TWO DIMENSIONAL DRIVE MOTOR WITH CIRCULAR CORE

N. Fujii and T. Kihara
Dept. of Electrical and Electronic Systems Eng., Kyushu University
Fukuoka, 812-81, Japan

SUMMARY

A surface induction motor is described that has smooth force for any directional drive including rotation, compared with other surface motors. This motor has a toroidal core with an armature winding as a primary member, and a secondary reaction plate composed of a conducting plate and a back iron plate. The thrust and normal force characteristics are studied by usinga test facility and two-dimensional electromagnetic analysis. This surface motor has a relatively high utilization factor for the thrust in spite of the circular shape. Compared with a single-sided linear induction motor, the performance of the magnetic circuit is the same or better, and the thrust is larger than that of two linear motors in a relatively small number of slots of the primary core. The large attractive normal force is suitable for magnetic suspension making use of the circular shape.

INTRODUCTION

Some motors called surface motors or planar motors for two-dimensional drive are being developed [1]-[3]. The authors have proposed the surface induction motor with a toroidal core as a primary core [4]. The secondary member is composed of a flat conducting plate with no directional qualities and a back iron plate as a secondary yoke. The primary member is composed of a toroidal core and armature winding which can be supplied current in every coil. Two types can be used for the method of armature winding; one of which is a ring winding supplied current at each slot and another of which is a double-layer winding supplied current to each coil.

In this paper, the basic structure of surface motorsand the simple type surface motor are shown respectively including the circuit for power supply. The thrust and normal force characteristics for linear motion are shown at standstill by using two-dimensional electromagnetic analysis [5], which are confirmed by experimental results. Characteristics for typical examples for current supply to the winding are studied for both double-layer winding type and ring winding type. To estimate the performance of the surface motor, it is compared with a single-sided linear induction motor. The effects of the thickness of conducting plate and the length of air gap are studied respectively. The distribution of normal force density is studied for the use of the magnetic levitation.

STRUCTURE AND WORKING PRINCIPLE OF THE SURFACE MOTOR

Figure 1 shows a schematic diagram of the surface induction motor. This motor has a toroidal core with armature winding as a primary member, and a secondary reaction plate composed of a conducting plate and back iron plate. In the figure the primary core is placed under the secondary plate to use the attractive normal force for magnetic levitation. The armature winding is supplied current in every coil in each slot for any directional motion. Two types of winding methods as shown in Figure 2 are conceivable. Figure 2(a) shows the (Gramme) ring winding. Figure 2(b) shows a double-layer winding as well as an ordinary axial-air-gap-type rotating motor.

The ring winding is a suitable method based on the operational principle of this surface motor although this winding is difficult to make. For rotating motion, all coils are used for ordinary rotating magnetic field in the same way as a rotating motor as seen in Figure 3(a). For linear motion, the winding is separated into two groups over each half of toroidal core for the axis of linear motion, then a partial traveling magnetic field is generated in every winding group as shown in Figure 3(b). In practical use, all windings will be supplied current for larger force even for a linear drive.

A conventional double layer winding also can be used, but each coil is supplied power independently. Figure 4 shows a sample of supply method of current for a linear motion. There is an overlap region of both windings around the axis of linear motion.

Figure 5 shows a basic power supply circuit for the surface motor with ring winding. Figure 6 shows a basic inverter circuit for the surface motor with double layer winding. The supplied power is controlled for each coil.

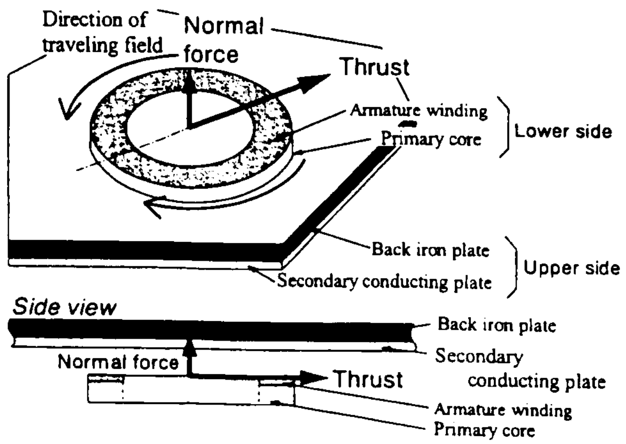
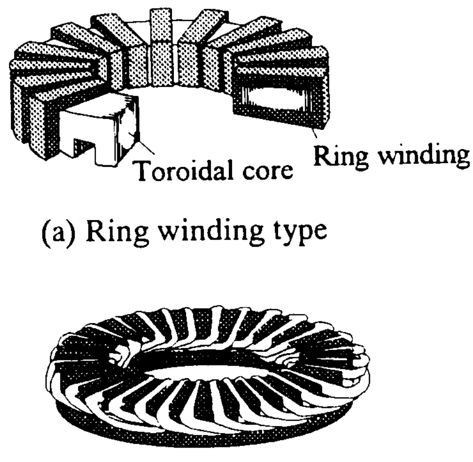


Fig. 1 Proposed surface induction motor.



(a) Ring winding type

(b) Double-layer winding type

Fig. 2 Primary member of the surface motor.

