711. The analysis of the control system for the bearingless induction electric motor

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Abstract. The paper deals with the problem of the actuation system in airborne application. Two problems are important. First, the frequency bandwidth of elements should be as wide as possible. The second, the applied actuators have the disadvantageously property, e.g. the overall efficiency, the friction forces, heat abstraction, the high complexity. The main element of the actuator is the bearingless induction electric motor. The construction of the motor is compound the active magnetic bearing and the more electric technology. So the new motor eliminates the disadvantages of the conventional motor. In the paper there are presented the new construction of the bearingless motor, models radial magnetic forces and torque. There are presented the simulation results of bearingless motor with control system, too.

Keywords: bearingless induction motor, active magnetic bearing, control system.

Introduction

The airborne systems have been developing very dynamic, during the last years. This is the result of the development of the „More Electric Aircraft" technology (MEA). This technology is improved the aircraft reliability, vulnerability, redundancy and reduce complexity, weight and running costs. In the flight control actuation systems, the MEA technology is considered in two areas: fly–by–wire (FBW) and power–by–wire (PBW). The FBW system comprises development and implementation of electronics for flight control systems. Electronic provides flight and actuator control functionality implemented using either centralized or distributed architectures. Distributed control systems reduce the processing load on flight control computers and offer more flexibility. Whereas, the PBW technology explores novel approaches to design the development of electrically powered actuators used to operate aircraft control surfaces. This includes the application and adaptation of electric drive technologies to suit the specific performance reliability and safety objectives of flight control applications [1].

The main purpose of the nacelle actuation system is converted electric control signal to move control surfaces of aircraft and it is a power amplifier of this signal. The elements of the actuators are the power amplifier, the motor, the screw – jack element, feedback loop, controller with implemented control law and the sensors. The interdependence of the all elements decides about the static and dynamic characteristics of nacelle actuation system.

The main influence of the actuator characteristics has the bearingless induction electric motor. So, we deal with the construction of the motor to eliminate the disadvantages of the conventional motor. The new construction of the bearingless induction motor is compound two mechatronic elements - squirrel cage motor and active magnetic bearing in one motor system. Advantages of the new construction are the lack of a mechanical contact between the journal and the bush, small additional losses, no need lubricants, no tear and wear, they have low cost of production due to smaller number of wires on the stator, etc.

In this kind of system no current supply needed from outside the rotor to create a magnetic field in the rotor. This is the reason why this kind of motor is so robust and inexpensive. The stator phases create a magnetic field in the air gap rotating at the speed of the stator frequency. The changing field induces a current in the cage wires which then results in the formation of a second magnetic field around the rotor wires. As a consequence of the forces created by these two fields, the rotor starts rotating in the direction of the stator field but at a slower speed. There are several ways to control an induction bearingless motor in torque, speed. They can be categorized in two groups: the scalar and the vector control.

The active magnetic bearings with electromagnetic coils are used to generate electromotive force of the operation point while electromotive forces are used to control the position of rotor in the air gap. In this kind of magnetic bearings the magnetic flux is a resultant one which flow through one magnetic circuit. In bearingless motor we apply the similar rule of operation, but in the motor are design the additional windings of the stator to generate magnetic force and torque. The principle of radial force generation of bearingless induction motor is to combine two winding sets with a difference of the pole pair number which works as a bearing and as a motor.

Bearingless motor and lab stand

The bearingless electric motor will assure the bandwidth, natural frequency, damping factor, diagnostic flexibility, high reliability and other operation properties. The motor processes an electrical adjustable signal for an angular velocity of rotor.

