Determination of inductance matrixes of bearingless electric motor for magnetic levitation

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Abstract: The paper deals with mathematical and experimental analysis of induction in bearingless electric motor. The motor are used magnetic levitation phenomenon to bearing of the rotor. In stator are implemented two winding groups. These are bearing and motor windings. In the paper are presented the mathematical model of windings and the experimental results of induction parameter measurements.

Keywords: bearingless motor, magnetic levitation, induction

1. Introduction

This paper discusses bearingless electric motor, that is eliminated mechanical contacts between stator and rotor, friction forces, small additional losses, etc. This motor assures proper bandwidth, natural frequency, damping factor, etc. The results of mathematical analysis of induction effects are described. The analyzed motor construction is elaborated and investigated at the Military University of Technology during research project O N509 032736.

Fig. 1. The view of bearingless motor stators: a) 2-phase; b) 3-phase

Rys. 1. Widok statorów silnika bezłożyskowego: a) 2-fazowy; b) 3-fazowy

The following phenomena are analyzed: 2-phase and 3-phase stators of bearingless motor (fig. 1). The stators consist of two groups of windings: suspension windings N_{sa}, N_{sb}, N_{sc} and motor windings N_{ma}, N_{mb}, N_{mc}. The diagram of stator windings is presented in fig. 2. Coordinate systems are also shown. In this motor, the suspension windings are generated levitation magnetic forces, whereas motor windings are generated turn of rotor (torque). The 2-phases stator are 40 suspension windings and 70 motor windings per groove. Whereas, the 3-phases stator are 12 suspension windings and 40 motor windings per groove. In these motors the air gaps occur, 2 mm and 3 mm respectively [3].

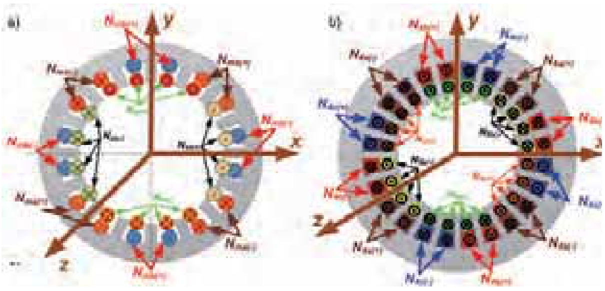

Fig. 2. The stators of the bearingless motor with the windings: a) 2-phase; b) 3-phase

Rys. 2. Stator silnika bezłożyskowego z zaznaczonymi uzwojeniami roboczymi: a) 2-fazowy; b) 3-fazowy

2. Mathematical analysis

The full model of bearingless motors with 2-phase and 3-phase stator is presented in [1–3]. The matrix of induction for 2-phase and 3-phase stators is described in eq. (1) and eq. (2). The parameters of matrix are influenced on magnetic energy E and magnetic flux ψ.

$$\begin{bmatrix} L_{ma} & M_{mamb} & M_{masa} & M_{masb} \\ M_{mamb} & L_{mb} & M_{mbsa} & M_{mbsa} \\ M_{masa} & M_{mbma} & L_{sa} & M_{sasb} \\ M_{masb} & M_{mbsb} & M_{sasb} & L_{sb} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} L_{ma} & M_{mamb} & M_{mamc} & M_{masa} & M_{masb} & M_{masc} \\ M_{mbma} & L_{mb} & M_{mbmc} & M_{mbsa} & M_{mbsb} & M_{mbsc} \\ M_{mcma} & M_{mcmb} & L_{mc} & M_{mcsa} & M_{mcsb} & M_{m\,csc} \\ M_{sama} & M_{samb} & M_{samc} & L_{sa} & M_{sasb} & M_{sasc} \\ M_{sbma} & M_{sbmb} & M_{sbmc} & M_{sbsa} & L_{sb} & M_{sbsc} \\ M_{scma} & M_{scmb} & M_{scmc} & M_{scsa} & M_{scsb} & L_{sc} \end{bmatrix} \tag{2}$$

where:
L – self-inductance of proper winding,
M – mutual inductance between proper windings.

