博士論文（要約）

Study on Rotary Actuators Utilizing Shape Memory Alloy Wires

（形状記憶合金ワイヤを用いたロータリアクチュエータに関する研究）

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Shape memory alloy (SMA) is an intermetallic compound that exhibits two unusual properties: shape memory effect (SME) and superelasticity. On the basis of the SME defined as an effect that the material recovers its predetermined shape during solid-state phase transformation caused by temperature increase, the SMA materials are utilized for actuators. Various types of SMA actuators have been devised and applied to diverse scientific and industrial fields such as robotics, aerospace engineering, biomedical engineering, automotive engineering, etc, due to its advantages as follows: high energy density (high power-to-weight and force-to-volume ratio), large recoverable strain, mechanical simplicity, smooth and silent operation, workability in corrosive environment, high strength, wear, and fatigue resistance, and so forth.

This study aims to develop novel SMA rotary actuators that could be practically utilized for multi-purpose in diverse fields, on the basis of attractive features such as mechanical simplicity, size-variability (compact sizeability), modularity for the structural features and bidirectional workability, continuous rotary motion, high-torque capability for the functional features. To achieve this aim, the study is performed with a focus on devising appropriate rotational driving mechanism, because the rotational driving mechanism affects significantly on structural and functional features of the SMA rotary actuator. The rotational driving mechanism for proposed SMA rotary actuators is devised based on wobble motor driving principle well known as a type of reduction system. In the actuator, this rotational driving mechanism functions effectively to convert expansion/contraction of SMA elements to bidirectional rotary motion with high-torque. With the driving mechanism, totally three different SMA rotary actuators are realized as first, second, and third versions.

As a part of basic study, a characterization on electro-thermomechanical behavior of SMA wire actuator is experimentally carried out to investigate fundamental actuating principle and properties. For this work, a suitable experimental setup is devised and implemented. In the experiment, the SMA wire specimen is firstly trained to stabilize strain-stress response, and then, characterization test is conducted. Experimental results obviously show the electro-thermomechanical behavior of NiTiCu SMA wire, such as variation of internal resistance of the material, solid-state phase transformation temperature, temperature hysteresis, kinetic strain, and so on. With the results on characterization, a heat transfer model that could be utilized to simulate the temperature variation of the SMA wire during the electrical heating and convective cooling is developed.

The first version of proposed SMA rotary actuators is conceptually designed with the devised rotational driving mechanism. The mechanism consisting of an internal gear as a wobbler, an external gear as a rotor, and three crankshafts is driven by phase-symmetrically positioned three SMA wires connected in series with bias-spring. The annular gear is wobbly driven by sequential activation of three SMA wires, and the external gear is resultingly rotated. In this operation, the wobbling motion of the annular gear is guided as curvilinear translation by triple parallel-crank-mechanism which is formed by radially symmetrically placed crankshafts. Based on this motion guide mechanism, the correct engagement between the wobbling internal gear and the rotary external gear could be kept during the operation.

In the case of the first version, an involute spur gear set is utilized for the function as the wobbler and the rotor, because it offers more reliable engagement without slipping in the motion transmission, as compared with other types of utilizable gear set such as a friction gear set, a permanent magnetic gear set, etc. An important point to consider in using the involute gear set is that some gear interferences may occur between gear teeth. The interferences, which are observed under the condition that a difference of number of teeth between two gears is quite small to achieve high reduction ratio, could cause an interruption of the actuator driving. Even though it could be prevented by using tooth profile shifted or modified gears, the optimization of profile shift coefficient must be involved for fine performance. For this reason, with an aim to propose an improved SMA rotary actuator which enables to effectively achieve high torque without the gear interferences, the second version is devised with a cycloidal driving gear set. Because this gear set consists of a pin/roller based annular gear as a wobbler and a cycloidal disc as a rotor, the wobbling motion caused by sequential activation of the SMA wires could be quietly and smoothly converted into the rotational motion by rolling contact based engagement between two components. Furthermore, cycloidal tooth profile of lobes of the cycloidal disc offers higher durability of the gear set than the involute gear set. With theses merits, the cycloidal driving gear set based mechanism is regarded as more suitable and functional motion converting mechanism for high-torque capability, and therefore it is applied to the proposed second version.

In designing the first and second versions, design parametric analysis is carried out to assess parametric effects of key design parameters on working performances of the actuators. For this analysis work, a simplified geometric model for the first and second versions is developed. Because the model fully reflects not only the structural features of the actuator but also thermomechanical characteristics of the SMA element, it could be effectively utilized to calculate working performances. With the model, trial calculation is firstly performed. The trial calculation, which focuses to observe variation of some geometric parameters during actuator driving, is utilized to grasp assessable performances, to select key design parameters, and to determine their parametric ranges for the analysis. With consideration for results of the trial calculation, three key design parameters are selected: length of SMA wire, stiffness of bias-spring, and number of phase. Obtained analysis results demonstrate that the values of the selected key design parameters strongly influence on actuator torque characteristics such as cogging torque, holding torque, torque ripple and so on.

On the basis of the results on design parametric analysis, the first and second versions are designed and fabricated as functional prototypes to carry out experimental driving characterization and working performance verification. Also, with consideration for the operating principle of the proposed actuators, an experimental setup consisting of instrumental devices and a braking system used to measure dynamic torque is devised. In the experimental tests, the driving characteristics affected by activation type depending on pulse duty cycle of applied three-phase pulsed voltage are investigated. And, dynamic torque characteristic, i.e. output torque-rotational speed characteristic, is observed.

The results on theoretical calculations and experimental performance verifications for the first and second versions show obviously that both actuators work successfully on the basis of the devised wobble motor driving mechanism. However, despite its superior functionality, the wobble motor driving mechanism applied to the first and second versions has some structural weak points caused by the crankshafts based wobbling motion guide mechanism. Even though structural weak points are not regarded as serious drawback in the operation of the actuator, to ensure more stable and reliable operation, it is required to improve the kinematic structure of the wobble motor driving mechanism. For this reason, the third version is devised with a structurally improved wobble motor driving mechanism, i.e. beam flexures based in-plane XY compliant mechanism. On the basis of this mechanism, the third version is designed with advantageous characteristics as the in-plane mirror symmetric configuration, the monolithic body of the motion guide mechanism, the four-phase system, and so on. In this study, The XY compliant mechanism is analytically designed, and then the values of key design parameters are determined with the design parametric analysis. In the analysis work, the parametric effects of geometric parameters of the beam flexure on the translational stiffness and maximum stress induced in the mechanism are mainly investigated. And, with the FEM based simulation, designed performances are verified. In the experimental tests, the function of the XY compliant mechanism as the wobbling motion guide is mainly tested. Experimental results on crosstalk tests and trial driving tests demonstrate obviously that the devised XY compliant mechanism performs the function as wobbling motion guide well in the SMA rotary actuator.

In this study, three novel SMA rotary actuators are successfully realized and related works are carried out. Significant achievements and remarkable contributions of the study could be briefly described as follows: analysis of the state of the art and technological trend of the SMA rotary actuators, characterization on electro-thermomechanical behavior of the SMA actuator, realization of wobble motor driven by SMA elements, application of a cycloidal gear set to the wobble motor driving mechanism, and innovative design of the wobble motor based on the in-plane XY compliant mechanism.