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Title(English)	Simple Controller Design and Characteristic Evaluation of Precision Systems with Pneumatic Artificial Muscles
著者(和文)	王少飛
Author(English)	Shaofei Wang
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DOCTORAL THESIS OUTLINE

Thesis Title: Simple Controller Design and Characteristic Evaluation of Precision Systems with Pneumatic Artificial Muscles

Name: WANG Shaofei

Supervisor: Associate professor Dr. Kaiji SATO, Professor Dr. Toshiharu KAGAWA

Affiliation: Department of Mechano-Micro Engineering, Tokyo Institute of Technology

In this thesis, a simple controller design method for precision motion of pneumatic artificial muscle (PAM) mechanisms was proposed. A mover connected to a pair of McKibben PAMs in the antagonistic structure is used as the experimental setup since this structure is widely used as a basic driving unit in PAM mechanisms. The usefulness of the controller design method was examined experimentally using that PAM mechanism. Then the energy consumption and the thermal phenomenon of the PAM mechanism were evaluated using the designed controller. The outline of the thesis is shown as follow.

1. INTRODUCTION

In this chapter, research background and research goals are introduced.

PAMs have many advantages, such as a high degree of safety, a high power-to-weight ratio, and no magnetic field generation. However, because of their significant nonlinearities, PAMs have low controllability, and consequently, it is difficult to move PAMs accurately. In recent years, various control methods have been applied to PAM mechanisms, but their control accuracies are still restricted in imprecision region. Therefore, applications of PAMs are limited even though they possess the aforementioned advantages. Besides, energy consumption and thermal phenomenon of PAM mechanisms are important in practical applications. However, they haven't been sufficiently clarified.

Therefore, the following two goals are determined and achieved in this

thesis. The first goal is to establish a controller design method of PAM mechanisms with features of providing precision motion and ease of design without exact mathematical models. The second goal is to provide knowledge regarding energy consumption and thermal phenomenon using the designed controller for precision motion of PAM mechanisms.

2. EXPERIMENTAL MECHANISM WITH PNEUMATIC ARTIFICIAL MUSCLES AND ITS MACROSCOPIC CHARACTERISTICS

In this chapter, the experimental setup with a linear antagonist structure using a pair of PAM was introduced. Meanwhile, the conventional dynamic model of the PAM mechanism and its subject are discussed.

The dynamic model includes a pneumatic part and a mechanical part. Nonlinear characteristics are shown both in pneumatic and mechanical process of the system. Through identification experiments, elements of the model were obtained. Using the identified model, open-loop responses were simulated and compared with the experimental ones. The comparison between experimental and simulated results shows that the dynamic model can represent the static characteristics of the real mechanism approximately and provide the same responses as experimental ones macroscopically in the low frequency region (< 1 Hz). However in a higher frequency region, small amplitude vibration was observed in experimental responses, but almost not in simulated ones. These results indicate the subject of the dynamic model.

The dynamic model is useful to represent macroscopic characteristics of the mechanism but not microscopic characteristics. Thus, it is not suitable for a precision motion controller design. In addition, the usage of the model makes it difficult to design the controller, and it is not expected in this research. Therefore, this model is not useful for precision controller design (not used in Chapters 3 and 4), but useful for discussing the general characteristics (used in Chapter 5).

3. PRECISION POINT-TO-POINT POSITIONING

A simple controller design method for precision positioning of PAM mechanisms was proposed in this chapter. According to this method, nonlinear compensators in the controller were easily-obtained from

open-loop responses without exact modeling. After that, conventional control elements such as a proportional-integral-derivative (PID) and an acceleration feedback elements were determined.

Using the designed controller, positioning experiments were carried out to validate its effectiveness. Experimental results show that sub-micrometer ($0.9\text{ }\mu\text{m}$; 0.09 % of the step from 0 mm to 1 mm) positioning accuracy and $0.5\text{ }\mu\text{m}$ positioning resolution were achieved. In the precision positioning, the residual vibration in the range of 5~20Hz were observed. This vibration limited the positioning accuracy. The solution of this problem was discussed in the next chapter.

4. PRECISION MOTION CONTROL

In this chapter, a simple controller design method for precision motion of PAM mechanisms was introduced. In order to reduce the residual vibration in positioning introduced in Chapter 3, microscopic characteristics were examined. According to the characteristics, a phase-lead element was designed to compensate phase-delay characteristic of the mechanism. The positioning results indicate that the designed controller reduced the maximum amplitude of the residual vibration from $0.9\text{ }\mu\text{m}$ to $0.7\text{ }\mu\text{m}$ (0.07 % of the step from 0 mm to 1 mm).

An inverse model of a 1st-order system was applied and a simple modified feed-forward element (SM FF element) was constructed to the control system for precision motion control. The tracking results indicate that the maximum tracking errors were less than 2 and $5\text{ }\mu\text{m}$ (0.04 % and 0.1 % of the tracking range from 0 mm to 0.5 mm) under 0.1- and 0.5-Hz sinusoidal tracking control, respectively. Besides, the problem of the overshoot in positioning was solved because of the suitable step-like reference.

5. ENERGY CONSUMPTION AND THERMAL PHENOMENON

In this chapter, the energy consumption and the thermal phenomenon of the PAM mechanism were evaluated during motion control.

(1) Energy consumption

The electrical energy for driving the servo valve and the air energy from the pressure supply were defined as energy source of the system and were

calculated using measured responses. The mechanical work done by the two PAMs and the amounts of energy loss caused by the friction between the guide and the mover, the damping and the spring elements were calculated using the dynamic model in Chapter 2. Most of the energy source was air energy, but only less than 0.05 % of the energy source was transferred to the energy related to the motion. The reason of low efficiency is considered that there is approximate 90 % of the air energy lost with air leakage. According to comparison to electric motor, it is known that the efficiency of the PAM mechanism was very low (< 0.005 % in the experimental conditions).

(2) Thermal phenomenon

The temperatures of the atmosphere, the PAMs, mechanical parts of the PAM mechanism were measured during the precision motion control in different motion conditions. According to the measured results, the temperature rise of the PAM mechanism depends on motion frequency and amplitude. When the amplitude became double, the temperature rise became more than doubled. When both the amplitude and the frequency doubled, the temperature rise became more than tripled. Comparing the air energy consumption and motion accuracy between before and after 20 minutes motion control, there was no significant difference.

6. CONCLUSION AND FUTURE WORK

Conclusions and future works were described in this chapter.