Design Method for Ultralightweight Motor Using Magnetic Resonance Coupling and its Characteristics

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In this paper, we propose a design method for a novel motor using magnetic resonance coupling (MRC) to enable the practical use of electric aircraft. The proposed motor can transfer electrical energy between a stator and a rotor via MRC, which does not require magnetic cores, thus realizing an ultralightweight design. Moreover, we detail the operating characteristics of the proposed motor and its equivalent circuit, analysis, and experiments. From the analysis, we clarify that the proposed MRC motor has a sufficient strength at an ultrahigh speed, and we describe its essential characteristics and the usefulness of its equivalent circuit. Further, our analytical and experimental results confirm that the proposed MRC motor can transfer electrical energy between a stator and a rotor, thereby generating torque.

Keywords: aircraft, coreless, electric vehicle, induction motors, light weight, magnetic resonance

1. Introduction

Recently, electric aircrafts have been significantly studied as next-generation energy-saving aircrafts. However, for the practical realization of electric aircrafts, significant improvements in the power density of their propulsion motors are required, for which it is essential to reduce the weight and increase the power of electric propulsion motors. With conventional motors, heavy magnetic cores are required to obtain high outputs, leading to a contradiction between the weight and power output requirements of motors. In this study, to simultaneously realize an ultralightweight design and a high-power motor, we proposed a novel technology combining the theory of magnetic resonance coupling (MRC) and an induction motor. Kurs et al. proposed a novel technology that can transfer electromagnetic energy between two separated coils via electromagnetic resonance coupling (1). Moreover, Sakai et al. (2-13) proposed a novel motor in which energy is converted through MRC between the three-phase windings of a stator and a rotor, and they also used the conventional induction motor technology.

In this paper, we described the principles, equivalent circuit, and analytical and experimental characteristics of the MRC motor technology.

The essential characteristics of the proposed MRC motor were analyzed through an equivalent circuit method and an electromagnetic field analysis. The MRC motor could achieve high output without heavy magnetic cores by utilizing the action of MRC. Moreover, the calculation results of the equivalent circuit method and performed magnetic field analysis agreed well, and the usefulness of the equivalent circuit method was confirmed. Furthermore, through experiments, it was confirmed that the MRC motor can be driven by the energy conversion between a stator and a rotor without using iron cores (magnetic cores). These characteristics showed values close to the calculation results.

![Conceptual schematic of a magnetic resonance coupling motor](image)

\[ \omega_1 = s \omega_1 + \omega_r \]

(a) Axial flux type

(b) Radial flux type

Fig. 1. Conceptual schematic of a magnetic resonance coupling motor.

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of an equivalent circuit method under certain conditions.

2. Principles and Behavior of the MRC Motor

The MRC motor is a novel motor that can perform energy conversion without iron cores (magnetic cores)\(^{12-13}\), and its operating principle combines the energy transfer technologies of MRC and induction motors. Basically, an induction motor transmits energy through the electromagnetic induction between a primary side and a secondary side through an air gap. In contrast, a magnetic coreless motor cannot transmit sufficient energy through electromagnetic induction because it is only composed of nonmagnetic materials, such as fiber-reinforced plastic (FRP) frames and copper wires. In other words, in a magnetic coreless motor, the leaked magnetic flux is very large, which is a significant low power factor. Also, secondary currents, which would be necessary for generating torque, cannot be sufficiently induced. Therefore, MRC is used to achieve high magnetic flux density without magnetic cores. Also, MRC is a technology that enables wireless energy transmission with high efficiency, even in spaces with low coupling coefficients. For example, the magnetic resonance phenomenon can be realized by connecting resonant capacitors to each of a power transmission coil and a power receiving coil, indicating that energy transmission is possible even between two air-core coils. Also, in an MRC motor, energy conversion can be performed without magnetic cores by applying MRC to the induction motor technology. In particular, this can be realized by connecting resonant capacitors to the primary windings and secondary windings of an MRC motor, causing the resonance phenomenon.

The resonance frequency is the power-supply frequency on the primary side, and the slip frequency is that on the secondary side. However, the angular frequency of the primary power supply is the sum of the secondary rotational angular frequency and slip angular frequency. Figure 1 shows the concept and basic configuration of an MRC motor. As shown in Figs. 1 (a) and (b), the two structures of the axial flux type and radial flux type motors can be considered. In the axial flux type MRC motor, the gap surfaces of the primary coil and secondary coil are on the same surface of the MRC motor, so the operational principle can be easily understood. In the radial flux type motor, since the coil can be expanded in the axial direction at the same motor outer diameter, the facing area of the primary side coil and secondary side coil increases. Therefore, in this paper, we used the radial flux type MRC motor.