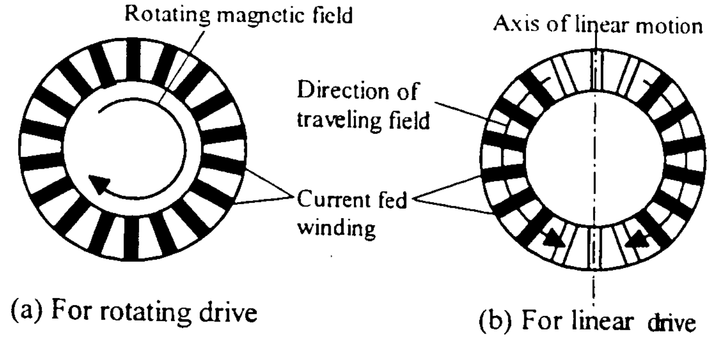


Fig. 3 Current supply method to armature windings.

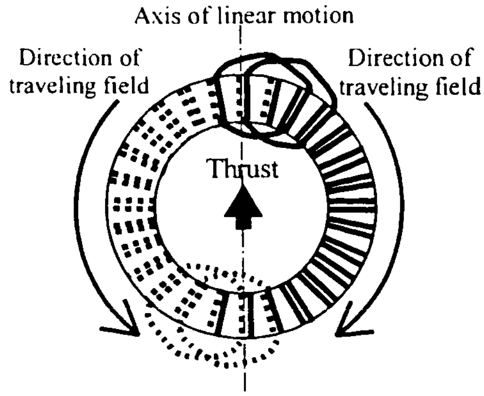


Fig. 4 Current supply method for double-layer winding type.

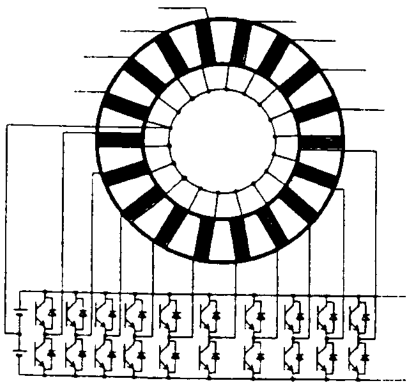


Fig. 5 Basic inverter circuit for the ring winding type.

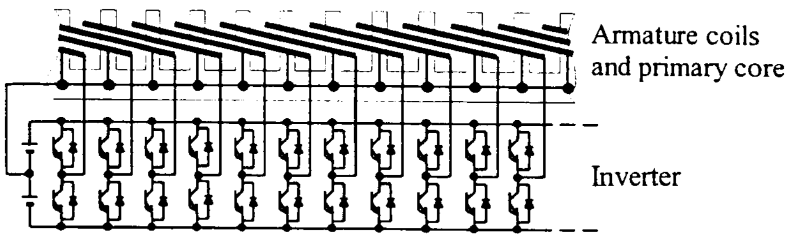
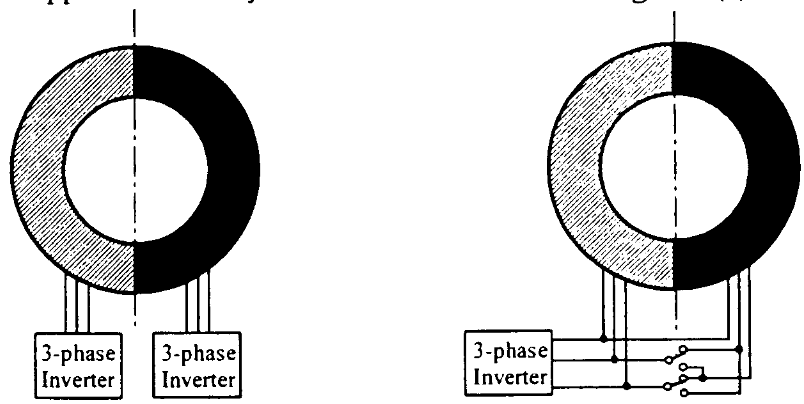


Fig. 6 Basic inverter circuit for the double-layer winding type.

