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Linear resonant electrostatic induction motor using electrical resonance with piezoelectric transducers

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ABSTRACT

This paper proposes an electrostatic linear induction motor resonating electrically with piezoelectric transducers. The motor is based on an electrostatic film motor composed of two thin plastic films containing fine pitch three-phase electrodes, which face each other across a short gap. The motor requires three-phase high voltages on the electrodes in both films to obtain thrust force. Our proposal in this paper is to utilize piezoelectric transducers to realize the high voltage on one of the films: the slider film, by using the transducers as inductive elements that resonate with the electrostatic motor. We describe specific design method of the piezoelectric transducers for this application, and analyze the influences of their properties on the performance of the motor. A working prototype was constructed with piezoelectric length-extensional bars as the transducers. The prototype demonstrated a maximum thrust force of 0.24 N with 500 $V_{0\text{-}p}$ three-phase excitation. When driven at high voltages, we observed a step-like motion caused by a non-linear behavior of the piezoelectrics, i.e., the jump resonance. The observation indicates a problem in optimal design of the piezoelectric transducers for this specific application.

1. Introduction

Electrostatic motors require fine electrode structure for good performance. One idea of utilizing this motor is to downsize the overall structure to microscopic level, which has been applied to actuators for MEMS (MicroElectroMechanical Systems). Another idea is to integrate hundreds and thousands of fine-pitched electrodes to form a macro-scale motor. This paper concerns the latter type of electrostatic motor; we introduce piezoelectric transducers to resonate with a macro-scale electrostatic linear motor, in order to produce high voltages that are necessary for large thrust force. The piezoelectric transducers enable the motor to operate without direct feeding of power to its slider; the absence of power cables allows the slider to travel long distance without disturbance. Further, because both the piezoelectrics and the electrostatic motor are non-magnetic, the whole actuator system is non-magnetic. Thus, the motor provides long-stroke linear drive that can be used in MRI (Magnetic Resonance Imaging) devices, in which the use of magnetic motors are prohibited.

The motor we propose originates in an electrostatic linear motor reported in Ref. [1], which is illustrated in Fig. 1(a). The motor is composed of a pair of plastic films with fine pitch electrodes, facing each other across a short gap. The motor is driven synchronously by applying three-phase ac high voltages (in order of kilo volts) to the electrodes in both films. The voltages excite a strong electric field in the gap and realize high power-to-weight ratio; e.g., the motor in Ref. [1] had output performance of 230 W/kg. One remarkable feature of the motor is in its non-magnetism; an open-loop position control of this motor in a strong magnetic field of an MRI scanner was demonstrated in Ref. [2]. One disadvantage of this motor is that both of the films require cables for direct feeding of power. Such cables disturb dynamic motion of the slider: the traveling film; thus, the motor is unsuitable for some systems requiring cable-free sliders, such as multi-DOF actuators [3].

The rotary motor in Ref. [4] showed one solution which can free the slider from cables. In the motor, the voltages are supplied only to the stator electrodes and the rotor electrodes are connected to coils, which resonate with the capacitance of the electrodes for voltage boosting. The motor is an asynchronous motor and thus referred to as a resonant electrostatic induction motor.

The name “electrostatic induction motor” was originally given to motors with their rotors made from dielectrics coated with slightly conductive materials [5–7]. In these motors, the rotor gains torque when put in a rotating electric field formed by exciting the electrodes in the stator. Characteristics of these motors are dependent on the slip: relative speed of the field to the rotor. The resonant electrostatic induction motor is also slip dependent,

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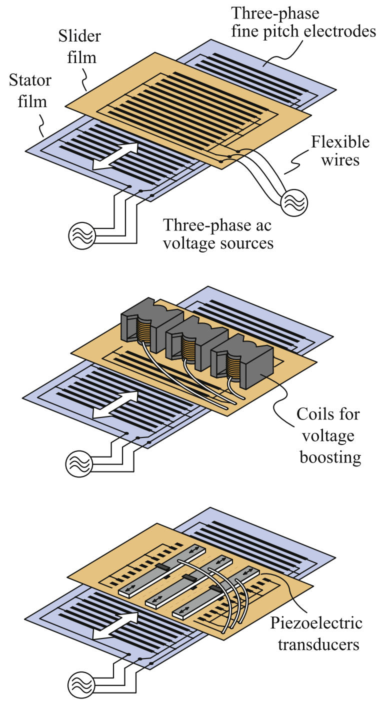

Fig. 1. Conceptual illustration of three electrostatic film motors: (a) a synchronous electrostatic motor with dual excitation, (b) a resonant electrostatic induction motor with mounted coils and (c) the same motor with coils replaced by piezoelectric transducers.

but differs greatly from other electrostatic induction motors in the rotor structure; it has electrodes embedded in them. The structure allows connection of electrical elements, such as coils for modification of characteristics.