In Fig. 1 there are presented the bearingless induction motor and his control loop and the organize 3-phase distribution of motor (N_{4a}, N_{4b}, N_{4c}) and suspension (N_{2a}, N_{2b}, N_{2c}) windings. The controller is divided into two parts: one is a radial position controller and the other is a motor controller. The motor controller structure is slightly different from that the bearingless motor although the radial position controller has the same structure. The bearingless machine has 4–pole and 2–pole windings designated as motor and suspension force windings, respectively. The mechanical synchronous speed command (*w*) is doubled to generate an electrical synchronous speed command. The mutual inductance (*M*) between the 4–pole and 2–pole windings is proportional to the rotor position in the air gap. The orientation of the air gap flux linkage is given by (*w*). The amplitude and direction of the air gap flux linkage is independently generated and the current amplitude and phase angle are adjusted so that the actual air gap flux linkage follows the modulation commands. In the modulation block, suspension currents are generated from suspension force commands, and the amplitudes of flux linkage derivatives are taken to be unity in the calculation [2].

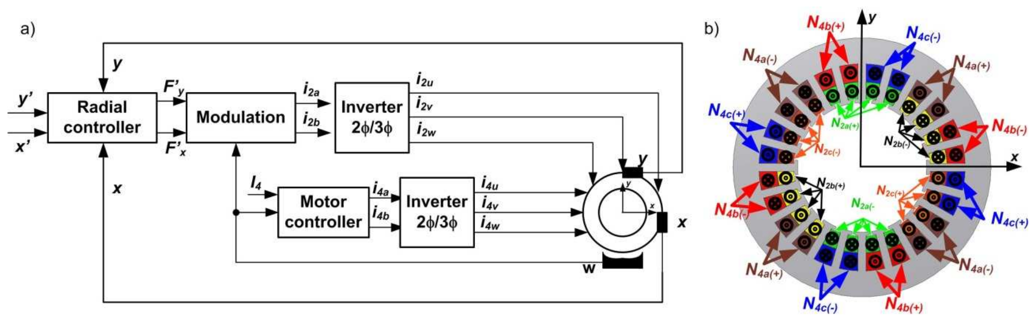

Fig. 1. The bearingless induction motor: a) the diagram of the control system, b) the 3-phase stator

The bearingless electrical motor joins property of the heteropolar active magnetic bearing and the alternating current electrical motor. The heteropolar active magnetic bearing uses the windings to generate magnetic force. In the magnetic circuit of bearing is two kinds of fluxes (see Fig. 1b). First magnetic flux is a constant and it is named the magnetic flux of working point (windings N_{4a}, N_{4b} and N_{4c}). Second magnetic flux depends from the position of the rotor in the air gap and it changes value of resultant magnetic flux in the air gap (windings N_{2a}, N_{2b}

and N_{2c}). It is named control magnetic flux. While, the magnetic force generates by the windings is change proportional to position rotor in the air gap [2].

If the motor windings of bearingless motor supply by the direct current, the bearingless motor works as the active magnetic bearing. If the motor windings supply by the alternating current, the rotor moves. The control currents in the windings N_{2a} and N_{2b} are modulated by the angular velocity of the rotor during the rotating rotor of the bearingless motor.