The inductances presented in matrixes can be derived by integration of the product of airgap flux and winding distribution [4]:

$$M_{mamb} = \frac{1}{2}\int_0^{2\pi} \psi_{mb} A_{ma} d\phi_s \quad (3)$$

$$L_{sa} = \frac{1}{2}\int_0^{2\pi} \psi_{sa} A_{sa} d\phi_s \quad (4)$$

$$M_{masa} = \frac{1}{2}\int_0^{2\pi} \psi_{sa} A_{ma} d\phi_s \quad (5)$$

where:
ψ – flux distribution produced by proper winding,
ϕ_s – angular position of rotor,
A – magnetic motor force generated by proper winding.

The air gap flux distributions produced by motor windings N_m and suspension windings N_s are described by eq. (6).

$$\psi_{sa} = P_0\left(\frac{1}{2}A_{sa} - \frac{N_{sa}x}{4g_0}\right) \quad (6)$$

$$\psi_{ma} = P_0\left(\frac{1}{2}A_{sa}\right) \quad (7)$$

where:
g_0 – nominal air length,
P_0 – permeance at an angular position ϕ_s,
N_s – amplitude of the fundamental component of magnetic motor force generated by proper winding.

Substituting eq. (3) – eq. (7) into above equations eq. (1) and eq. (2) and solving the integrations result in a simple mathematical form. The induction matrixes are described by eq. (8) – eq. (10) [4].

$$\begin{bmatrix} L_{ma} & M_{mamb} \\ M_{mamb} & L_{mb} \end{bmatrix} = \frac{\pi\mu_0 RlN_m^2}{4g_0}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} L_{sa} & M_{sasb} \\ M_{sasb} & L_{sb} \end{bmatrix} = \frac{\pi\mu_0 RlN_s^2}{4g_0}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} M_{masa} & M_{sasb} \\ M_{mbsa} & M_{mbsb} \end{bmatrix} = \frac{\pi\mu_0 RlN_s N_m}{8g_0^2}\begin{bmatrix} x & -y \\ y & x \end{bmatrix} \quad (10)$$

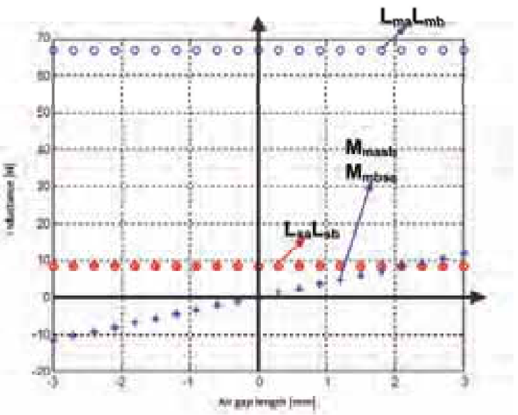

Fig. 3. Simulation characteristics of self-inductances and mutual inductances of bearingless motor [3]
Rys. 3. Charakterystyki symulacyjne indukcyjności własnych i wzajemnych silnika bezłożyskowego [3]

The self-inductances L_{ma}, L_{mb}, L_{mc} and L_{sa}, L_{sb}, L_{sc} are a product of airgap permeability, axial length, rotor radius, winding turns, and the inverse of airgap length. The mutual inductances M_{mamb}, M_{mamc}, M_{mcmb} between motor windings are zero, because windings N_{ma} and N_{mb} are perpendicular to each other. The same is true for M_{mamb}. These represent the coupling between motor and suspension windings. These mutual inductances are proportional to rotor radial displacements x and y [3–4]. The simulation characteristics of inductances are shown in fig. 3.

3. Experimental results

Figure 4 presents the laboratory stand to measure of electrical parameters designed motors. There are the precision LCR meter LCR-8101, LCR-Bridge HM8118 and stators.

The inductances of windings and other electrical parameters are tested in frequency range 20 Hz – 1 kHz. The parameters of motor stators are presented in tab. 1.

