Control of Bearingless Electric Machines Dedicated for Aviation

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ABSTRACT

This paper discusses the advantages and major issues associated with the implementation of magnetic suspension in aircraft systems such as nacelle actuators, generators and small gas turbines. Magnetic bearings eliminate mechanical contacts between stator and rotor, friction forces, removes the negative effects of operation such as heat and wear on the friction elements, lubrication, heat dissipation, noise, etc.

The development of a bearingless system is presented in detail, including control system design, FEM modelling and rig testing. The concept of the active magnetic suspension system for a gas turbine engine to be applied in a UAV powerplant or auxiliary power unit (APU) is investigated. A full-scale demonstrator model was built on the basis of a turbine starter from a retired military fighter in which the rolling-element bearings were replaced with magnetic suspension.

1.0 INTRODUCTION

New airborne systems have been developing very rapidly. During the last few years in aviation, there has been a trend to use electrical equipment instead of pneumatic, and hydraulic systems, e.g. hydraulic actuators are replaced by electric servo-actuators and mechanical control systems have evolved to fly-by-wire systems. The expansion of electrical receivers and other electrical devices is (subject-expansion) caused by the increase in demand for the on-board electrical energy. The classic on-board sources of aircraft are insufficient. Therefore, our research group analysed a phenomena in new aircraft, electrical on-board sources and electric machines. The new structure of electric aviation machines will supply electrical anti-icing system, glass cockpit and other on-board receivers. This on-board revolution is called 'More Electric Aircraft' (MEA) technology [2].

Thanks to the MEA concept, new aircraft should produce less noise and pollution. Their weight and fuel consumption will be reduced. Thus, new technology will improve aircraft reliability, vulnerability, maintainability, reduce complexity, redundancy, costs and finally enhanced flight safety [3]. The More Electric Aircraft concept is being use in passenger aircraft such as Boeing B787, Airbus A380, multi-role fighter F-35 and in unmanned aircraft Predator and Global Hawk [1].

The on-board electrical power system (Boeing 787) designed according to More Electric Aircraft technology was presented in Figure 1a. The increase in the number of electrical power receivers caused a considerable growth of electric power requirements To meet these requirements in modern electrical systems, a phase voltage level was raised from 115 VAC (phase to phase voltage 200 V) to 230 VAC (400 V). Using greater voltage improves the efficiency of power system, reduces the loss of power and the weight of wiring.

The MEA engine is more efficient than the classical engine because compressed air is not carried away/moved to another on-board installation. Thanks to this capability, thrusts are higher than in conventional engines. The structures of modern engines are characterised by high pressure starter generator (HPSG), fan shaft drive generator (FSDG), power electronics module (PEM), electric oil pump, electrical actuation systems for various applications, 350 VDC electrical network, and most importantly, Active Magnetic Bearings (AMB) (Figure 1b) [1]. The MEA technology enables the use of active magnetic suspension in aircraft engine structure. Active magnetic bearings are perfectly suitable to support both the fan and the 'hot' section in the engine because of their maintenance and resistance properties at high temperature.