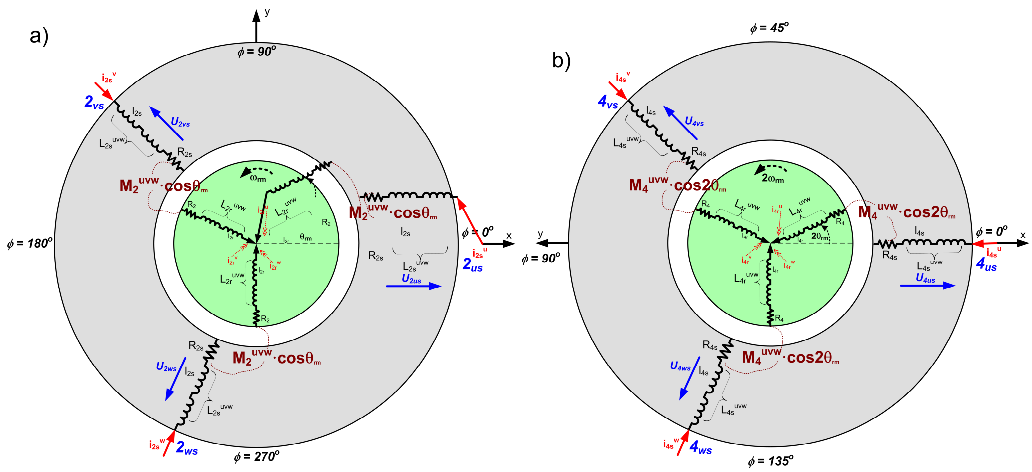

Fig. 2. Equivalent circuits of 3-phase bearingless motor: a) 2-pole windings, b) 4-pole windings

The model of bearingless induction motor and dynamic equivalent circuit is shown in Fig. 2. There are presented 2-pole and 4-pole circuits, which are equivalent of bearingless windings.

Three-phase 2-pole windings: 2_{us}, 2_{vs}, 2_{ws} and three-phase 4-pole windings: 4_{us}, 4_{vs}, 4_{ws} are shown in the stator core (index "*s*"). In the stator windings flows three-phase sinusoidal currents: i_{2us}, i_{2vs}, i_{2ws} and i_{4us}, i_{4ws}, i_{4vs}. In the rotor circuits voltages and currents were similar with indexes "*r*". R_{2s}, R_{2r}, R_{4r}, R_{4s} – winding resistances for stator and rotor, l_{2s}, l_{2r}, l_{4r}, l_{4s} – leakage inductances of stator and rotor, M_{2uvw}, M_{4uvw} – effective mutual inductances, L_{2suvw}, L_{2ruvw}, L_{4ruvw}, L_{4suvw} – self-inductances of stator and rotor windings.

The starting step in the mathematical modelling of bearingless motor is to describe them as coupled stator and rotor polyphase circuits in terms of so-called phase variables. The magnetic coupling is expressed in terms of an inductance matrix which is a function of position θ. The next step is to transform the original stator and rotor frames of reference into a common *0dq* frame in which the new variables for voltages, currents, and fluxes can be viewed as 2-D space vectors. In this common frame the inductances become constant independent of position.

Simulation model of bearingless motor with control systems

Bearingless induction motor is a complex system of inductances, so in order to model this system we must formulate the equilibrium equations of electrical and mechanical. The model of the motor may, but need not be an accurate representation of the construction of electric motor, however, should be characterized by reconstruction of magnetic flow, as in a real motor. The coil system is described in differential equations, characterizing the magnetic coupling between them. In order to present a dynamic mathematical model of the motor must be presented the coordinate systems associated with the stator and the rotor of bearingless motor, see Fig. 3.

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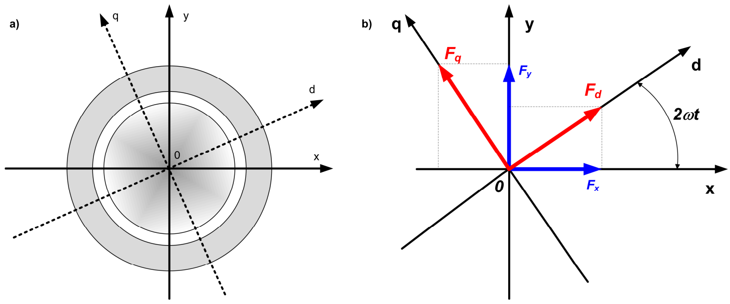

Fig. 3. The coordinate systems of bearingless motor (*0xy* is relevant with stator and *0dq* is relevant with rotor)

The mathematical model of bearingless motor based on Newton's law (the calculation of forces in each axis) and the equation of moments for the motor. In order to simplicity the simulation 3-phase windings of bearingless were transformed to the 2-phase windings. The equations of motion in matrix form are as follows [2]:

$$\begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & J \end{bmatrix} \cdot \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{\varphi} \end{bmatrix} = \begin{bmatrix} F_x \\ F_y \\ M_z \end{bmatrix} + \begin{bmatrix} G_x \\ G_y \\ -M_0 \end{bmatrix} \tag{1}$$

where: m - the mass of rotor; J - moment of the rotor inertia; F_x, F_y - suspension forces in the direction of the axis $0x$, $0y$; M_z - electromagnetic torque; M_0 - load torque; G_x, G_y - disturbances.