The resonant capacitor values of the primary side and secondary side were determined by the inductance and resonance frequency of each coil. The primary side and secondary side comprise nonmagnetic materials, and the proposed MRC motor mainly consists of coils and resonant capacitors, making it ultralight.

3. Equivalent Circuit Method of the MRC Motor

In this section, we described an equivalent circuit of the novel MRC motor to qualitatively evaluate its characteristics by comparing the equivalent circuits of the induction motor and MRC.

Figure 2 shows a T-type equivalent circuit of the MRC motor in the case of using a constant current power source with a current value \(I_1\). As shown in the figure, the circuit comprises primary and secondary winding resistances, a mutual inductance coupled with windings, primary and secondary leakage inductances, primary and secondary main inductances, and primary and secondary capacitors that induce the resonance phenomenon. Moreover, by comparing the equivalent circuits of the induction motor and MRC motor, that of the MRC motor had no equivalent iron loss resistance and had a resonant capacitance. The T-type equivalent circuit of the MRC motor is based on a T-type transformer of an electric circuit theory. Further, the capacitors to resonate at the source and slip frequencies are added to the primary and secondary circuits, respectively. However, the frequency of the secondary circuit of the rotor is different from the power-supply frequency of the primary circuit as the stator because the frequency of the secondary circuits is a slip frequency. Thereafter, all circuit constants in the secondary circuit are divided by slip of “s” to obtain the equal frequency.

In the equivalent circuit of Fig. 2, \(l_1\) and \(l_2\) denote the primary and secondary leakage inductances, \(L_{10}\) and \(L_{20}\) are the primary and secondary main inductances, respectively, and \(M\) is the mutual inductance resulting from the magnetic flux interlinking between the primary and secondary windings. Among the interlinkage magnetic flux between the primary and secondary windings, the inductance resulting from the magnetic flux generated by the primary winding is the primary main inductance \(L_{10}\). Similarly, the magnetic flux generated by the secondary winding is regarded as the secondary main inductance \(L_{20}\). In other words, the relationship between the main inductances \((L_{10} \text{ and } L_{20})\), leakage inductances \((l_1 \text{ and } l_2)\), and self-inductances \((L_1 \text{ and } L_2)\) can be expressed by Eq (1) for both the primary and secondary sides. Further, \(r_1\) and \(r_2\) are the primary and secondary winding resistances, \(C_1\) and \(C_2\) are the primary and secondary resonant capacitances, respectively, \(s\) is the slip, and \(\omega\) is the angular frequency of the power supply. However, since the influence of the eddy current of the copper wire was not considered, the alternating current loss generated in the strand of the coil conductor at high-frequency driving was not considered. Also, the eddy current loss generated in the metal parts of
the peripheral parts, such as the shaft and bearing, was not considered. The winding resistances \((r_1\) and \(r_2\)) had the same values of those used in the magnetic analysis using the finite element method (FEA), as described in the next section. In addition, the self-inductances \(L_1\) and \(L_2\), mutual inductance \(M\), and leakage inductances \(l_1\) and \(l_2\) had the values obtained using FEA.

The resonance capacitances \((C_1\) and \(C_2\)) were obtained from the self-inductance \(L_1\), and \(L_2\) was obtained from FEA and the resonant frequency using Eq (2). The resonant frequency on the primary side is the power-supply frequency, and the resonant frequency on the secondary side is the slip frequency. The synthetic impedance \(Z\), which can be viewed from the primary side of the equivalent circuit of Fig. 2, can be represented by Eq (3) when it is deformed using Eq (1). When the synthetic impedance \(Z\) of Eq (3) is divided into a real part and an imaginary part, they can be represented as Eqs (4) and (5), respectively. Since the resonant capacitances \((C_1\) and \(C_2\)) are based on the conditions shown in Eq (2), Eqs (4) and (5) can be rearranged as Eqs (6) and (7). From Eqs (6) and (7), the impedance is only the real part, and the imaginary part is zero, as the resonant capacitor is connected and the resonance phenomenon is occurring. Using Eqs (6) and (7), the impedance \(Z\) becomes as in Eq (8). From Eq (8), the impedance is only composed of the mutual inductance and winding resistances. In short, the impedance of the MRC motor is composed of the effective component of the resonance phenomenon. Thus, the MRC motor is capable of driving because the impedance is only the effective component regardless of the magnetic coreless motor. Normally, in magnetic coreless motors, the impedance of the leakage magnetic flux is enormous, and the low power factor and torque are significant issues. Since this equivalent circuit uses a constant current power source, the primary line to the line voltage \(V_1\) can be represented by Eq (9) based on the impedance \(Z\) and the primary current \(I_1\). From Eq (9), the primary voltage is expressed using the effective impedance.