Fig. 4. Laboratory stand to measure electrical parameters of bearingless motor stators
Rys. 4. Stanowisko laboratoryjne do pomiaru parametrów elektrycznych silników bezłożyskowych

The measurements of electrical parameters are executed for different conditions. First, there are used the frequency characteristics of self-inductance, resistance and impedance of rotor windings. The results of these investigations are presented in fig. 5 for 2-phase stator and fig. 6 for 3-phase stator. The same measurement is executed for mutual inductance of windings. The selected characteristics are presented in fig. 7–8. In the next step, the inductances parameters for differ position for rotor in stator are measured. So, there are changed the air gap length. The results are presented in fig. 8–10.

Tab. 1. Electrical parameters of stator of bearingless motor
Tab. 1. Parametry elektryczne statora silnika bezłożyskowego

Bearingless motor windings		Resistance parameters [Ω]	
		2-phase	*3-phase*
Levitation windings	N_{sa}	2,98	3,202
	N_{sb}	2,97	3,216
	N_{sc}	-	3,226
Motor windings	N_{ma}	4,566	0,764
	N_{mb}	4,541	0,783
	N_{mc}	-	0,773

Figure 5 presents the frequency characteristic of electrical parameters of 2-phase stator of bearingless motor. The linear range of self-inductance L is equal 100 Hz.

The resistance parameters change from 3,055 Ω (N_{sa}) and 3,037 Ω (N_{sb}) to 4,095 Ω (N_{ma}) and 4,08 Ω (N_{mb}) for frequency 20 Hz. For frequency 1 kHz, these parameters are equal to 41,4 Ω and 39,8 Ω, repectively.

The next measured parameter is self-inductance of stator windings. The linear characteristic is to frequency 100 Hz. The inductance change from 3,82 mH (N_{sa}), 3,79 mH (N_{sb}), 4,03 mH (N_{ma}) and 4,01 mH (N_{mb}) for frequency 20 Hz to 24 mH and 38 mH for frequency 1 kHz [3].

The impedance characteristic are also presented. The impedance are changed from 5,66 Ω for frequency 20 Hz to 238,3 Ω for frequency 100 Hz.

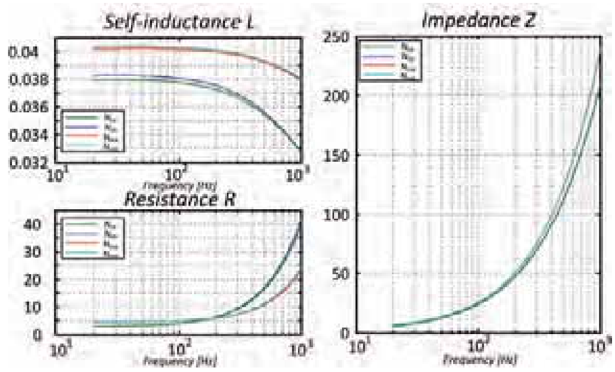

Fig. 5. Frequency characteristics of electrical parameters of 2-phase stator

Rys. 5. Charakterystyki częstotliwościowe parametrów elektrycznych uzwojeń statora dwufazowego

Whereas, in fig. 6 are presented the frequency characteristics of electrical parameters for 3-phase stator. The results are as follows:

- resistances R are changed from 6,7 Ω (suspension windings) and 0,62 Ω (motor windings) for frequency 20 Hz to about 1,3 kΩ (suspension windings) and 53,5 Ω (motor windings) for frequency 100 Hz,
- inductances L are changed from 50,4 mH (suspension windings) and 29,2 mH (motor windings) for frequency 20 Hz to about 27,5 mH (suspension windings) and 1,94 mH (motor windings) for frequency 100 Hz,
- impedances Z are changed from 4,6 Ω (sus-pension windings) and 0,62 Ω (motor windings) for frequency 20 Hz to 164,2 Ω (suspension windings) and 0,92 Ω (motor windings) for frequency 100 Hz.

Figures 9–11 present investigation results of motor windings inductance in function of air gap length. The voltages of proper windings U and current in initial winding I are measured. The methodology of inductances measurement is described in detail in [3–4]. Then, the inductances are calculated from eq. (11) and eq. (12).

