoot. In other words, supplementary compensation schemes for the coupling effect are needed.

The second proposal is an application of MIMO decoupling control theory to the 2-DOF controller design. Since the robot behaves as a MIMO system, decouplers are applied to realize pseudo SISO plants independent of each other in the aspect of control. The 2-DOF controller is then designed for each of the decoupled SISO plants. The effectiveness of the proposed decoupling design is experimentally confirmed. Although the control quality obtained is satisfactory, this method's applicability is limited to the flexible robots whose dynamics can be approximated to a linear MIMO system.

The two last proposals are independent-joint compensation strategies for the coupling torques, where the third proposal is a disturbance observer (DOB)-based scheme while the fourth one is a 3M model-based FF compensation design. Besides, though the two proposed designs can effectively reject the influence of the coupling torques on the controlled arm-side angles, the vibrations still occur at the load sides due to the coupling effect. Therefore, reference filters are additionally applied to suppress the coupling vibrations. Numerical simulations and experiments are conducted to verify the proposed methods' effectiveness compared to a conventional rigid-body model-based compensation scheme. As being independent-joint control schemes, the third and fourth proposals are applicable to any other types of flexible-joint flexible-link manipulators whose joints behave as 3M systems.

論文審査結果の要旨

This thesis aims to propose frequency domain-based controller designs that can realize high-speed high-precision responses for the positioning system of a serial two-link elastic-joint lightweight-link manipulator in which each joint can be modeled as a three-mass (3M) system. Aiming at the fast positioning, the two-degree-of-freedom (2-DOF) control framework consisting of both feedforward (FF) and feedback (FB) components is employed for each joint, where the FF filters are designed according to the coprime factorization (CpF) method, whereas the FB controllers are conventionally synthesized using P-PI control. However, the performance with the conventional 2-DOF control design is severely degraded if the influence of the coupling torques generated in a concurrent movement of the robot joints becomes significant. Hence, four compensation schemes are proposed in this study to address the coupling effect.

The first proposal is an application of $H\infty$ control theory to synthesize the FB controllers. An $H\infty$ synthesis is applied to shape the closed-loop transfer functions from the coupling torque to the controlled output besides the sensitivity and complementary sensitivity functions. Experimental verification proves that the $H\infty$ controller outperforms the conventional P-PI controller, especially residual vibration suppression capability. However, the expected control targets are not satisfied due to a high overshoot. In other words, supplementary compensation schemes for the coupling effect are needed.

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