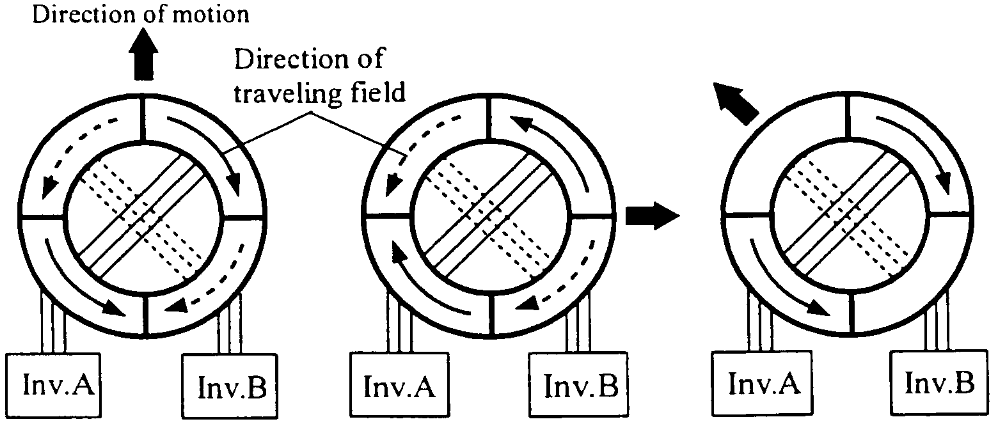
Simple Type Surface Induction Motor

By limiting the two functions of the linear drive as fixed direction translation and rotation, the simple forms are obtained as shown in Fig.7. The simple type has two groups of ordinary three-phase windings. In Figure 7(a), the current is supplied to two groups of windings from two inverters respectively, and each traveling field can be controlled individually. Figure 7(b) shows the method of supply by one inverter using a three-phase sequence changeover switch. For linear motion, each winding is excited to generate the different direction of traveling magnetic field, and for rotation the two groups of windings are excited to generate the rotating field over all.

Figure 8 shows the simple type surface motor with four groups of three-phase armature windings. Two groups of windings, related by diagonal position to each other, are connected. This type is also supplied three-phase current by two inverters to the two electrical groups of windings. For forward motion, the traveling field in each winding is generated in the direction shown in Figure 8(a). The necessary traveling field for the transverse motion is obtained by the change of only the three-phase sequence of Inverter A, as shown in Figure 8(b). For the diagonal motion, the current is supplied from only one inverter, as shown in Figure 8(c).



(a) Two inverters configuration (b) One inverter configuration
Fig. 7 Simple type for one direction linear motion and rotating motion.



(a) For forward motion (b) For transverse motion (c) For diagonal motion
Fig. 8 Simple type for three directions of linear motion.

NUMERICAL EXAMPLE AND ARRANGEMENT OF WINDING

This paper deals with the surface induction motor of the test facility. The number of slots is 24, and other detailed parameters are shown in Table 1. A three-phase supply is assumed for the armature winding. There are many different supplies for current. Figure 9 shows four examples of current supply to each coil for linear motion in the case of double-layer winding. Here the arrangement is expanded to a linear model. The name S4 means that the axis of linear motion is at the center of a slot and the coil arrangement is four poles per one-side winding. T3 means that the axis of linear motion is at the center of a tooth and the current-fed coil arrangement is three poles per one-side winding. In S4 and T4, right-side winding is marked by the gray color in order to clear the boundary.

Table 1 Numerical example for the surface motor.

Name	Numerals
Primary core	
Av. Diameter of core	D_a = 120mm
Width of core	h = 25mm
Height of core	d_c = 53mm
Width of tooth	w_t = 9.5mm
Width of slot	w_s = 6.5mm
Number of slots	N_s = 24
Armature windings	
Turns / coil	N_t = 69turns
Turns / slot	138 turns
Secondary	
Material of conducting plate	Copper
Thickness of the conductor	d_2 = 2mm
Thickness of back iron	d_1 = 5mm

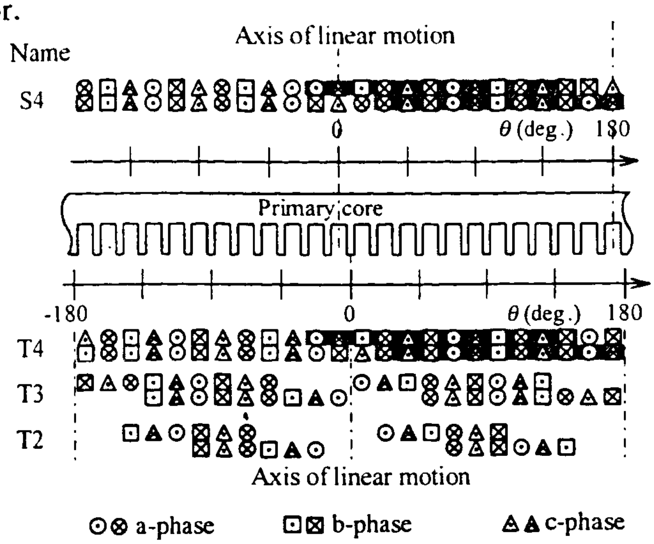


Fig. 9 Examples of three-phase current supply to each coil for linear motion.

CHARACTERISTICS OF THE SURFACE MOTOR

The following calculated values were obtained by using two-dimensional electromagnetic analysis using Fourier Series of surface current for the winding [5].

Flux Density Distribution

Figure 10 shows the distribution of magnetic flux density on the surface of the primary core in the direction of circumference for the case of type S4 without secondary plate. The measured values were obtained by using a Hall element. It is confirmed that the number of poles is four per one side. Large ripples appear in the distribution because of slot harmonics. The calculated values agree with the measured values.