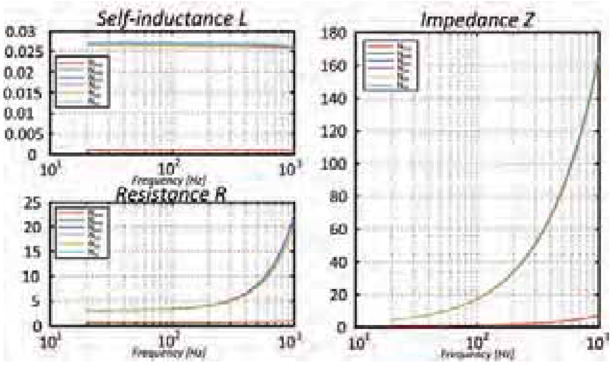

Fig. 6. Frequency characteristics of electrical parameters of 3-phase stator

Rys. 6. Charakterystyki częstotliwościowe parametrów elektrycznych uzwojeń statora dwufazowego

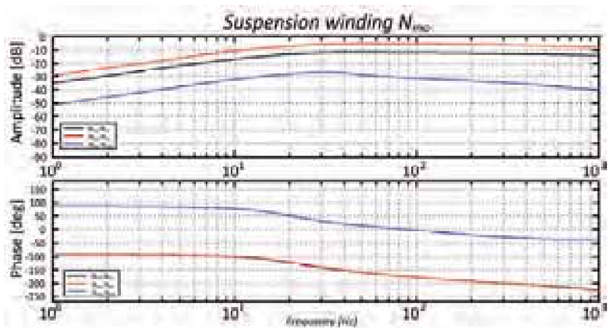

Fig. 7. Frequency characteristics of mutual inductances between windings of 2-phase stator

Rys. 7. Charakterystyki częstotliwościowe indukcyjności wzajemnych uzwojeń statora dwufazowego

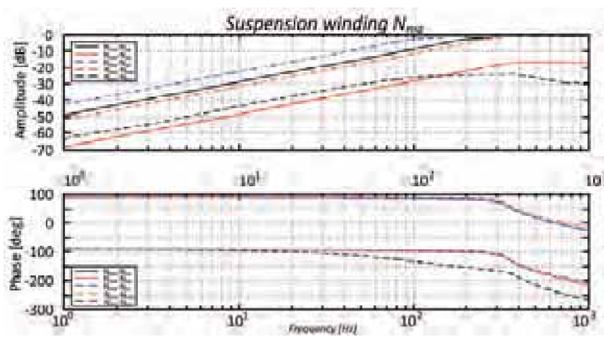

Fig. 8. Frequency characteristics of mutual inductance between windings of 3-phase stator

Rys. 8. Charakterystyki częstotliwościowe indukcyjności wzajemnych uzwojeń statora trójfazowego

$$L_{ma} = \frac{\sqrt{\left(\frac{U_{ma}}{I_{ma}}\right) - R_{ma}^2}}{\omega} \quad (11)$$

$$M_{masa} = \frac{U_{sa}}{\omega I_{ma}} \quad (12)$$

where:

R_{ma} – resistance of winding N_{ma},
V_{ma} – value of voltage on winding N_{ma},
I_{ma} – value of current in winding N_{ma},
ω – angular frequency of the power source.

In eq. (11) and eq. (12) the indexes are represented equivalent windings. For these electrical parameters are substituted proper value of windings.

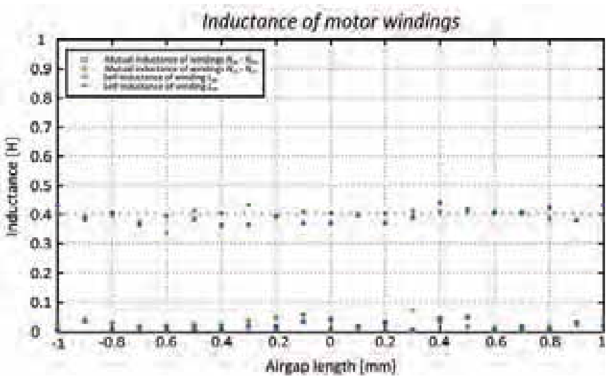

Fig. 9. Characteristics of mutual inductances between windings N_{sa} and N_{sb} and self-inductances of windings N_{sa} and N_{sb}
Rys. 9. Charakterystyki indukcyjności wzajemnych uzwojeń N_{sa} i N_{sb} oraz indukcyjności własnej uzwojeń N_{sa} i N_{sb}

