Effect of Traveling Voltage Wavelength on Electrostatic Induction Actuators Driving Performance

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This paper investigates the effect of voltage traveling wavelength on the driving performance of a six-phase linear electrostatic induction motor designed for handling of plain paper copier (PPC) paper sheet. In the search for a stable and reliable thin sheet induction actuation, there is an interest improving driving performance through stator design. For this purpose, four different actuator designs were prototyped to generate different wavelengths, by changing the pitch between electrodes. Experimental results showed that the highest performance is achieved with shortest traveling potential wavelengths, with the maximum speed of the paper slider decreasing linearly with increasing traveling wavelength and the optimal traveling wave speed decreasing. The maximum speed of the slider reached 230 mm/s at a frequency of 300 Hz for the actuator with 7.2 mm wavelength, 309 mm/s at a frequency of 500 Hz for 4.8 mm traveling wave length, 344 mm/s at a frequency of 700 Hz and 383 mm/s at a frequency of 1300 Hz for 2.4 mm traveling wavelength. The maximum thrust force was measured to 13.7 mN for 2.4 mm traveling wavelength.

1. Introduction

Electrostatic induction actuators have been known for a long time, but new applications are being proposed until this day. Recent studies [1] described its application for sheet handling and demonstrated handling of, e.g., plain paper copier (PPC) sheet. The actuation technology can realize thin and flexible design for paper handling in information devices, and thus can create new applications that were not possible with the conventional paper handling mechanism. For example, the technology was applied for human computer interaction in [2], where a thin and transparent electrostatic induction actuator was integrated onto a surface of a flat-panel display in order to integrate computer generated animations and actuation of physical objects for better interaction.

The actuation was realized by utilizing parallel poly-phase electrodes. Applying poly-phase sinusoidal wave of the same number of phases to the electrodes creates traveling potential waveform on the electrodes. This traveling wave induces charge wave of the same wave length on the slider surface, which gives rise to thrust force. Many different design parameters affect the actuation performance, some of which can be estimated through theoretical discussions given by some previous papers [3-5]. However, theoretical discussions often assume simplified electrode structure and thus do not always predict the correct performance of the real actuators. Hence, experimental evaluation is still quite important in practical design.

This paper experimentally investigates how the performance of paper sheet actuation changes with different wavelengths of the traveling potential wave. Four actuators were designed, with different electrode pitches, to generate four different traveling wavelengths. The maximum velocity and static thrust force were measured to reveal the performance tendency.

2. Actuation Principle

The basic structure of the electrostatic actuator is shown in Fig. 1. The stator consists of six-phase parallel electrodes and the slider is a thin sheet made out of dielectric material, in this case normal PPC paper. The signal synthesizer generates a six-phase sinusoidal wave that is thousand-fold amplified by high-voltage amplifiers before being fed to the electrodes. This creates a traveling potential wave that induces a charge on the slider by surface current and dielectric polarization. The induced charge wave has the same wavelength and the same traveling speed as the excitation potential wave, but has a spatial phase lag due to the surface resistance and/or dielectric relaxation. The phase lag gives rise to the lateral electrostatic force and drive the slider in the same direction as the waves travel (see Fig. 2).

3. Experimental Setup

A regular Japanese B5 size (182 mm by 257 mm) PPC paper, with a surface resistance of 10^{13} Ω, was used as a slider. The sketch in Fig. 1 also illustrates the measurement setup. The slider displacement was measured using a laser displacement sensor (Omron ZX-100). To facilitate the measurement, a round object with 35 mm diameter and

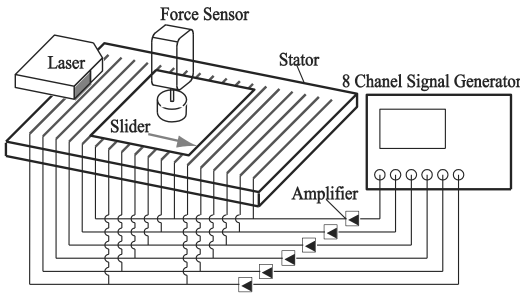

Fig. 1 Sketch of the thin sheet paper actuator with displacement laser and force sensor.

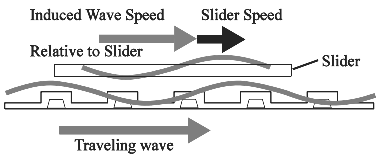

Fig. 2 Driving principle with sinusoidal traveling wave

Table 1 Actuator Design Parameters

Wavelength (mm)	Pitch (mm)	Electrode Width (mm)
7.2	1.20	0.50
4.8	0.90	0.38
3.6	0.60	0.25
2.4	0.45	0.19

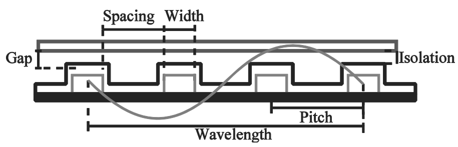

Fig. 3 Cross sectional view of the stator electrodes

20 mm height was placed at the center of the slider as a target point for the laser. The velocity of the slider was calculated by numerical differentiation from the displacement data. For static thrust force measurement, a load cell (Kyowa, LVS-50GA) was placed above the actuator to measure the force at the center of the round object attached on the slider sheet.