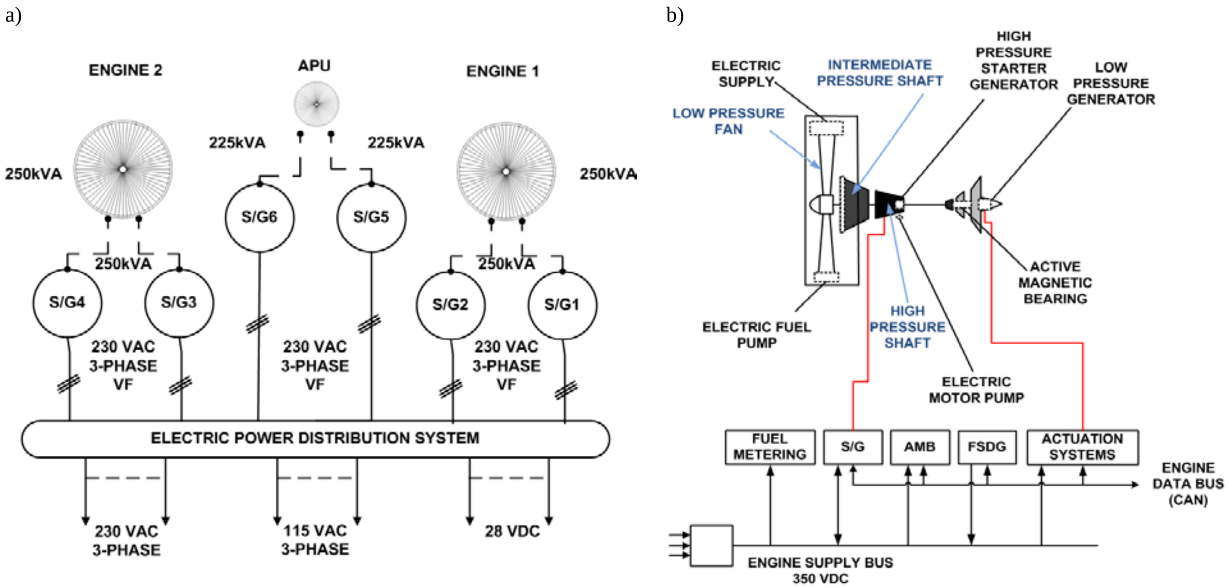

Figure 1. MEA technology implementation:
a) architecture of Boeing 787 electrical power system;
b) architecture of modern electric aircraft engine.

The MEA technology enables us to use magnetic suspension capabilities in aviation and space technology. An electric machine with implemented magnetic bearing technology is called a bearingless machine. This machine is defined as the electric machine in which a magnetic induction generates torque and suspension forces. The structures of these machines are connected with active magnetic bearing and classic electric machine technology. Active magnetic bearings (AMB) are devices, which use magnetic forces to provide stable rotor levitation at work point. New systems can work in rugged conditions, e.g. high and low temperature, low pressure, vacuum [3].

The main purpose of the control and actuation system in bearingless electric machines is to convert the electrical control signal to move control surfaces of aircraft, and to act as a power amplifier of this signal. The elements of the actuators include the power amplifier, the motor, the screw – jack element, feedback loop, controller with implemented control law and the sensors (Fig. 2). Measured output signal is compared with the input signal and the difference of above signals activates the controller to make the output proportional to the input signal. This signal is powered with an electric power amplifier and controls the movement of the servo-motor. The motion is the change in the displacement by screw-jack element. The interdependence of these elements determines the static and dynamic characteristics of the control system. The main influence of these characteristics is the motor of the actuator. In our structure, it is the bearingless induction electric motor.

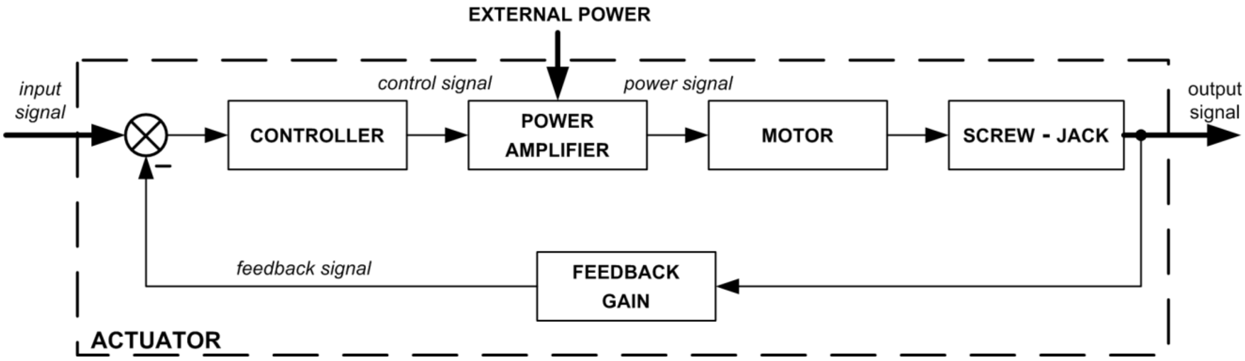

Figure 2. The structure of the actuation control system.