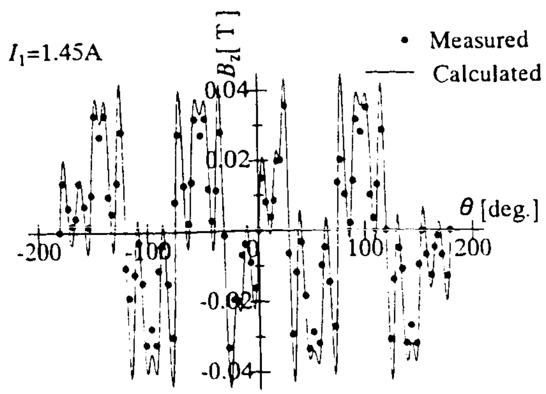
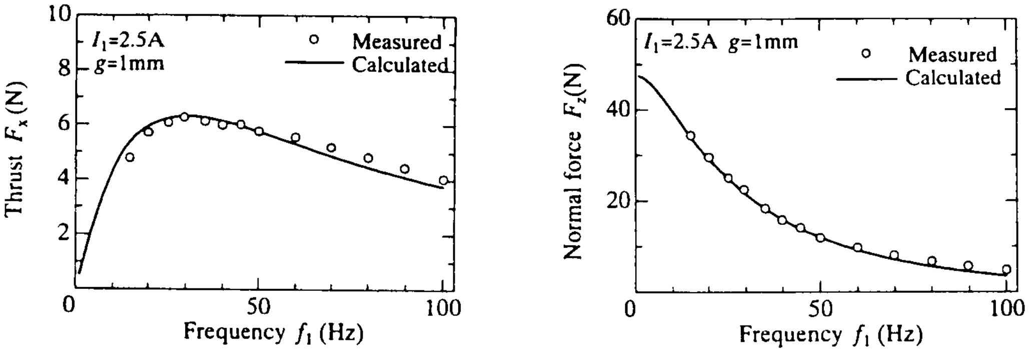


Fig. 10 Flux density distribution.

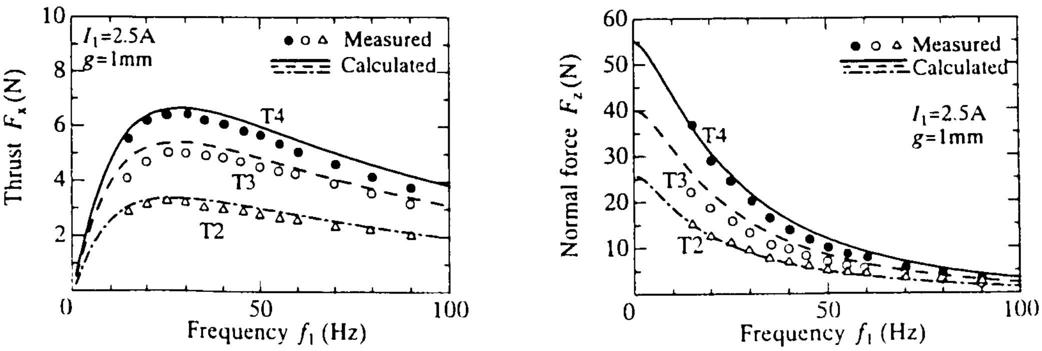
Figure 11(a) and Figure 11(b) show the thrust and the normal force characteristics respectively at standstill for linear drive operation for type S4. The condition is that the coil current is fixed at 2.5A and the air gap between the primary core and the secondary conducting plate is 1mm. The calculated values agree with the measured values. The thrust of more than 98% of the maximum thrust is obtained in the frequency range from 24Hz to 38Hz. The normal force is an attractive force between the primary core and secondary plate. The normal force decreases largely as frequency increases. The value of normal force varies from 25.9N to 17.0N in the frequency range of 24Hz to 38Hz. The ratios of the normal force to the thrust are 4.16 at 24Hz and 2.72 at 38Hz respectively. The ratio of the surface motor is generally larger than that of linear induction motor.



(a) Thrust (b) Normal force

Fig. 11 Thrust and normal force versus frequency for type S4 at standstill for linear drive.

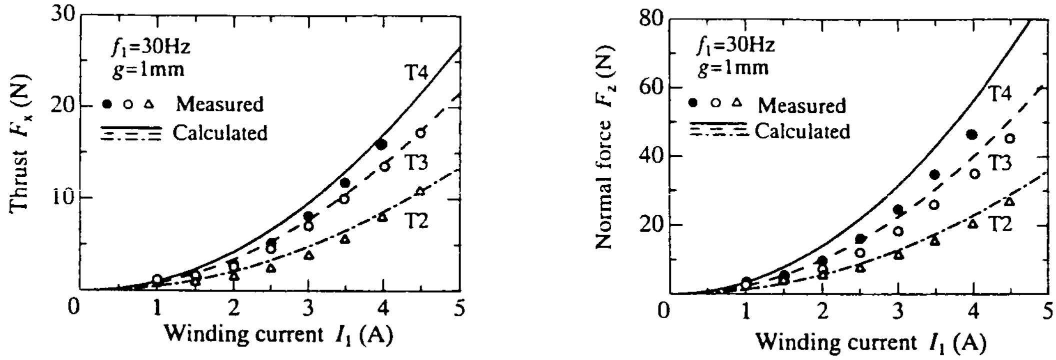
Figure 12 shows the force characteristics as functions of frequency for type T4, T3 and T2. In the thrust characteristics shown in Figure 12(a), the maximum thrust of T2 with two poles is about 1/2 of that of T4 with four poles in spite of different utilization factors for thrust. The maximum thrusts per one pole for T4, T3 and T2 are 1.67N, 1.81N and 1.69N respectively. That is, T4 is a worst case from the standpoint of utilization for thrust because of the circular core. In T2, it is a worst case for the arrangement of winding because of the large single-layer region. In the normal force in Figure 12(b), the attractive forces at 30Hz for T3 and T2 are 0.71 and 0.41 times respectively as large as that of T4.