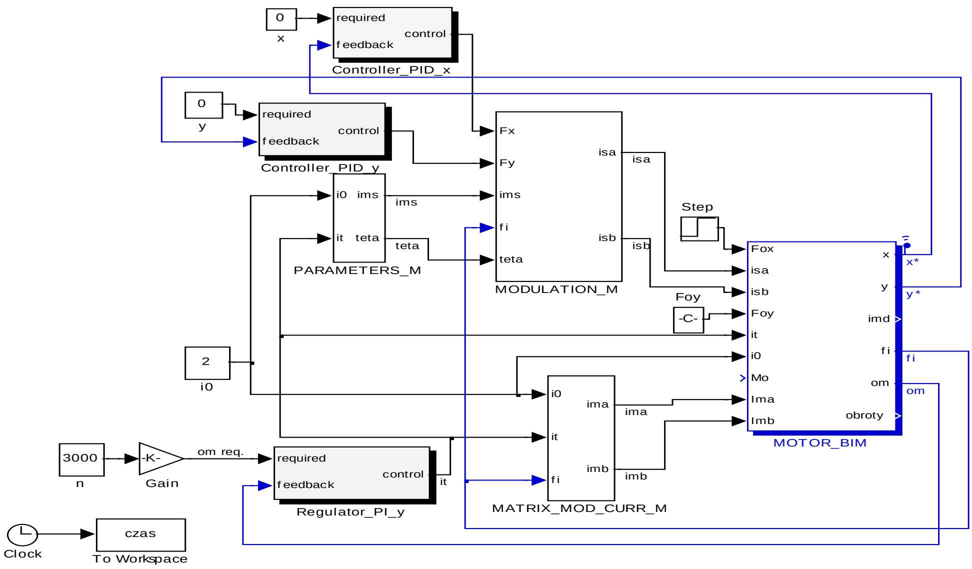

Fig. 4. Simulation model of bearingless motor with closed loop of control

Forces and moment can be obtained as:

$$\begin{bmatrix} F_x \\ F_y \\ M_z \end{bmatrix} = \begin{bmatrix} M' I_4 \cos(2\omega t + \Theta) & M' I_4 \sin(2\omega t + \Theta) & 0 & 0 \\ M' I_4 \sin(2\omega t + \Theta) & -M' I_4 \cos(2\omega t + \Theta) & 0 & 0 \\ 0 & 0 & M' & M' \end{bmatrix} \cdot \begin{bmatrix} i_{2a} \\ i_{2b} \\ i_{4d} \\ i_{4q} \end{bmatrix} \tag{2}$$

where: *M’* - mutual inductance; I_4 - excitation current in the motor windings.

Equations relevant with forces matrix was obtained from the partial derivatives of the stored magnetic energy. Expression relevant with moments in the bearingless motor is associated with mechanical part (cage of rotor). Transforming current in the motor windings from *0xy* coordinate to *0dq* coordinate by the matrix:

$$\begin{bmatrix} i_{4d} \\ i_{4q} \end{bmatrix} = \begin{bmatrix} \cos(2\omega t) & \sin(2\omega t) \\ -\sin(2\omega t) & \cos(2\omega t) \end{bmatrix} \cdot \begin{bmatrix} i_{4a} \\ i_{4b} \end{bmatrix} \tag{3}$$

