博士論文（要約）

Displacement Estimation of Electrostatic Film Motors Using Driving Currents

（駆動電流を利用した静電フィルムモータの変位推定）

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Thesis summary

Synchronous type electrostatic film motors are expected to be used in, for example, computer human interface (CHI) systems, dynamic billboards in the street, autonomous shading systems for windows and ultra-thin position stages, due to their mechanical flexibility, ultra-thin structures, and optical transparency. In these applications, the motors might be operated in the air and their output forces can be limited due to the low applied voltages. As a result, “out-of-synchronous” or “step-out” is inevitable. Even when step-out occurs, the slider displacement needs to be monitored in those applications. A simple displacement monitoring system with low cost is expected, in which an estimation resolution can be compromised.

There is no suitable displacement sensing method that is acceptable in those applications. For example, conventional position sensors, such as linear encoders, spoil the merits of the electrostatic film motors due to their thick body and high rigidity. To fully profit the merits of the electrostatic film motors, two types of built-in sensors were proposed in the previous studies, which can realize slider displacement estimation with high accuracy without spoiling the merits of the film motors. However, they utilize high frequency sensing signals to achieve high accuracy and thus require high-frequency amplifiers and oscillators which increases the complexity of the systems. Such complicated sensing systems are not suitable for the applications mentioned above. Therefore, this work proposes a new simple method to estimate the slider displacement for the synchronous type electrostatic film motors. The proposed method estimates the slider displacement from the applied voltages and the driving currents. The additional components required for the estimation are current sensors only, and the total system can be realized at a low cost.

The proposed method shares the similar concept with sensorless position estimation methods for electromagnetic motors. However, due to the intrinsic differences between the electrostatic film motors and electromagnetic motors, some technical challenges exist. 1) How to transplant the sensorless position estimation technologies of the electromagnetic motors to electrostatic film motors? Although there is an analogy between electrostatic motors and electromagnetic motors, the synchronous type electrostatic film motor does not have an exact counterpart in the field of electromagnetic motors. Therefore, the sensorless position algorithm in electromagnetic motors cannot be directly utilized. 2) The impedance of the electrostatic film motors is very high and, as a result, the driving currents are considerably small. Therefore, it is difficult to measure the currents with high accuracy, which causes problems in displacement estimations. 3) How to deal with the impulsive currents during pulse voltage operation? The electrostatic motors are often driven by pulse voltages, which create impulsive driving currents. Such

impulsive currents cannot be measured properly and thus make the displacement estimation difficult.

This dissertation describes the research work carried out to solve the challenges.

1) This work analyzed the driving currents of the synchronous type electrostatic film motors, based on which the concept of the displacement estimation is proposed. Although the driving currents can be easily derived by using the previous theory on the electrostatic film motors, the details of the driving currents have not been studied extensively in the previous studies. This work clarifies the relation with the slider displacement and the driving currents such that the displacement estimation becomes possible. From the analyzed results, it can be easily understood that the information of the slider displacement can be extracted from the driving currents.

2) Three-phase sine voltages are typical driving voltage waveforms for the electrostatic film motors. In this work, three displacement estimation methods were proposed for sine voltage operation, which are called "Method-Remove-offset", "Method-HPF-dq" and "Method-HPF-uvw". In these estimation methods, the measured driving currents are converted into simpler signals by using Clarke and Park transformations, to facilitate easy extraction of slider displacement information. The resulting signal consists of an offset (corresponding to the base current) and a feature component (corresponding to the slider displacement). After removing the offset, the slider displacement can be calculated by using arc-tangent function. The three proposed methods differ in how to remove the offset. In "Method-Remove-offset", the offset is removed using its pre-estimated value. As the offset is difficult to be estimated with high accuracy, "Method-Remove-offset" may not be practical. In the other two methods, the offset was removed by using a high pass filter (HPF), before or after Clarke and Park transformations. Simulation results revealed that "Method-HPF-uvw" is the only practical method, which has relatively higher noise immunity.

3) The displacement estimation method proposed for sine voltage operation was modified for pulse voltage operation. Differently from sine voltage, impulsive currents appear at the switching time of the pulse voltage. Simulations showed that "Method-Remove-offset" is not suitable for pulse voltage operation. Therefore, the method was modified to deal with the impulsive currents, which is called "Method-PULSE". In "Method-PULSE", considering the short time-duration of the impulsive currents, the displacement estimation is temporarily suspended during the impulsive currents, and the previous estimated displacement is kept during the suspension. Simulation results and the experiment results verified that "Method-PULSE" can work well under various operation conditions.

4) Finally, this work derived a generalized theory of the displacement estimation for the electrostatic film motor, which is called "Method-ARBITRARY". In the derived method, any

set of three voltage waveforms are converted into three-phase sine voltage expressions with offsets. Based on the converted expression, the slider displacement is estimated. Such a method is useful when a motor is driven using pulse voltages generated by low-power amplifiers. If the driving power amplifier has a limited output current, the resulting pulse voltages will be distorted. For distorted pulse signals, “Method-PULSE” can easily fail and therefore, the generalized method, “Method-ARBITRARY”, will be effective. To verify the proposed method, simulations were carried out for pulse voltages with various rise times. The simulation results verified that the method works well in case of the skewed motor, in which slider electrodes are skewed to suppress output force ripple, under various conditions. However, it worked well only under a limited condition, in case of the regular motor.

Overall, this work proposed displacement estimation methods for the synchronous type electrostatic film motors by utilizing the driving currents. To realize this concept, this work analyzed the details of the driving currents and developed the estimation methods for three different operations: sine-voltage operation, pulse-voltage operation and arbitrary-voltage operation. In theory, the slider displacement can be estimated with high accuracy using the proposed method. In practice, the low measurement accuracy of the driving currents limited the resolution of the displacement estimation at around one electrode pitch. However, it can estimate the slider displacement even when the slider steps out from the synchronization by disturbances, and thus is useful for the above-mentioned applications.