(a) Thrust (b) Normal force

Fig. 12 Force – frequency characteristics for type T4, T3 and T2 respectively.

Figure 13 shows force characteristics as functions of current for type T4, T3 and T2. In Figure 13(a), the thrust increases in proportion to the square of current in this range. In the normal force shown in Figure 13(b), there is a quantitative difference between the calculated values and measured values because magnetic saturation is not considered in the analysis.



(a) Thrust (b) Normal force

Fig. 13 Force – current characteristics for type T4, T3 and T2 respectively.

This surface motor has two kinds of axes of linear motion, that is, one expressed by type S is at the center of slot and the other expressed by type T is at the center of tooth. Figure 14 shows the comparison the forces of type S4 and T4. In both thrust and normal force, the forces of S4 and T4 are almost equal. This is desirable because the force does not vary with the direction of motion.

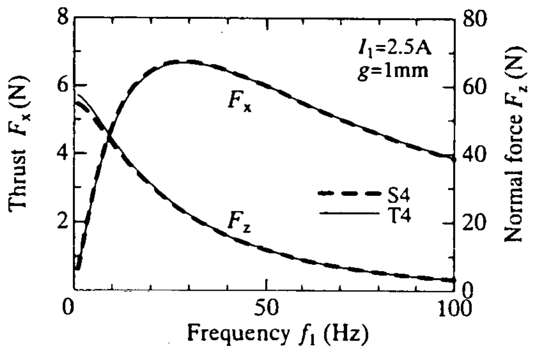


Fig. 14 Comparison between the forces of type S4 and T4.

Evaluation of the Thrust

Figure 15 shows the calculated utilization factor defined as a ratio of the thrust F_x to the tangential force F_t. The utilization factors for T4, T3 and T2 at 30Hz that gives maximum thrust are 74%, 83% and 90% respectively.

Figure 16 shows the ratio of thrust of the surface motor and that of single-sided linear induction motor as functions of total number of slots. The conditions are that the magnetomotive force of each coil, the slot pitch and the pole pitch are fixed at the values shown in Table 1 respectively for the double-layer winding. For two-dimensional motion using a conventional linear motor, four linear motors would be generally used, with two parallel motors used for every x- or y- directional motion. The solid line shows the ratio of thrust of the surface motor T4 to the total thrust of two linear motors with core length of half circumference of the toroidal core. The broken line shows for one linear motor with the length of circumference of the toroidal core. The thrust of the surface motor is larger than that for two linear motors in the number of slots 24 or less in spite of circular core because all slots are used effectively.

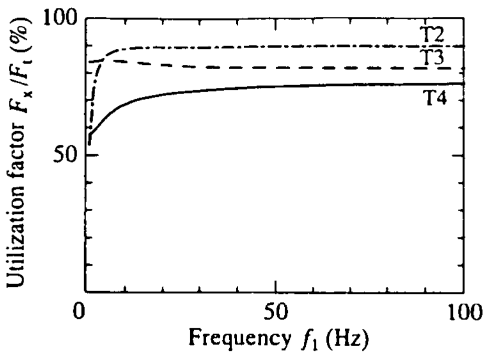


Fig. 15 Utilization factors of thrust for T4, T3 and T2 respectively.

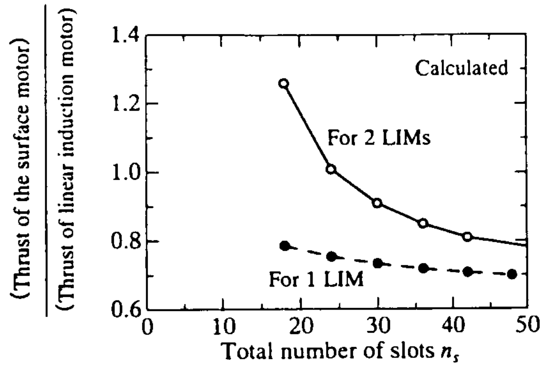
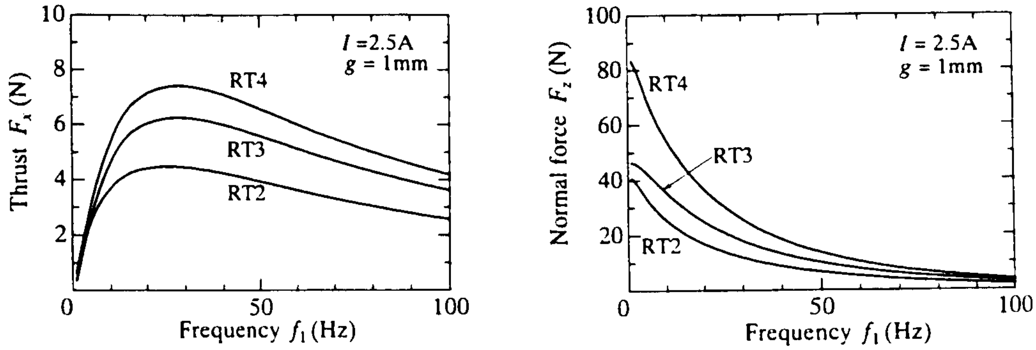


Fig. 16 Comparison between thrust for the surface motor and linear induction motor.