The static and dynamic characteristics of the control system are deciding for the parameters of the flight control system. Currently, in the structure of actuators are implemented the AC electric motors. In the paper, there are presented structures of the bearingless induction motor, models radial magnetic and torque forces not to mention the simulation analysis.

2.0 BEARINGLESS ELECTRIC MOTOR

The research team elaborated and investigated the bearingless motors, i.e. bearingless induction motor and bearingless motor with surface mounted permanent magnets. Figure 3 presents two kinds of motor structures and Figure 4 simulation and investigation results.

Bearingless electric motor combines the property of the heteropolar active magnetic bearing and the alternating current electric motor. The heteropolar active magnetic bearing uses the windings to generate a magnetic force. Two kinds of fluxes are in bearing magnetic circuit. First magnetic flux is a constant and it is called the magnetic flux of working point. Second magnetic flux depends on the position of the rotor in the air gap, and it changes the value of resultant magnetic flux in the air gap. It is called the control magnetic flux. While the magnetic force generates by the windings is change proportional to position rotor in the air gap – the magnetic force generated by the windings is changed proportional to position rotor in the air gap [4], [5], [7].

a)

b)

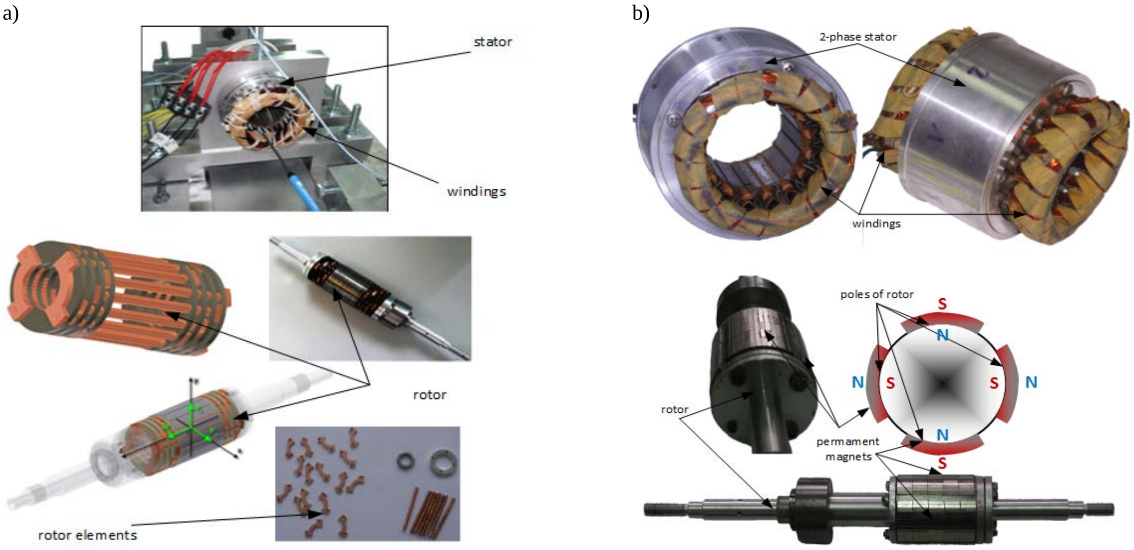

Figure 3. Investigated bearingless motors:
a) induction motor;
b) electric motor with permanent magnets [4].

