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AMBs for high-speed motor-generators in aerospace

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Abstract

We report progress in the development of an active magnetic bearing actuator. This work includes finite-element modelling results and comparison with analytic models and literature. Static test results have been used to validate some aspects of the finite element models and a dynamic test rig has been designed to enable validation under levitated and rotating conditions. Particular attention is given to force–displacement characteristics, loss mechanisms and predicted rotordynamic behavior. Discrepancies between FEA and analytic models are discussed. The test rig architecture and planned instrumentation strategy are also outlined, forming the basis for forthcoming experimental correlation.

Keywords : Aerospace, Rotordynamics, Actuator, Manufacturing, Modelling, FEA

1. Introduction

This paper outlines the development activities undertaken by NEMA moving towards production of an Active Magnetic Bearing (AMB) system for levitation of a 60,000 rpm Motor-Generator unit (MGU) for a commercial helicopter turboshaft engine. A 12 pole segmented actuator has been designed and modelled using Finite Element Analysis (FEA) and analytic approximations. An experimental setup to keep the rotor at known position within the stator has been developed and implemented to characterise the force-current-rotor position relationship and validate the static models. A dynamic test rig has also been designed which will allow rotation up to 6000 rpm and versatile levitated supercritical test conditions under a range of unbalance conditions.

Dynamic performance characteristics have been ascertained from FEA analysis and their value compared to literature and analytic equations.

1.1. High-Speed rotating machines in aerospace

High speed rotating machinery is required for many aspects of aerospace propulsion including: pumps & compressors, turbo-engines & microgas turbines, motor generator units. The main benefits of AMBs which can be utilised in these applications are: high rotational speed operation including super critical, no/low maintenance, intrinsic rotor health condition monitoring and the ability to hermetically seal the rotor. The incumbent technology in most of these applications are thin film bearings, where AMBs outperform this kind of bearing is in shock resilience, dynamics stiffness and low noise due to large airgaps, among others.

There are a number of challenges specific to aerospace applications:

1.2 Shock and vibration

Unlike most terrestrial housings the frame of an aerospace AMB is subject to many accelerations shock and vibrations. These environmental conditions are described in the industry standards (RTCA/DO-160G, 2010). A typical shock and vibration spectrum are shown in Fig. 1. The AMB system as a whole must allow the rotor to continue uninterrupted operation throughout all these conditions.