Next, the torque \(T\) is expressed by Eq (10). As shown in Eq (10), \(P_m,\omega_m,\) and \(p\) denote the mechanical output power, rotational angular frequency, and number of poles, respectively. From Eq (10), the torque is obtained by dividing the mechanical output power by the rotational angular frequency. The rotational angular frequency is represented by multiplying \(2\pi/60\) by the speed formula of the induction motor. The mechanical output power is as shown in Eq (11). In particular, the mechanical output power is the equivalent mechanical output power resistance multiplied by the square of the secondary current. Herein, the quality factor of the primary and secondary windings is shown in Eq (12), and it is determined based on the power-supply angular frequency, self-inductance, and winding resistance. Moreover, the quality factor \(Q\), which integrates the quality factors \(Q_1\) and \(Q_2\) of the primary and secondary windings, respectively, is defined as in Eq (13). Further, the square of the mutual inductance \(M\) is used with the coupling factor \(k\), quality factors \((Q_1, Q_2,\) and \(Q)\), winding resistances \((r_1\) and \(r_2))\), and power-supply angular frequency \(\omega\), as shown in Eq (14). Eq (15) shows

\[
\begin{align*}
L_1&=L_1 \\
L_2&=L_2 \\
C_1&=\frac{1}{\omega L_1} \\
C_2&=\frac{1}{(s\omega)^2 L_2} \\
Z&=r_1+j\left(\omega L_1 - \omega M - \frac{1}{\omega C_1}\right) + j\omega M \left(\frac{(r_1^2 + (\omega L_2 - \omega M - \frac{1}{s\omega C_2})^2}{s} + \frac{(\omega M)^2 r_2}{s}\right) \\
Re(Z)&=r_1 + \frac{s(\omega M)^2}{r_2} \\
Im(Z)&=j\omega L_1 - \omega M - \frac{1}{\omega C_1} + \frac{s(\omega M)^2}{r_2} + \frac{\omega M}{s} + \frac{\omega M^2}{s} + \frac{(\omega M)^2}{s} \\
Q_1&=\frac{\omega L_1}{r_1} \\
Q_2&=\frac{\omega L_2}{r_2} \\
M^2&=\left(k\sqrt{Q_1 Q_2}\right)^2 \frac{\pi r_2}{r_2} = \left(kQ\right)^2 \frac{\pi r_2}{r_2} \\
W_{C_1}&=3r_1 I_1^2 \\
W_{C_2}&=3r_2 I_2^2 \\
I_2&=\frac{\omega M}{r_2} I_1 \\
T&=\frac{3}{2}\frac{1}{s} \frac{r_1 I_1^2}{r_2} = \frac{3(\omega M I_1)^2}{r_2} \frac{1}{s} \frac{r_1 I_1^2}{r_2} \\
S_1&=\sqrt{3} V_1 I_1 \\
P_1&=P_m + W_{C_1} + W_{C_2} \\
\eta_m&=\frac{P_m}{P_1} \\
\eta_m&=\frac{3(\omega M I_1)^2}{3r_1 I_1^2 + 3(\omega M I_1)^2} \frac{1}{s} \frac{r_1 I_1^2}{r_2} \frac{1}{s} \frac{r_1 I_1^2}{r_2} \frac{1}{s} \frac{(\omega M)^2}{s} \frac{1}{s} \frac{(\omega M)^2}{s} \frac{1}{s} \frac{(\omega M)^2}{s} \\
\end{align*}
\]
the primary and secondary copper losses. In the equivalent circuit of Fig. 2, only the DC copper loss is considered. Here, because the MRC motor has no magnetic cores, no iron losses are present. Moreover, using the fact that the effective power of the secondary circuit calculated using Eq (8) and the primary current \( I_1 \) is equal to the power calculated using Eqs (11) and (15), the secondary current \( I_2 \) is calculated as shown in Eq (16). From Eq (16), the secondary current is formed by the slip, power-supply angular frequency, mutual inductance, secondary winding resistance, and primary current. In this equivalent circuit, the mutual inductance and secondary winding resistance are constant values. Thus, in the case of using the constant current power source, the secondary current depends on the slip frequency (secondary frequency). When Eq (10) is rearranged using Eqs (11), (14), and (16), the torque is expressed using Eq (17). From Eq (17), the torque is proportional to the square of the primary current. In other words, the MRC motor can easily obtain the torque by increasing the input current at the operation point at which torque is required. The primary apparent power is shown in Eq (18), and it is expressed by the product of the primary voltage \( V_1 \) and primary current \( I_1 \). Next, the primary active power is expressed by Eq (19) using the mechanical output power and the primary and secondary losses. The motor efficiency is expressed by Eq (20) using Eqs (11), (15), and (19). From Eq (20), the efficiency \( \eta_m \) of the MRC motor depends on the slip frequency. In short, the peak point of the MRC motor efficiency depends on the slip frequency in spite of the same rotational speed. The power factor \( PF \) is represented as in Eq (21) using Eqs (18) and (19). From Eq (21), the power factor of the MRC motor is 1.0. This is because the imaginary part of the impedance becomes zero, as in Eq (7), by connecting the capacitance defined by Eq (2) to the winding of the motor.