In research work, two kinds of bearingless electric motors are investigated: the induction squirrel-cage motor (Figure 3a) and motor with surface -mounted permanent magnets (Figure 3b). The stator consists of two groups of windings: suspension windings and motor windings. In this motor, suspension windings are generated by magnetic levitation forces, whereas motor windings are generated by turn of a rotor (torque).

Figure 3b presents a rotor with permanent magnets. Four groups of magnets are mounted on the iron surface, and they have generated four magnetic poles. Steel can usually cause wraps permanent magnets to avoid irreversible demagnetisation because suspension flux is superimposed to the magnetic field and can act in opposite to magnet polarity. The single pole of rotor consists of 65 permanent magnets with dimensions 10x2,5x1 [mm] and direction of magnetization along dimension 1 [mm]. Thin permanent magnets are more effective in generating radial suspension forces. Therefore, small permanent magnets are mounted on the iron core of the rotor. In general, high air gap flux density is preferred to maximise torque capability (except for high-speed motors). In addition, thin permanent magnets may be irreversibly (or permanently) demagnetised. It is necessary that permanent magnet thickness and air gap length should be designed so that air gap flux density and permanent magnet demagnetisation issues and need for high suspension force per unity suspension current [2].

Control system for this kind of motors was presented in Figure 4. The system consists of stator and rotor, angular position sensor, eddy-current displacement proximity sensors and self-aligning bearing. There is not the touchdown bearing. These kind of bearing is used for safe of shafts. In our case, the lab-stand of BEM has self-aligning bearing that acts as the support unit for BEM rotor. The signal from displacement proximity sensors is necessary to avoid levitation effect. The angular position sensor is indispensable in motor work mode, and it is used to detect instantaneous rotor angular position. This signal is connected to modulation block in control loop of motor windings.

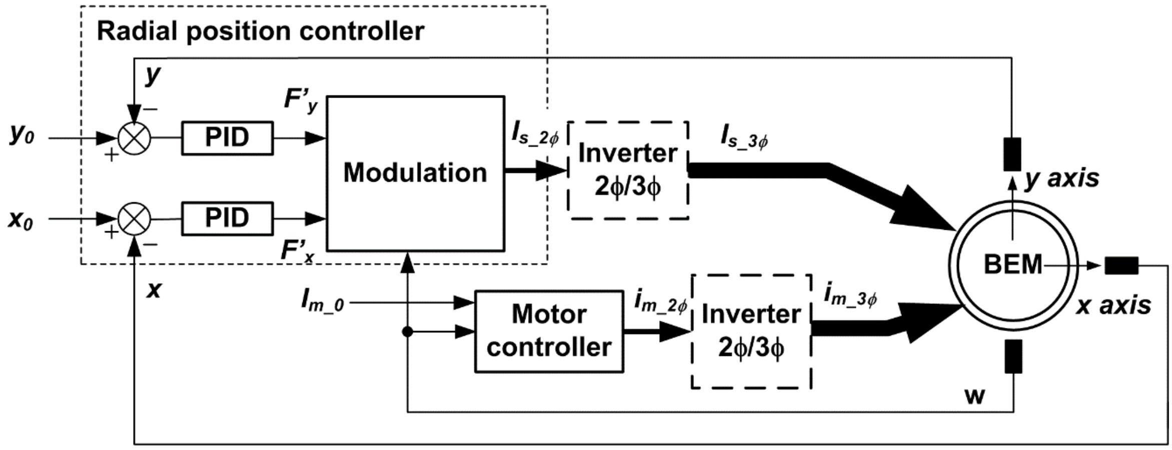

Figure 4. Control system of bearingless electric machines.