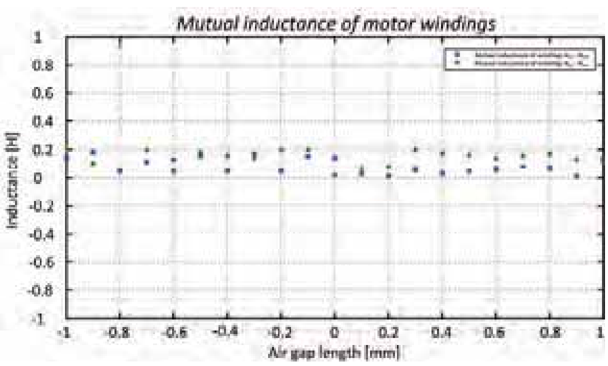

Fig. 10. Characteristics of mutual inductances between windings N_{sb}-N_{mb} and N_{sa}-N_{ma}
Rys. 10. Charakterystyki indukcyjności wzajemnych uzwojeń N_{sb}-N_{mb} oraz N_{sa}-N_{ma}

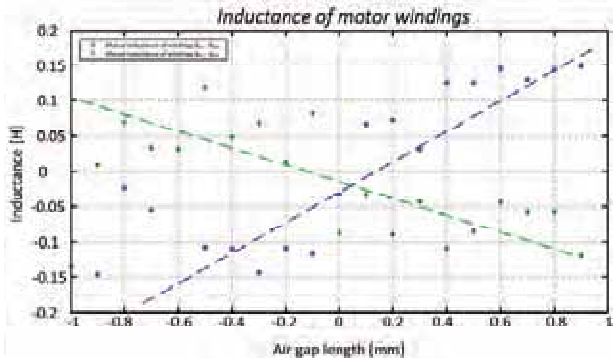

Fig. 11. Frequency characteristics of mutual inductance of 3-phase stator
Rys. 11. Charakterystyki częstotliwościowe indukcyjności wzajemnych uzwojeń dla trójfazowego statora

The characteristics are confirmed by the theoretical analysis of inductance model described in Section 2. These mutual inductances are zero when rotor is positioned in center of stator. If these inductance are zero, there is no induced voltage in the suspension winding when motor revolving magnetic field is generated. On the other hand, no induced voltage appears at the motor terminals when the suspension winding current generates suspension revolving magnetic field. Therefore, the voltage requirement for suspension winding is low. The self-inductances are constant and are equal about 0,4 H. Whereas, the mutual inductance between motor windings are zero [3–4].

Figure 11 presents the mutual inductances of suspension windings N_{sa}, N_{sb} and motor windings N_{ma} and N_{mb}. The simulation results of these parameters are shown in fig. 3. The investigation results are ambiguous, but the trend of characteristic is proper. This is the effect of research errors.

4. Summary

Research into magnetic bearings has been conducted at the Military University of Technology for many years. This paper discusses the mathematical and experimental analysis of electrical parameters of 2- and 3-phase stators. In stators two winding groups are implemented (bearing and motor windings). The frequency characteristics present electrical parameters of stators. There are the resistance, self-inductance, mutual inductance and impedance of windings. The characteristics in function of air gap length are also presented. These analysis and investigations are used in identification of bearingless motor performances.

Acknowledgment

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Wyznaczanie parametrów macierzy indukcyjności bezłożyskowego silnika elektrycznego

Streszczenie: Prowadzone obecnie w WAT prace badawcze stanowią odpowiedź na rozwój technologii More Electric Aircraft. W artykule przedstawiono wyniki analizy matematycznej macierzy indukcyjności dla bezłożyskowych silników dwu i trójfazowych. Uzyskane podczas tej analizy wyniki zostały zweryfikowane podczas badań laboratoryjnych. W tym celu dokonano pomiarów elektrycznych statorów obu silników oraz parametrów indukcyjności w funkcji szczeliny powietrznej.

Słowa kluczowe: silnik bezłożyskowy, lewitacja magnetyczna

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