In the next section, we studied the characteristics of the MRC motor using the equations described above.

4. Analytical Investigations of the MRC Motor

In this subsection, analytical models are described. The analytical models are radial flux motors with wound rotors, and the primary and secondary three-phase windings are distributed windings. The shape of the rotor is assumed to be a cylinder with only a space for the coil. The cylindrical rotor comprises a fiber-reinforced composite material and supports the rotor winding and capacitors.

Furthermore, the MRC motor was driven to a high frequency of about \(-9\) kHz. Since no magnetic cores were used, no iron losses occurred. However, eddy currents were generated in the conductor strands of the winding, causing an AC copper loss. Therefore, we performed two types of magnetic field analysis by considering and not considering the AC copper loss. Figures 3 and 4 show analytical models, where Fig. 3 shows a model not considering the AC copper loss, and Fig. 4 shows a model considering it. The difference between Figs. 3 and 4 is whether or not the strand is modeled. In the model of Fig. 4, to equalize the alternating current impedance of the strands constituting one turn, the strands were transferred. The analytical model is 1/8 of the whole model, and the number of primary and secondary slots and the coil pitch are the same. Therefore, at the time of the strength analysis, it is 1/4 model of the whole one. The numbers of the elements in the case of the mesh division of the models of Figs. 3 and 4 are 23,049 and 210,451, respectively. A strength analysis and a two-dimensional steady-state magnetic field analysis were performed in J MAG, which is a finite element magnetic field analysis software. For the MRC motor, when a steady-state analysis was performed, it was confirmed that the steady-state value obtained by conducting a transient response analysis after passing through the transient state from the startup to the steady-state rotation stages almost agrees with the steady-state value. The reason is that the
characteristics linearly change because no magnetic materials were used.

It can be seen from Figs. 3 and 4 that the ratio of the rotor outer diameter to the stator outer diameter is higher than that of conventional motors with magnetic cores. Conventional motors are designed with the ratio of 0.5–0.6. In contrast, the ratio of the analytical model of the MRC motor is 0.88. This ratio causes an increase in effective inductance and magnetic flux linkage because the cylindrical area of the mechanical air gap on the surface of the rotor is large. Moreover, the ratio of the leakage flux to the total flux decreases owing to the cylindrical area of the mechanical air-gap part. Further, the MRC can select a significantly high ratio because no magnetic saturation is present in the stator core. The MRC motor has a nonmagnetic material in the part corresponding to the magnetic cores, and it also has low thermal conductivity. However, since magnetic cores are unnecessary, they are considered to directly cool the coil by providing a flow path of a cooling medium around it.

Figure 5 shows an analytical circuit when the AC copper loss is not taken into consideration. The power source uses a constant current power source, and a resonant capacitance is connected in series to the primary and secondary windings.

Table 1 shows the specifications of the analytical model. The calculation of the primary self-inductance was obtained from the induced voltage generated in the primary winding by flowing a constant current through the primary winding. The secondary winding was then opened, and the rotor (secondary side) became stationary. The calculation of the secondary self-inductance is the same as the calculation of the primary self-inductance, and the primary winding was open. Also, the primary and secondary leakage inductances and the mutual inductance were determined from the short circuit inductance, which was determined from the induced voltage generated in the primary winding when the secondary winding was shorted and a constant current flowed in the primary winding.

### 4.2 Strength Analysis

When the motor rotates, a centrifugal force acts on the rotor. In particular, since an MRC motor is assumed to rotate at an ultrahigh speed of ~100,000 rpm, it is necessary to evaluate the mechanical strength. The centrifugal force is proportional to the mass of the rotor and the square of the velocity. Table 2 shows the conditions of the strength analysis, and Fig. 6 shows the von Mises stress distribution when using a copper wire. The analytical model is a quarter model of the rotor, and the speed is 100,000 rpm. The maximum tensile strength of FRP is generally 3.5 GPa, and it produces up to 7 GPa.