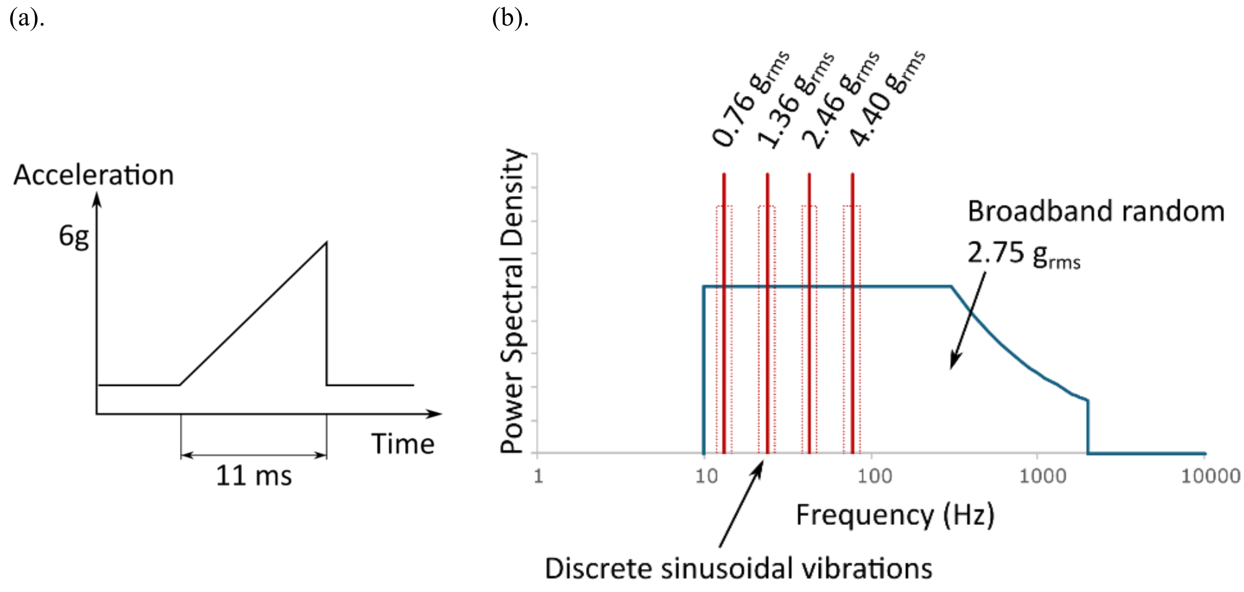


Fig. 1 Typical Shock (a) and vibration (b) conditions experienced during operation in a commercial aerospace application. The characteristics described here are standard operating shocks for all classes of equipment (a). and the vibration environment for helicopter equipment in zone 4; Engine and gearbox (b).

2.3 Reliability

Typically equipment related to the main power train of the aircraft must have probability of catastrophic failure of less than 10^{-9} hr^{-1} (ARP4761, 1996) and have a mean time to failure of 10^{6} hours. To meet these stringent reliability targets redundancy is required in most electrical systems and is likely that all AMBs will be required to be redundant to some degree. This is partially resolved by the necessity of having auxiliary bearings in the system but designing auxiliary bearings which will maintain performance is highly challenging. Some AMB topologies are inherently redundant and can be designed to continue a large fraction of their duty with one or more actuator channel faults (coil, power electronics or control circuitry).

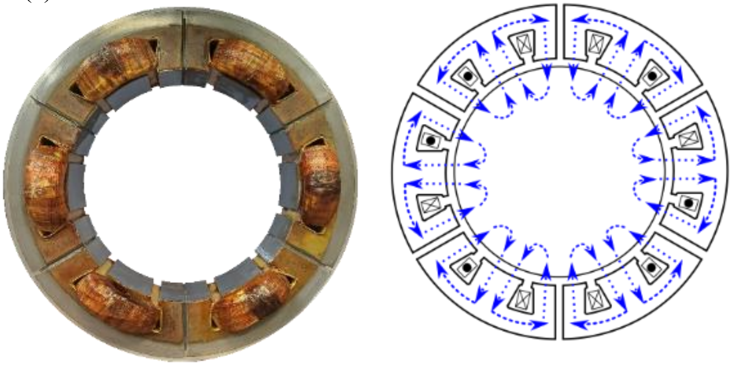
2.4 Weight

The American federal aviation authority (FAA, 2024) have calculated that each 1 kg of aircraft weight requires around 100 kg of fuel burn per year and displaces that much payload, making light weight component in aerospace systems critical. In AMBs to achieve the lowest possible weights load capacity must be sacrificed (steel saturation). Therefore it is expected that to make a viable aerospace AMB load sharing with the auxiliary bearings must be implemented. This means that transient contact dynamics (Su et al., 2021) become important and re-levitation is required while avoiding the highly damaging backward whirl touchdown scenario.

2 Simulation

Commercial FEA software produced by ANSYS has been used to model the electromagnetic performance of a 12pole radial actuator designed by NEMA. The topology of the actuator is shown in Fig 2. The static force-current-rotor position was modelled in Fig 3. using magnetostatic simulations in 2 & 3D and then measured up a maximum force before the test rig stiffness was overcome by the magnetic force. 3D FEA gives a more accurate prediction of the force than 2D which is to be expected.

(a).



(b).

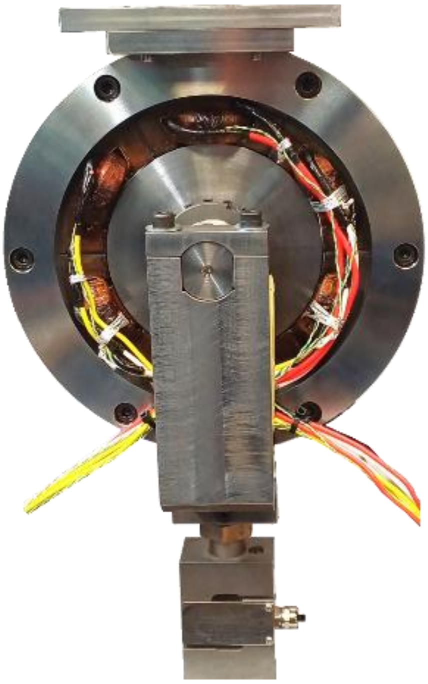


Fig. 2 (a) 12 pole segmented radial actuator designed by NEMA. And (b) static test rig used to measure radial force applied to rotor.