Forces for the Surface Motor with Ring Winding

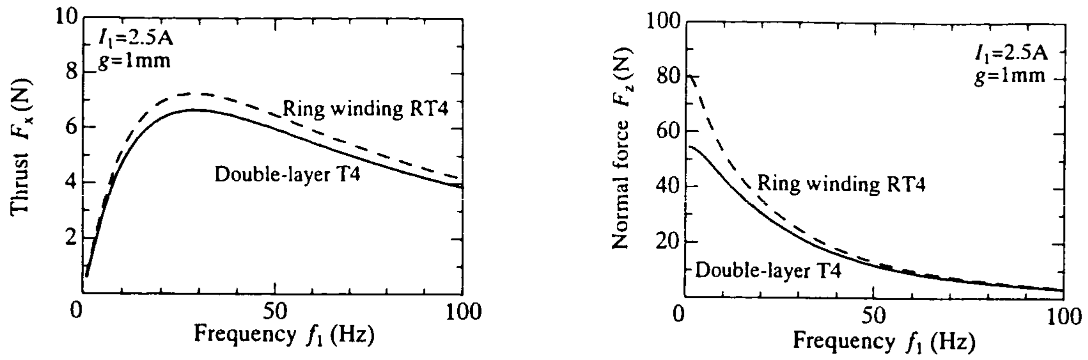
Figure 17(a) and 17(b) show the thrust and the normal force of the surface motor with ring winding respectively. The parameters are those of Table 1, the number of turns per coil is 138, equal to the number of turns per a slot in this case. RT4, RT3 and RT2 mean 4-pole, 3-pole and 2-pole supply of current respectively in the ring winding type. That is, all 24 coils are used for RT4 and 12 coils are used for RT2. The maximum thrusts of RT3 and RT2 are 0.84 times and 0.61 times of that of RT4, these ratios are larger than those for double-layer winding in Figure 12(a). The normal forces at 30Hz for approximately maximum thrust of RT3 and RT2 are 0.70 times and 0.46 times of that of RT4, these ratios are almost equal to those for double-layer winding in Figure 12(b).



(a) Thrust (b) Normal force

Fig. 17 Force characteristics of the ring winding type surface motor with 4-pole, 3-pole and 2-pole respectively.

Figure 18 shows the comparison between the forces of the double-layer winding type T4 and the ring winding type RT4.The ring winding type has about ten percent larger force for the maximum thrust and for the normal force at 30Hz respectively compared with the double-layer winding type.

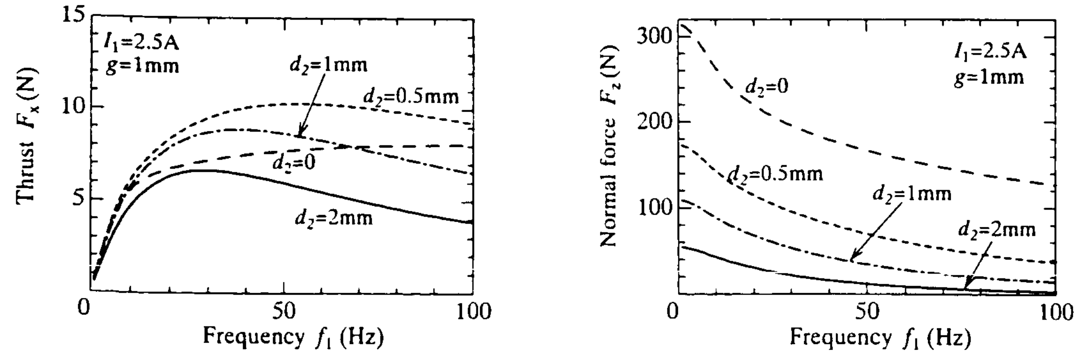


(a) Thrust (b) Normal force

Fig. 18 Comparison between forces of the double-layer winging type and the ring winding type.

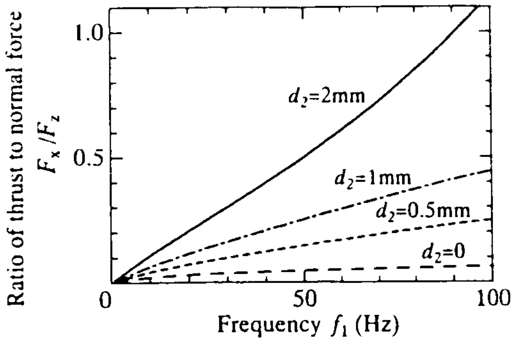
Effect of Thickness of Conducting Plate

Figure 19 shows the effect on the thrust and the normal force of the thickness of copper plate as a secondary conducting plate. The conditions are that the supply current is fixed at 2.5A in the type T4, the conductivities of copper and back iron are 5.273×10^7 S/m and 9.524×10^6 S/m respectively. The frequency at the maximum thrust for each thickness d_2 increases as the thickness decreases because the secondary resistance increases. The extreme value for maximum thrust is obtained at the conductor thickness of 0.5mm, as shown in Figure 19(a). The normal force increases as the conductor thickness decreases, as shown in Figure 19(b). The ratio of thrust to normal force for each conductor is approximately proportional to the frequency, as shown in Figure 19(c). The ratios for d_2 = 2mm and d_2 = 0.5mm at maximum thrust are 0.30 and 0.16 respectively.