Figure 6 shows that the MRC motor has sufficient strength, even when driven at 100,000 rpm. From this result,
the characteristics were examined at a rotational speed of about 100,000 rpm in the following sections.

4.3 Calculation Results of the Equivalent Circuit Method

From subsection 4.2, the MRC motor showed to have sufficient strength at a rotational speed of 100,000 rpm. In this subsection, the characteristics of the MRC motor were examined using the equivalent circuit method. In particular, from Eq (21), the efficiency of the MRC motor depends on the slip frequency. Then, the characteristics were examined using the equivalent circuit method, where various constants (inductance, winding resistance, etc.) of the analytical model of Fig. 3 were used. The mechanical output power and efficiency results calculated using the equations of the equivalent circuit are described in Section 3, and the constants of Table 1 are shown in Fig. 7, which demonstrates the MRC motor characteristics at different slip frequency values at six kinds of rotational speed. In Fig. 7, the rotational speed was fixed and the slip frequency was varied. Herein, the input primary current was 48 A with a current density of approximately 10 A/mm². Table 3 shows the characteristic values at the slip frequency with the highest efficiency.

From Fig. 7 (a), the mechanical output power increased in proportion to the slip frequency because the secondary current increased in proportion to the slip frequency (Eq (11)). Since the torque is proportional to the secondary current, it increased in proportion to the slip frequency. Here, the mechanical output power is the product of the torque and the rotational angular velocity. Then, since the rotational velocity was constant, it was proportional to the torque. That is, the mechanical output power was proportional to the slip. Also, the mechanical output power was increasing in proportion to the speed because the secondary current and torque do not depend on the speed. As described above, since the mechanical output power is the product of the torque and speed, the mechanical output power increased in proportion to the speed under constant torque.

From Fig. 7 (b), the efficiency had an extremum at the slip frequency. This is because, as described above, both the mechanical output power and secondary current increased in proportion to the slip frequency. Since the MRC motor does not use magnetic cores, the electrical and magnetic losses were only those of the copper losses. In this subsection, since the equivalent circuit was used, the considered losses were the primary and secondary DC copper losses. The DC copper loss is expressed by the winding resistance and the square of the current. Therefore, the primary and secondary winding resistances and the primary current were constant with respect to the slip frequency, and only the secondary current was proportional to the slip frequency. Therefore, the primary copper loss was constant with respect to the slip frequency, and the secondary copper loss was proportional to the square of the primary current from the above results. It was considered that the efficiency had an extremum because the mechanical output power increased in proportion to the slip frequency, the primary copper loss was constant, and the secondary copper loss increased in proportion to the square of the current.

From Table 3, the slip frequency at which the efficiency was highest was approximately the same at each rotational speed. Further, the value of the highest efficiency increased with the increase in the rotational speed. This is because the slip frequency, which is the highest efficiency, was almost the same at each rotational speed and it yielded to the same torque and the same secondary copper loss. Then, the output power increases in proportion to the rotational speed with the constant secondary copper loss. Also, a smaller slip with increase in rotational speed means that the efficiency increases with increase in rotational speed.

Table 3. Calculation results using the equivalent circuit method at the slip frequency with the highest efficiency.

| Rotational speed (rpm) | 20,000 | 40,000 | 60,000 | 80,000 | 100,000 | 120,000 |
|------------------------|--------|--------|--------|--------|---------|---------|
| Power supply frequency (Hz) | 1520 | 2850 | 4185 | 5520 | 6850 | 8185 |
| Slip | 0.1228 | 0.06433 | 0.04421 | 0.03382 | 0.02676 | 0.02260 |
| Slip frequency (Hz) | 186.66 | 183.33 | 185 | 186.66 | 183.33 | 185 |
| Secondary current (A) | 6.436 | 6.321 | 6.379 | 6.436 | 6.321 | 6.379 |
| Torque (Nm) | 2.74 | 2.69 | 2.72 | 2.74 | 2.69 | 2.72 |
| Mechanical output power (kW) | 5.74 | 11.2 | 17.1 | 23.0 | 28.2 | 34.2 |
| Efficiency (%) | 77.9 | 87.6 | 91.4 | 93.4 | 94.6 | 95.5 |
4.4 Magnetic Field Analysis Without the AC Copper Loss

By the inductance of each winding and the resonant capacitance, the MRC motor resonated at the power-supply frequency on the primary side and at the slip frequency on the secondary side, thereby improving the power factor and enabling operation with sufficient output. The following two methods can be considered as the necessary MRC motor operation methods for obtaining sufficient output. The first method is varying the resonant capacitance on the secondary side according to the varying of the slip frequency while keeping the power-supply frequency fixed. The second method is varying the resonant capacitance on the primary side according to the varying of the power-supply frequency by retaining constant control of the slip frequency. Here, it is technically difficult to vary the capacitance on the secondary side. Therefore, the constant control of the slip frequency was kept, and the secondary side was examined using the resonance operation method in the overall operation region without varying the secondary resonant capacitance. The primary side varies the capacitance according to the varying of the power-supply frequency.