Four different stator electrodes were tested to evaluate the effect of the different wavelengths. The stator electrodes were fabricated using typical printed circuit board technology and have electrode pitches of 1.2 mm, 0.9 mm, 0.6 mm, and 0.45 mm (see table 1). The electrodes were configured in six-phase, which resulted in wavelengths of 7.2

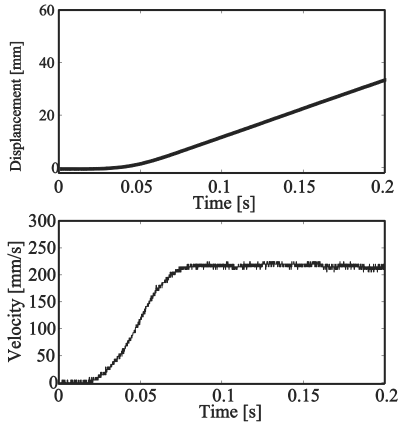

Fig. 4 Experiment setup with a displacement laser and measuring object.

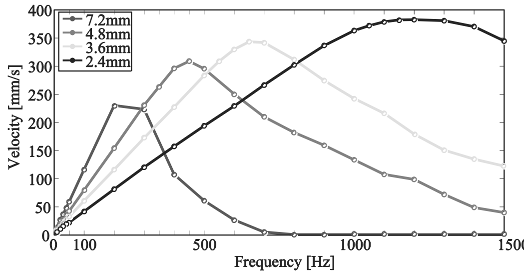

Fig. 5 Maximum velocity obtained for different applied frequencies and difference wavelengths

mm, 4.8 mm, 3.6 mm and 2.4 mm, respectively.

The specific design parameters are shown in table 1 and the definition is illustrated in figure 4. The electrode width was designed to keep a constant ratio against electrode pitch (see Fig. 3). Electrode height was designed the same for all the electrodes and was about 0.04 mm. An epoxy insulation layer of 0.254 mm thickness covers the electrodes. Glass beads of 100 µm diameter were scattered on the surface of the stator electrodes to lower the friction and create an air gap between the stator and slider. All the experiments were conducted inside a sealed volume with silica gel to keep a stable low-humidity condition.

4. Results and Discussions

Figure 4 shows a displacement data and calculated speed from one measurement. The measurement was repeated three times for each frequency. The maximum velocity was calculated for each measurement and averaged for the final results.

Figure 5 shows the measured maximum speed of the slider for applied frequencies from 0 to 1500 Hz with 0.7 $kV_{0\text{-}p}$ applied voltage. The maximum value displayed in figure 5 is the mean value of the three repeated measurements. The maximum speed of the slider reached 230 mm/s at a frequency of 300 Hz for the actuator with 7.2 mm wavelength, 309 mm/s at a frequency of 500 Hz for 4.8 mm traveling wave length, 344 mm/s at a frequency of 700 Hz for 3.6 mm and 383 mm/s at a frequency of 1300 Hz for 2.4 mm traveling wavelength. The optimum wave speed, which is calculated as a product of optimum frequency and wavelength, was found increasing as the wavelength decreases (see Fig. 6). In an ideal system, the maximum possible velocity should be the same throughout the boards, but achieved at a different frequency. From this data, the performance of the electrostatic actuator is higher with lower traveling voltage wavelength. However, it should be noted that the minimum pitch distance between electrodes is limited by physical constraints, as the shorter pitch distances gives higher chance of discharge.

The static force was measured for frequencies between 0 and 50 Hz. The steady state thrust force of the slider for all four traveling wavelengths is shown in figure 7. The maximum thrust force of 12.7 mN was generated by 2.4 mm traveling wavelength with a 12 Hz applied frequency. While 3.6 mm traveling wavelength generated 12.5 mN with at 8 Hz, 4.8 mm traveling wavelength generated 11.2 mN at 6 Hz and 7.2 mm traveling wavelength generated 7.5 mN at 5.5 Hz. The results almost follow the known performance curve for induction motors.

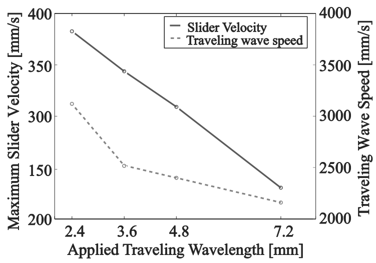

Fig. 6 Maximum velocity of slider and corresponding traveling wave speed for each traveling wavelength

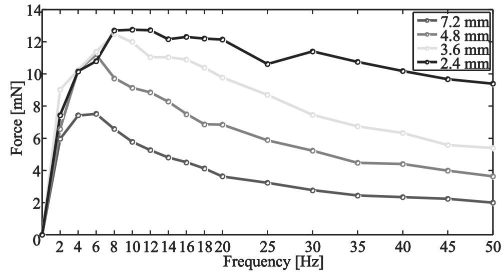

Fig. 7 Measured static thrust force for different applied frequencies

4. Conclusion

The experiment results showed that shortest traveling potential wave of 2.4 mm gave the best driving performance for PPC sheet actuation and the maximum velocity of the slider did not reach a common value between the different wavelengths. These results are valid only for stators with constant gap, constant electrode height of 0.04 mm and a constant 0.47 ratio between pitch and electrode width. Different designs should be investigated in the future.

Acknowledgements

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