As was demonstrated with a linear resonant electrostatic induction motor in Ref. [8], when the coils are mounted on the slider as in Fig. 1(b), the slider could be released from electrical connections to external equipments. However, by having the coils, the motor has lost the great advantage of electrostatic motors: the non-magnetism.

Fig. 1(c) illustrates a concept we proposed in our previous work to realize a non-magnetic resonant electrostatic induction motor [9]. In this motor, the coils are replaced with piezoelectric transducers. Such replacement is possible because piezoelectric transducers behave inductively near resonance. The inductive behavior comes from the inertia of the oscillating transducers; hence they provide electrical inductance without using magnetic materials nor producing magnetic field. By having this non-magnetic inductance to resonate with the capacitance of the electrodes, the motor can operate with large force while maintaining its non-magnetic property. Further, as shown in the figure, mounting the transducers on the slider realizes linear drive with no power cables connected to the slider. These two characteristics make the motor suitable for devices used in MRI scanners, especially for those requiring long-stroke linear drive. In this paper, we report an analysis which relates the properties of the piezoelectric transducers to the motor's performance. Our previous work in Ref. [9] explained the design concept of the motor based on admittance characteristics of the transducers and proved the feasibility of the idea with a working prototype. However, details on the design method considering the performance of the motor were not provided. Thus, in this work we provide detailed analysis to establish a design method for this motor.

The outline of this paper is as follows. First, in Section 2, we explain the principle of the resonant electrostatic induction motor

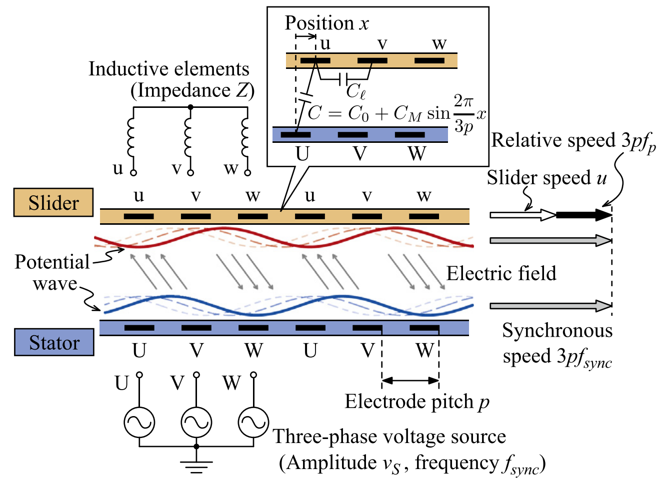

Fig. 2. Schematic showing the principle of a resonant electrostatic induction motor.

and construct a model including piezoelectric transducers. Then, Section 3 describes the prototype of the motor, with emphasis on the design of the piezoelectric transducers. Section 4 provides experimental results. In these experiments, to simplify experimental conditions, the transducers are placed beside the motor instead of being mounted on the slider. Measured results include the slider voltage, the thrust force and the slider motion. In the experiments, the prototype showed step-like motion in some conditions, which cannot be explained under linear assumption of the piezoelectrics. The cause of such motion is discussed in Section 5. Finally, a conclusion follows in Section 6.

2. Modelling and analysis

This section explains a lumped-parameter model of the resonant electrostatic induction motor with piezoelectric transducers. We keep the explanations on the operating principle and the basic modeling brief and concentrate on the introduction of piezoelectrics; details on the basics are found in Ref. [4].

2.1. Principle of resonant electrostatic induction motor

Fig. 2 shows the principle of the resonant electrostatic induction motor. The motor is driven by a three-phase ac voltage applied to the three-phase electrodes in the stator film. The voltages excite an electric field traveling at a synchronous speed determined by the electrode pitch p and the excitation frequency f_{sync}. As the charges induced by the field travel on the slider, currents flow into the slider electrodes through the inductive elements. These currents induce voltages across the inductive elements, which form a potential wave on the slider. When this wave is displaced from the potential wave on the stator, the electric field exerts tangential forces to the charges on the slider and produces a thrust force.

The speed of the traveling field relative to the slider's actual speed has great influence on the motor's thrust force. The relative speed is represented by a frequency called the slip frequency f_p, which is defined as

$$f_p = f_{sync} - \frac{u}{3p}, \qquad (1)$$

where u is the slider's speed. All voltages and currents in the slider side alternate with this frequency and the impedances of the inductive elements change accordingly.

Supposing that inductive elements with impedance Z are connected in Wye configuration, the voltage on one of the electrodes