In this subsection, we discussed the analysis of the case in which the AC copper loss was not taken into consideration, as shown in Table 4. The rated rotational speed was 100,000 rpm, at which the MRC motor had sufficient strength. In addition, the slip frequency was kept constant at a value at which a sufficient torque could be obtained in the vicinity of the slip frequency, which was the highest obtained efficiency, as described in subsection 4.3. The slip frequency was a value at which ~20 Nm of torque could be generated when the primary current was maximum. When the slip frequency was kept constant and the rotational speed was increased, the power-supply frequency varied. Therefore, the primary resonant capacitance varied in accordance with the varying power-supply frequency. This way, both the primary side and secondary side had resonance. The maximum current density was about 25A/mm², which is a proven value when using water cooling and oil cooling in the motors of electric and hybrid vehicles. Also, the primary voltage varied with the input current at a range of up to ~1 kV.

Figure 8 shows the results of the magnetic field analysis and the calculation results of the equivalent circuit. In Fig. 8, “_FEA” indicates the magnetic field analysis results, and

| Table 4. Conditions of the magnetic field analysis without the AC copper loss. |
|-----------------------------|-----------------------------|
| Rotational speed (rpm)      | 0–125000                    |
| Frequency (Hz)              | 223.33–8556.8               |
| Slip                        | 0.0261–1                    |
| Slip frequency (Hz)         | 223.33                      |
| Primary resonant capacitance (µF) | 2.480–3641               |
| Secondary resonant capacitance (µF) | 49.89                |
| Input current (A)           | 93.7–120                    |
| Maximum primary voltage (V) | 1055                        |

Fig. 8. Results of the magnetic field analysis without the AC copper loss.
the other names of markers indicate the calculation results obtained using the equivalent circuit. The characteristic analysis result is an average value of three analysis results at which the position of the rotor was 0°, 3.75°, and 7.5°, with 0° being the state at which the primary winding and secondary winding are completely opposed.

As shown in Fig. 8, the calculation results of the equivalent circuit method and magnetic field analysis when the AC copper loss was not considered agree well, thus proving the usefulness of the equivalent circuit. As shown in Fig. 8(a), the power factor was 1.0 in the overall rotational speed regions. Since this is slip frequency constant control, the secondary resonant frequency was kept constant. Therefore, the secondary side resonated in the overall rotational speed regions even when the secondary capacitance was fixed. Also, the primary capacitance varied according to the varying of the power-supply frequency. Therefore, the primary side resonated, and the power factor became 1.0 in the overall rotational speed region. From Fig. 8 (b), the primary voltage increased in proportion to the speed, and it became constant starting from 100,000 rpm. This is because the primary input current decreased since the limiting voltage of 1 kV was reached. From Fig. 8 (b), the primary current decreased. Also, from Fig. 8 (c), the secondary current was constant with respect to the rotational speed. However, it became smaller with respect to the speed at the boundary of 100,000 rpm. This is because the secondary current became constant at a constant slip frequency. However, the secondary current decreased because the primary input current decreased after reaching 1 kV of the limit voltage.

From Fig. 8 (d), the torque was constant with respect to the rotational speed. However, it became smaller with respect to the speed from 100,000 rpm. This is because, like the characteristics of the secondary current, when the slip frequency was constant, the torque became constant until reaching 1 kV, which is the limit voltage. The mechanical output power was proportionally higher up to 100,000 rpm and was proportionally lower from 100,000 rpm. Since the torque decreased in proportion to the square of the primary current, the slope was large. However, the mechanical output power is a product of the torque and rotational angular velocity, so it decreased more gently than the torque. From Fig. 8 (e), the efficiency increased with the increase in the speed because the electrical and magnetic losses of the MRC motor were only those of the copper losses. The secondary current was proportional to the primary current, and the copper loss was proportional to the square of the current. Also, as described above, the torque was proportional to the square of the primary current. However, the mechanical output power is the product of the torque and rotational speed. Thus, the higher the speed, the higher the efficiency.

### 4.5 Magnetic Field Analysis with the AC Copper Loss

The MRC motor was driven at ultrahigh-speed rotational speed of 100,000 rpm. Therefore, the current flowing in the winding of the MRC motor had high frequency. When the current flowing in the winding had high frequency, current deviation occurred inside the conductor, and the substantial resistance of the winding increased. In this subsection, an analysis was performed to take the AC copper loss into consideration. Since the MRC motor did not use magnetic cores, the electrical and magnetic losses were only those of the copper losses. Therefore, almost all the main losses of the MRC motor could be taken into account by considering the AC copper loss. In this analysis, slip frequency constant control was performed, as in subsection 4.4.