(a) Thrust (b) Normal force

Fig. 19 Forces for various thickness of conducting plate.

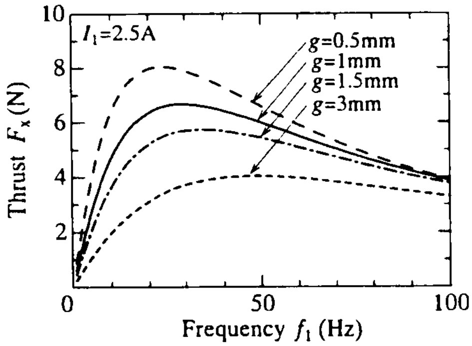


(c) Ratio of thrust to normal force

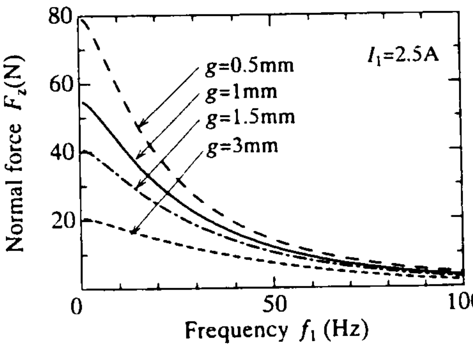
Fig. 19 Forces for various thickness of conducting plate.

Effect of Length of Air Gap

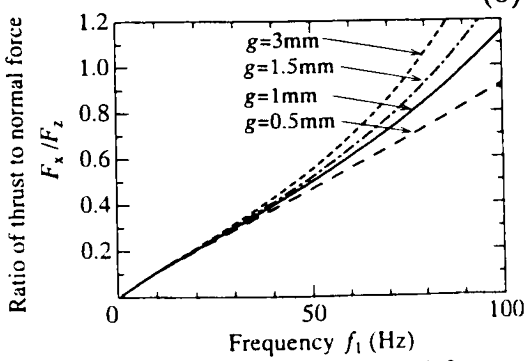
Figure 20 shows the effect on the thrust and the normal force of type T4 of the length of air gap. The current is fixed at 2.5A. The frequency at maximum thrust for each air gap increases about 5Hz each as the air gap decreases by 0.5mm, because the magnetizing reactance decreases. The maximum thrust at each air gap is 1.21 times for g=0.5mm, 0.86 times for 1.5mm and 0.61 times for 3mm compared to that for g=1mm, as shown in Figure 20(a). The effect of length of air gap on the normal force is larger than that on thrust, as shown in Figure 20(b). The normal force at each maximum thrust is 1.48times for g=0.5mm, 0.72times for 1.5mm and 0.33times for 3.0mm compared to that for g=1mm. The ratio of thrust to normal force is almost independent on the air gap in the frequency 40Hz and less, and is proportional to frequency as shown in Figure 20(c).



(a) Thrust



(b) Normal force

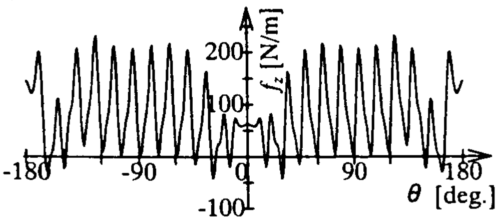


(c) Ratio of thrust to normal force

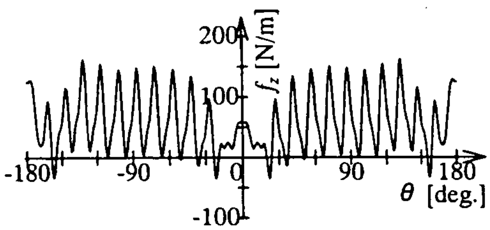
Fig. 20 Forces for various air gap

Distribution of Normal Force Density

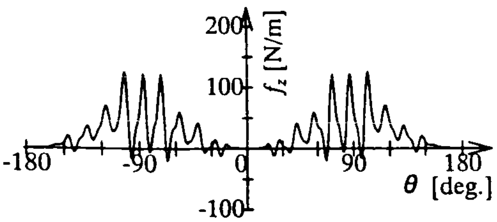
To use the large attractive type normal force for magnetic levitation , since this shape is suitable for stable suspension, the distribution of force density is studied. Figure 21(a), 21(b), 21(c) and 21(d) show the space distributions in the circumferential direction of the normal force of type S4,T4 T2 and RT4 respectively for the linear motion. The axis at $\theta = 0$ is the front end of motion on the axis of linear motion, and $\theta = \pm 180°$ is the rear end of traveling field on the axis of linear motion. All coils are supplied the same current of 2.5A. There is a difference between the distributions around the axis of linear motion for S4 shown in Figure 21(a) and T4 shown in Figure 21(b) because of the interference between two winding groups. In the case of a two-pole supply, there is no interference as shown in Figure 21(c). In the ring winding, the ripple appears in the distribution because of the influence of alternating magnetic field. In all types, the normal forces for right-side and left-side of the axis of motion are in equilibrium.