Figure 4 shows 3-phase bearingless motor and his control system with two controllers. The first control radial rotor position and the second control angular speed of the rotor. The bearingless machine has 4–pole and 2–pole windings designated as motor and suspension force windings, respectively. Mechanical synchronous speed command w is doubled to generate an electrical synchronous speed command. Mutual inductances M between 4–pole and 2–pole windings are proportional to rotor position in the air gap. The orientation of air gap flux linkage is given by speed command w. Amplitude and direction of air gap flux linkage are independently generated, and current amplitude and phase angle are adjusted so that actual air gap flux linkage follows modulation commands. In the modulation block, suspension currents are generated from suspension force commands. Amplitudes of flux linkage derivatives are taken to be unity in calculation [2].

Active magnetic bearings are objects, which have unbalanced structure. Therefore, they require a suitable control system with controller, which provides proper characteristics of the system. The simplest controller, which assures the correct work of AMB is a PD controller. That structure allows to stable the system but it does not reduce control error to zero. Therefore, most often, in the practical application the PID controller was used, which assures the best dynamic and static features of the control system by reducing control error to zero. The disadvantage of this solution is an increase in settling time parameter and readjustment.

The response of a closed-loop system with the PID controller is described by equation (1) [3].

$$G_Z(s) = \frac{k_i(K_p + \frac{1}{T_i} + T_d s)}{ms^2 - k_s + K_p k_i + \frac{k_i}{T_i s} + k_i T_d s} \tag{1}$$

During analysis, it was assumed that damping coefficient ζ equates 0.5, whereas setting time t_r = 6 ms. Then, characteristic equation should have three poles, two of them described as:

$$p_{1,2} = \omega_0 \varsigma \pm i\omega_0\sqrt{1-\varsigma^2} \tag{2}$$

where:

p_1 – following pole;
ω_0 –frequency of proper vibration, $\omega_0=3.2/\zeta t_r$

It is assumed that the third pole of the closed-loop system does not influence the system features (pole – placement method). Parameters of the PID controller are the following/Below are listed the parameters of the PID controller:

$$K_p = \frac{-(p_1+p_2+p_3)m}{k_i} \tag{3}$$

$$K_i = \frac{(p_1 p_2 p_3)m}{k_i} \tag{4}$$

$$K_d = \frac{-(p_1p_2+p_2p_3+p_3p_1)m+k_s}{k_i} \tag{5}$$

3.0 EXPERIMENTAL RESULTS

Experimental studies of the bearingless motor have allowed determining the performance characteristics of the system in time and frequency domain as well. Experimental research concerned the analysis of compensation of excitation by the control system with the PID controller. These disturbances were introduced to control system in the form of the measurement signal in the feedback loop (forced displacement). Figure 5 and Figure 6 presented the results and the laboratory stand [6].

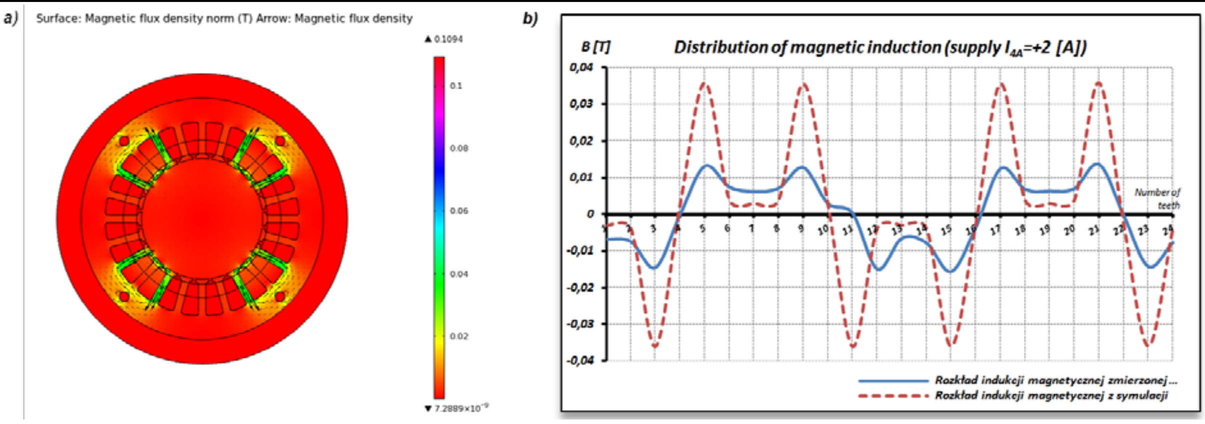

Figure 5. Numerical and experimental results of bearingless motor
a) numerical visualization;
b) experimental and numerical results of distribution magnetic induction.