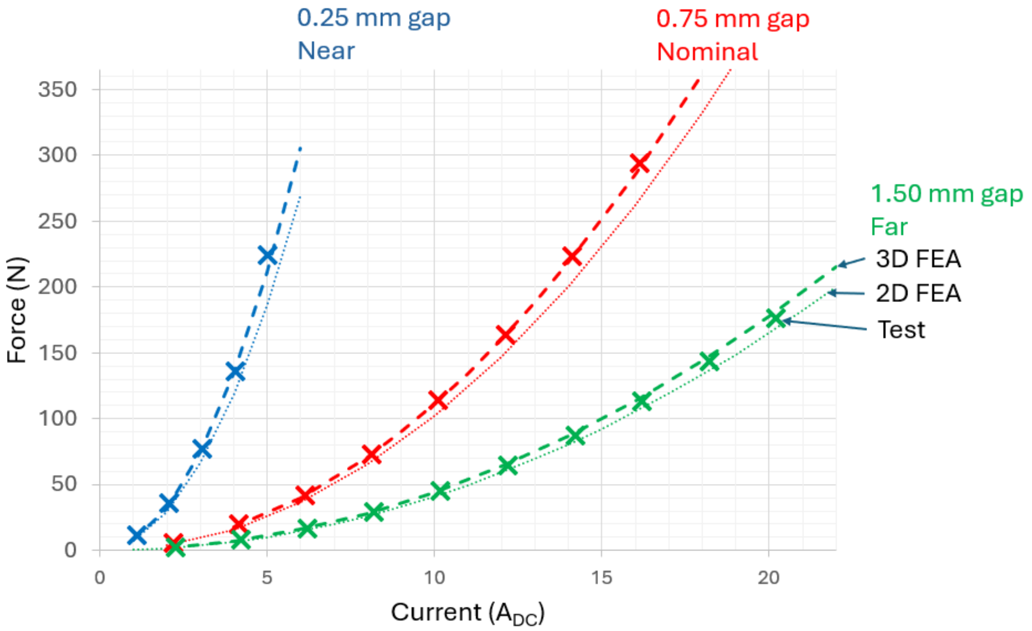


Fig. 3 Force-current-rotor position relationship modelled by FEA and measured by linear force gauge.

The Coil impedance is an important parameter for design of the control and power electronics, the DC resistance is simple to calculate from the winding wire properties but the impedance and AC affects on the resistance are more complex. The frequency dependent inductance was modelled with an AC magnetics (eddy current) solver in 3d as per Fig 4. Modelling of the individual strands is required to improve the fidelity of the model.

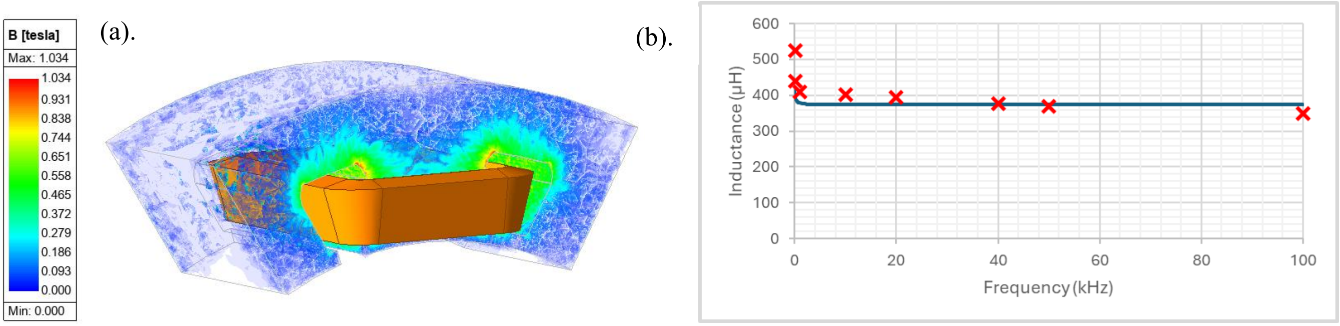


Fig. 4 3d "eddy current solves (a) of the segment impedance (b), good agreement with measurement at high frequency but some discrepancies below 1 kHz.