This subsection describes the analysis in the case of considering the AC copper loss, as shown in Table 5. The rated speed and slip frequency did not change and were the same as in subsection 4.4. The slip frequency was maintained constant, and the power-supply frequency varied with the speed. The secondary capacitance was fixed, and the primary capacitance varied with the power-supply frequency. This way, both the primary side and secondary side were in resonance. The maximum current density and primary maximum voltage were approximately 25 A/mm² and 1 kV, respectively, as in subsection 4.4.

Figure 9 shows the magnetic field analyses results of considering and not considering the AC copper loss. In Fig. 9, “FEA” indicates the result of the magnetic field analysis without considering the AC copper loss, and “litz wire” indicates the result of the magnetic field analysis with considering the AC copper loss. The characteristic analysis result is an average value of the three analysis results at the rotor positions of 0°, 3.75°, and 7.5°. The rotor positions were shifted as the reference position where the center axis of the secondary winding aligns with that of the primary winding.

As shown in Fig. 9 (a), the power factor in the case of considering the AC copper loss was 1.0 in the overall rotational speed regions. Since slip frequency constant control was performed and the primary capacitance was varied, resonance occurred in the overall rotational speed regions. Further, from Figs. 9(b) and (c), the primary voltage, primary current, and secondary current in the case of considering the AC copper loss substantially agreed with those in the case of not considering the AC copper loss. Since the constant current power source was used, the primary and secondary currents coincided in both cases. Furthermore, since the power factor was 1.0, the primary voltage was the same as in the case of not considering the AC copper loss. From Fig. 9 (d), the torque and mechanical output power in the case of considering the AC copper loss were lower than in the case of not considering the AC copper loss. Also, from Fig. 9 (e), the efficiency in the case

### Table 5. Conditions of the magnetic field analysis with the AC copper loss.

| Rotational speed (rpm) | 0–125000 |
|------------------------|---------|
| Frequency (Hz)         | 223.33–8556.8 |
| Slip                   | 0.0261–1 |
| Slip frequency (Hz)    | 223.33 |
| Primary resonant capacitance (µF) | 2.431–3568 |
| Secondary resonant capacitance (µF) | 48.59 |
| Input current (A)      | 93.7–120 |
| Maximum primary voltage (V) | 1055 |
of considering the AC copper loss was lower than that in the case of not considering the AC copper loss because the substantial resistance of the alternating current increased.

At a rated rotational speed of 100,000 rpm, Table 6 shows the calculation results of the equivalent circuit method, the magnetic field analysis when not considering the AC copper loss, and the magnetic field analysis when considering the AC copper loss. From Table 6, the results when the equivalent circuit method and AC copper loss were not considered almost agreed. In the case of considering the AC copper loss, the mechanical output power was 193 kW, and the efficiency was 91.7%. In the case of considering the AC copper loss, the primary AC copper loss accounted for the majority of the losses. This is because the secondary side was considerably lower than the primary side because it has a slip frequency. Furthermore, the power density with respect to the weight was about 15 kW/kg in all the models, so the standard of the drive motors for large passenger aircrafts can be realized.

5. Experimental Investigations of the MRC Motor

In this section, we conducted drive experiments of the MRC motor and examined its feasibility. The MRC motor is a novel motor that uses magnetic resonance coupling. Therefore, we experimentally examined whether it can actually be driven. The MRC motor was successfully driven using magnetic resonance coupling despite the fact that it had no magnetic cores.

5.1 Experimental Model

Figures 10 and 11 show the stator and rotor of the rotational test prototype of the MRC motor. The setup of the experiment is shown in Fig. 12. It only consists of an acrylic frame and a copper coil, and it is an experimental prototype that does not use any magnetic materials. Table 7 shows the specifications of the rotational test prototype of the MRC motor. The inductance was measured using an
inverter to consider the mutual inductance for each phase. Only the fundamental components were extracted for measurements. In this experiment, to measure the secondary current and the temperature on the secondary side, the secondary side circuit was pulled out using a slip ring.

5.2 Temperature Characteristics of the Resonant Capacitor

In this subsection, the temperature characteristics of the resonant capacitor connected to the winding of the MRC motor were considered. The MRC motor could be driven using the magnetic resonance coupling phenomenon. Therefore, it was important to know the characteristics of the used resonant capacitor. A constant voltage (about 80 V at 403.3 Hz) was applied to the resonant capacitor (about 22.5 μF), and the varying in the capacitance due to the temperature change of the capacitor was measured. Table 8 shows the specifications of the used capacitors in the experiment, and Fig. 13 shows the examination results of the temperature characteristics of the resonant capacitor.