If we used equations (2) and (3) in the equation (1) the model of motion of bearingless motor is described by equation (4). The model was build in Matlab-Simulink, which allowed to visualize and identify the phenomena of motor (Fig.4):

$$\begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & J \end{bmatrix} \cdot \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{\varphi} \end{bmatrix} = \tag{4}$$

$$= \begin{bmatrix} M' I_4 \cos(2\omega t + \Theta) & M' I_4 \sin(2\omega t + \Theta) & 0 & 0 \\ M' I_4 \sin(2\omega t + \Theta) & -M' I_4 \cos(2\omega t + \Theta) & 0 & 0 \\ 0 & 0 & -M'\sin(2\omega t) & M'\cos(2\omega t) \end{bmatrix} \cdot \begin{bmatrix} i_{2a} \\ i_{2b} \\ i_{4d} \\ i_{4q} \end{bmatrix} + \begin{bmatrix} G_x \\ G_y \\ -M_0 \end{bmatrix}$$

Simulation and testing results

The bearingless motor has got three feedback loops (blue line and light gray blocks – Fig. 4). The two feedback loops control position of the rotor in the air gap. There are eddy current sensors and PID controllers. The sensors measure displacement of the rotor in the air gap and the information about moves in the *0x* and *0y* axis is used in the PID controller to change the magnetic forces. The third feedback loop controls angular speed of rotor, that is measured by encoder. There is used the PI controller. In the control system are modulated the suspension currents in the function angular position of the rotor.

The Fig. 5a presents displacements of rotor after turn on the power supply. The rotor moves fro to the working point. This is the nominal position of rotor when the air gap is equal 0,3 [mm]. Whereas, the Fig. 5b presents current distributions in the moment of rotational speed *w*=20 [rad/sec]. In the stator is begins to flow sinusoidal currents, when the speed reference is required. The currents relevant with the motor are modulated by suspension currents.

All these simulations were performed for two-phase model bearingless motor. In order to change the model two-phase into three-phase model need multiplied by the invereter (Fig.1).

Conclusions

The newest technology named “More Electric Aircraft” (MEA) is introduced in the modern military and commercial aircraft. This technology is included onboard system: the energy power extraction, the advanced electric power system and the flight control system. The main element of nacelle actuation system is the electric motor. It decides about static and dynamic characteristics of nacelle actuation system. The electric motor is a transducer, that it processes an electrical adjustable signal for an angular velocity of the rotor. There is a feedback from the position of servo-piston displacement. The DC electrical drivers were used in construction of actuators. Present the AC electrical driver implements in construction of actuators. This change comes up to the modern construction of inverters. They ensure control of angular velocity and position of the rotor of the electrical motors.

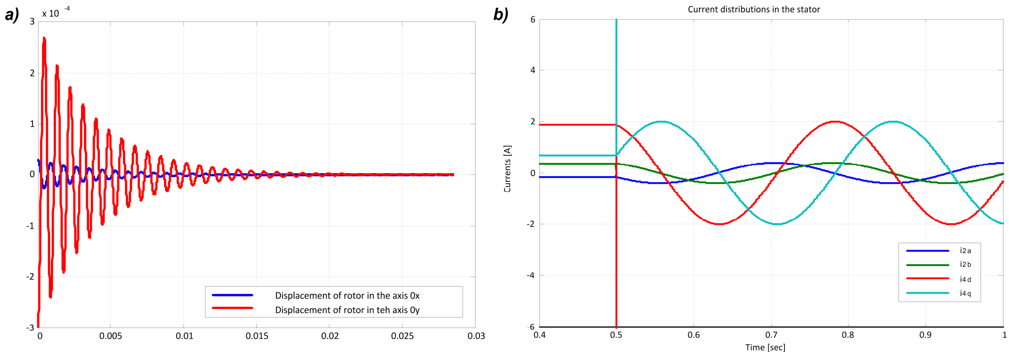

Fig. 5. Simulation results: a) simulation waveforms of displacement of rotor in working point; b) current distributions in the stator at w = 20 [rad/sec]

There are presented results of the simulation of the bearingless motor with PID control system responsible for suspension forces and PI control system responsible for generation torque. The next step in our investigations will be verification of the model in the lab-stand and testing another types of control this kind of system.

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