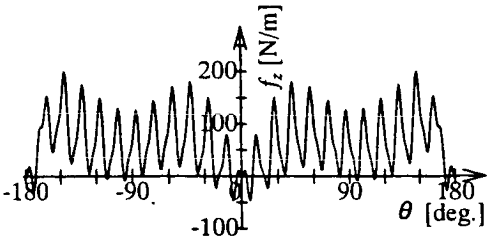
(a) Type S4



(b) Type T4



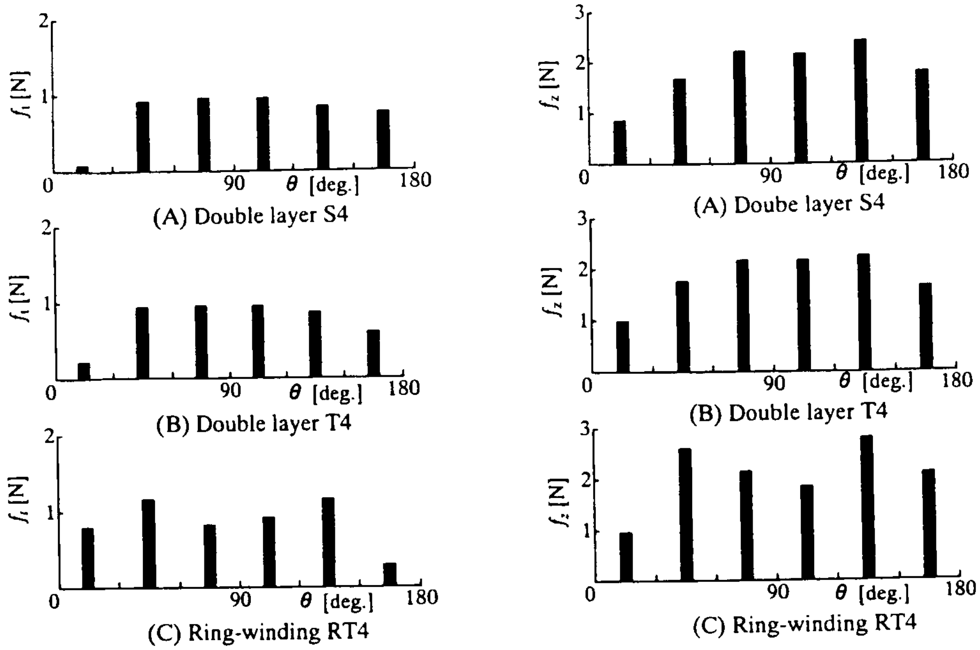
(c) Type T2



(d) Type RT4

Fig. 21 Distribution of normal force density in circumference direction in the case of linear motion.

Figure 22(a) and 22(b) show the distribution of the tangential force and the normal force respectively for every region of 30 degrees. In the tangential force, from which the thrust is produced, the force distribution around the middle of each group of winding is uniform for the double-layer winding S4 and T4. The tangential force distribution of ring winding is not uniform because of alternating field. On the other hand, the attractive normal force around the front end $\theta = 0$ is smaller than that around the rear end $\theta = \pm 180°$ in all types, as shown in Figure 22(b). Some technique will be required for the magnetic levitation.



(a) Tangential force (b) Normal force

Fig. 22 Distribution of force for every region of 30 degrees.

CONCLUSIONS

This surface induction motor has the following good characteristics, although the driving circuit is complicated.

1. The quality of the magnetic circuit is the same or better compared with that of a linear induction motor.
2. This surface induction motor has a relatively high utilization factor of 74% or more for thrust in spite of a circular core.
3. The thrust is larger than that for two linear motors with length of semicircle of the toroidal core in relatively small number of slots 24 or less.
4. There is little difference in thrust and normal force for any directional motion.
5. As the ratio of normal force to thrust is large, the attractive normal force should be used for magnetic suspension making use of the circular shape.

ACKNOWLEDGMENT

This study has been supported partially by the Grant-in-Aid for Scientific Research (B) from the Ministry of Education, Science, Sports and Culture of Japan.

REFERENCES

[1] Y. Ohira, Y. Yamamoto, K. Takeuchi, H. Yamada: "Magnetic Circuit Analysis of X-Y Linear Induction Motor", Trans. IEE of Japan, Vol.109-D, pp.675-681 (1989)

[2] D. Ebihara, T. Watanobe, M. Watada: "Approximated Three-dimensional Analysis of Stepping Surface Motor", Trans. IEE of Japan, Vol.114-D, pp.1235-1241 (1994)

[3] D. Trumper, W. Kim, M. E. Williams: "Design and Analysis Framework for Linear Permanent-Magnet Machines", IEEE Trans. on IA, Vol.32 pp.371-379 (1996)

[4] N. Fujii, K. Nishimura, Y. Imazu: "Surface Induction Motor for Two-dimensional Plane Drive Including Rotating Operation", National Convention Record IEE Japan - Industry Application Society, No.211, pp.899-903 (1994)

[5] N. Fujii, T. Kihara, M. Fujitake: "Electromagnetic Analysis of Surface Induction Motor", IEE of Japan Technical Meeting on Linear Drives, LD-97-51, pp.33-38 (1997)