The DC copper losses are a significant source of power loss in the system especially at low speeds. Losses which contribute to braking the rotor are also important the hysteresis and eddy current losses in the rotor are the main mechanisms which cause this. 2d transient solves were used to predict the rotor iron losses, which manifest as a braking torque, for unbiased and biased case. In Fig 5. Analytic equation for the losses are given by Schweitzer (2020) as:

Eddy current power loss $$P_e = \frac{1}{6\rho}\pi^2 e^2 f_{remag}^2 B^2 V_{fe}$$

Hysteresis power loss $$P_h = k_h f_{remag} B^{1.6} V_{fe}$$

Where: ρ is the steel resistivity, e is lamination thickness, f_{remag} is the re-magnetization frequency, B_m is the maximum flux density, V_{fe} is the iron volume and k_h is the lamination steel hysteresis loss coefficient. It was found from magnetostatic simulation that the radial component of the flux at the surface of the rotor iron gave the best estimate of the losses throughout the speed range.

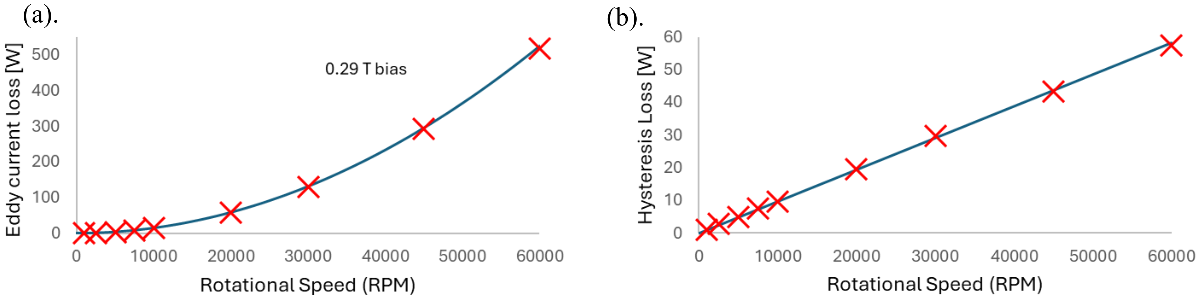


Fig. 5 2d transient solves of the two primary loss mechanisms Eddy current (a) & hysteresis loss (b) which produce a torque drag on the rotor.

The same analytic models have been used to predict the losses of work by Kasadra et al. (1999) & Breńkacz et al. (2021). The predicted values are found to agree with the presented data sufficiently considering the lack of detail of material and dimensional detail included.

3 Dynamic test rig

A test rig has been designed to experimentally validate models and provide a development platform for AMB control. A schematic of the test rig is shown in Fig 6. The rig has been designed to allow complete axial freedom of the positions of the components of the system: unbalance disks, rotor position sensor targets, AMB rotors & auxiliary bearings. The test rig also allows operation using stiff rolling element bearings this will allow for validation of rotordynamic models of the system.

Force gauges on the bearing / auxiliary bearing mounts allow phase dependent measurements of the bearing forces. This will allow for inspection of touchdown scenarios.