As shown in Fig. 13 (a), the current flowing to the resonant capacitor decreased with time because the impedance of the resonant capacitor increased. In other words, the capacitance decreased. As shown in Fig. 13 (b), the temperature of the capacitor increased and the capacitance decreased with time. This is because the capacitor indicated in Table 8 has a characteristic that the capacitance varies with temperature.

![Fig. 10. Stator of experimental prototype of MRC motor.](image)

![Fig. 11. Rotor of the experimental prototype of the MRC motor.](image)

![Fig. 12. Experimental setup of the MRC motor.](image)
From this consideration, it was found that the current flowing in the resonant capacitor and the capacitance vary with the increase in temperature.

5.3 Experimental Motor Driving Characteristics

In this subsection, we examined the experimental drive characteristics of the MRC motor, and the conditions of the driving experiment are shown in Table 9. As mentioned in Section 4, the MRC motor was driven at an ultrahigh rotational speed of about 100,000 rpm. However, since this experiment was the first experimental rotational test of the MRC motor prototype, the test was performed at a low speed (about 60 rpm). By connecting a resonant capacitance to the primary and secondary windings according to each inductance, the primary and secondary capacitances were resonant capacitances at slip 0.99 and are fixed.

Figure 14 shows the results of the driving test of the MRC motor, and Table 10 shows the calculation results of the equivalent circuit method and the experimental results. In Table 10, in the equivalent circuit method, each characteristic value was calculated using the primary current supplied in the experiment. As shown in Table 10, “Equivalent circuit method (1)” is when the temperature change of the capacitance is disregarded, and “Equivalent circuit method (2)” is when considering the temperature change of the capacitance, which can be obtained by multiplying the room capacitance by 0.67 with reference to Table 9. The value of 0.67 is determined by the maximum decrease in capacitance due to temperature rise is −33% as shown in Table 8.

From Fig. 14 (c), the MRC motor could generate torque despite the fact that it had no magnetic cores. Thus, it was proven that the novel MRC motor can be driven. However,
it can be seen from Table 10 that there was a significant difference between the calculated torque using the equivalent circuit method (2nd. column), in which the temperature change of the capacitance was ignored, and the experimental torque (1st. column). This is because the temperature of the capacitance was increasing. This can also be concluded from Fig. 14(a), which also shows that the primary phase current and primary phase voltage were out of phase. Based on these results, it was considered that the power factor was lowered, a sufficient induction current was not induced, and the torque was lowered. Further, it can be seen from Table 10 that capacitances should be designed by considering the temperature change of the capacitance value to obtain a higher power factor and torque. Although deviations exist because we could not obtain the actual capacitance values due to the temperature increase of the capacitor during the experiment, Table 10 shows that the calculation result of the torque in the equivalent circuit method (3rd. column), which considered the temperature change of the capacitance and the torque of the experimental result (1st. column), showed a similar value. Thus, it was considered that improvements in the power factor and torque can be expected by considering the temperature change of the capacitance in the design.

6. Conclusions and Future Work

In this paper, we proposed a novel MRC motor that eliminates the need for heavy magnetic cores. We confirmed the feasibility of the MRC motor using the proposed equivalent circuit method, a magnetic field analysis, and experiments. Our results confirmed that the proposed MRC motor can transfer electrical energy between a stator and a rotor, thereby producing torque. We derived the equivalent circuit of the MRC motor and verified its usefulness. The calculation results using the equivalent circuit agreed with the analytical results. Also, it was confirmed that the MRC motor has sufficient strength at a rotational speed of 100,000 rpm. Furthermore, we performed an analysis that took the AC copper loss into consideration. It was confirmed that a mechanical output power of 193 kW and an efficiency of 91.7% can be achieved. Also, the experimental results showed that the MRC motor can actually be driven. However, due to the temperature change of the capacitance, the torque was much lower than estimated. However, when the torque was estimated using the equivalent circuit method, it was considered that improvements in the power factor and torque can be expected by considering the temperature change of the capacitance in advance.

Thus, in the future, we plan to study the application of the constant slip frequency control to keep the capacitor constant in the rotor. Further, design should consider the temperature change of the capacitance. Additionally, considering a water jacket to cool the coil and FRP housing and a capacitor mounting position inside the rotor are necessary, taking into account the mechanical strength. Furthermore, we will aim at realizing an ultralightweight high-power MRC motor.

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