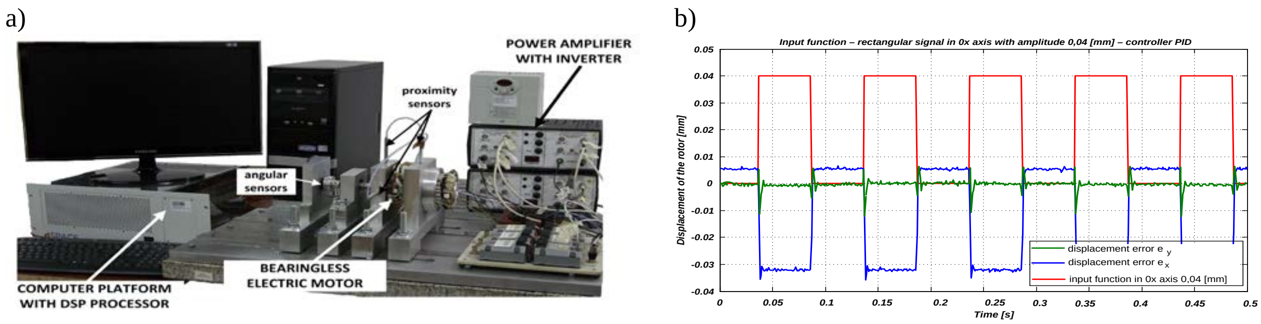

Figure 6. Laboratory stand (a) and experimental control system results (b).

The bearingless motors are investigated during laboratory tests in the whole range of rotational speed, increasing dynamic stiffness and load tests. There are measured electrical parameters designed motors and determined frequency characteristics of self-inductance, resistance and impedance of motor windings, too. These parameters and characteristics are measured for different rotor position in the stator.

The proprieties of the bearingless electric machine with different controllers are verified by experimental investigations. The investigations of the described control system are conducted on the laboratory station (Figure 6). The lab stand consists of AMB, power amplifier, air gap sensors, power supply and dSpace platform. The measurement of rotor position in the air gap in axes Oz and Oy are used by the non-contact, eddy-current sensors. The power amplifier are supplied electromagnets. The virtual module of controlling was realized in the Matlab – Simulink. Using the library RTW (Real Time Workshop), the designed system was transferred to DSP processor and it was implemented in dSPACE platform.

There are measured time and frequency characteristics of the control system with PD and PID controllers. Figure 7a and 7b illustrates experimental step responses and Bode characteristics of the control system with the PID controller.

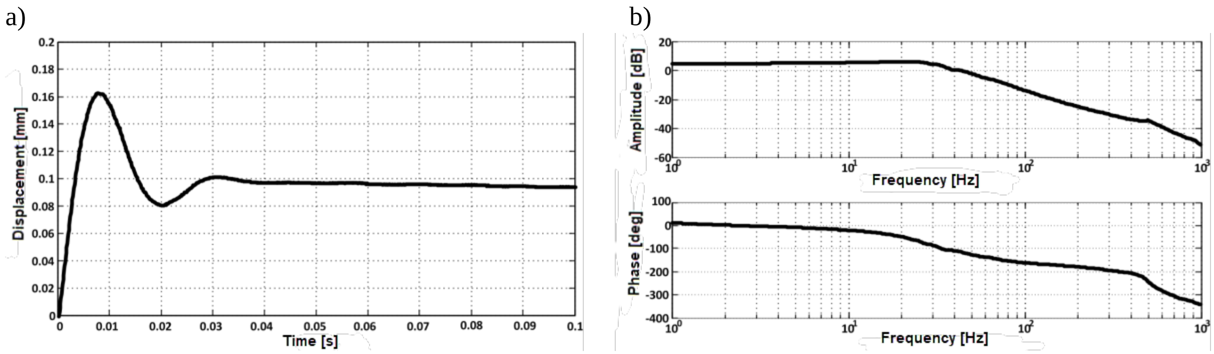

Figure 7. Step characteristic of control system with PID controller (a) and Bode characteristic of this kind of control (b).

On this kind of research, we can prove that the system is stable and is robust for disturbances. It was observed that the system with AMB reaches the required state of work very fast.

4.0 FUTURE WORK

After successful tests at the laboratory stand with the use of motors: a bearingless induction motor and a bearingless motor with permanent magnets, a laboratory stand was built using a small jet engine, Figure 8.

Figure 8. Small jet engine on the lab stand [8].

This engine was completely digitised, controlled by the LabView environment and prepared for future-proof magnetic suspension technology.

To implement the idea of magnetic bearings (Figure 9a) to this project a laboratory stand (Figure 9b) with two radial magnetic bearings and one axial bearing was constructed in to determine the basic characteristics of their operation.

a) b)

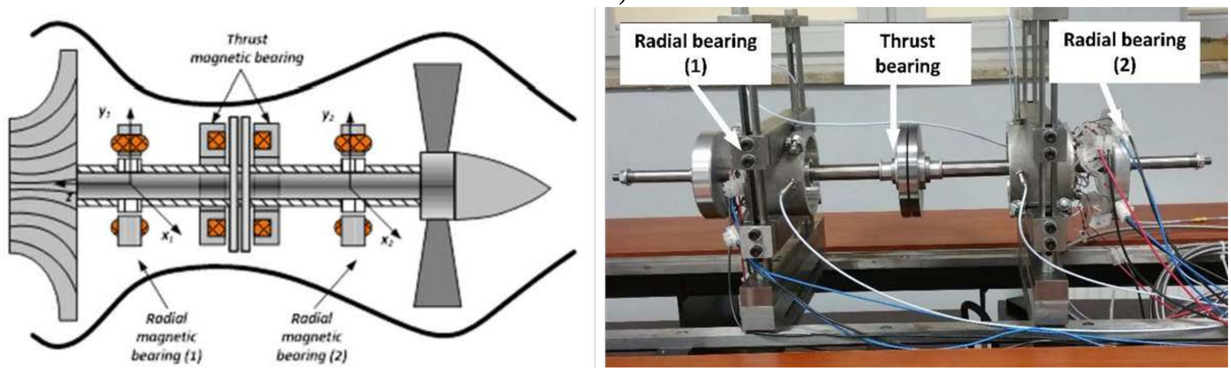

Figure 9. Diagram of jet engine structure with idea of magnetic suspension system (a), the laboratory model of magnetic suspension system of jet engine (b) [8].

After completing the work at this station, the idea of this type of bearing will be implemented on the lab stand with the small jet engine, and the concept of a bearingless electric motor will be developed in the future. Individual components of the laboratory stand reached TRL IV, while the implementation of the magnetic bearing in the jet engine is planned to achieve the TRL V level.

5.0 CONCLUSION

Present aircraft are designed according to the More Electric Aircraft concept , which provides for larger utilization of electrical energy in the airborne systems. This technology allows using magnetic suspension phenomenon in aviation and space technology, as well, e.g. in the actuation system, aircraft engine, starter/generator. The use of new solutions can improve the safety and reliability of airborne structures except for the improvement of technical parameters. Developed lab stand with the bearingless induction motor and the positive effect of research has opened new perspectives for the development work associated with the structure of this type of electric machines.

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