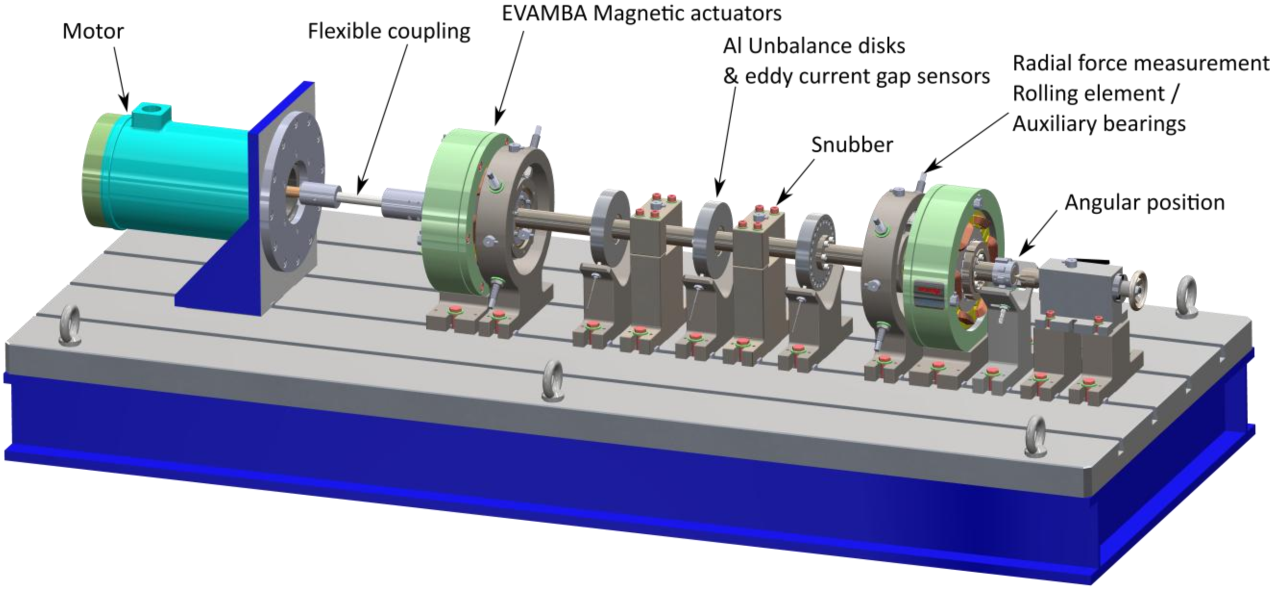


Fig. 6 Model validation and AMB control development rig. Tapered lock hubs allow complete axial freedom of the different components.

3.1 Rotordynamics

A 2d rotordynamics software; ROSS (Timbó 2020)was used to predict the resonant behaviour of the test rig and the test rig was designed to have a 1st bending mode in the accessible speed range (0-6000 rpm), so, with stiff rolling element bearings or softer AMBs super critical operation can be investigated.

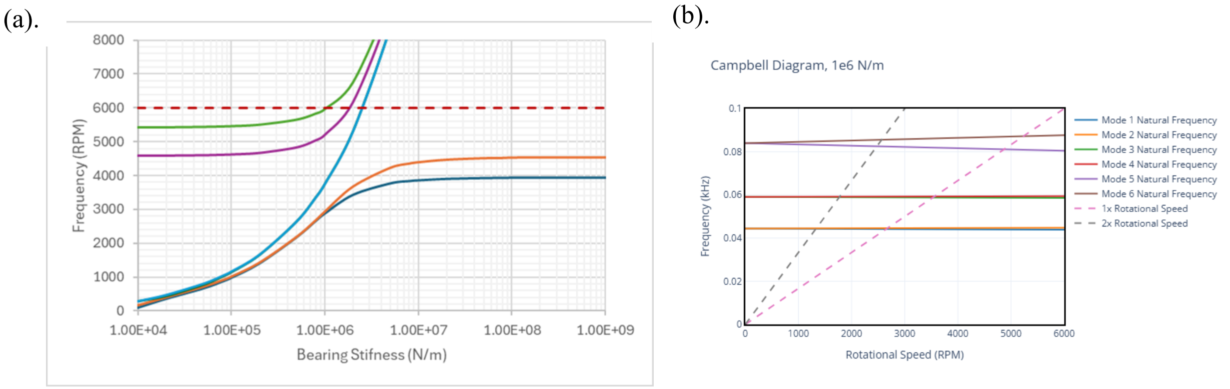


Fig. 6 Predicted resonant behavior of the test rig allow super critical operation on stiff or soft bearings.

3.1 Conclusions

2 & 3D FEA models have been developed for an AMB actuator, the 3D magnetostatic FEA models have been found to be in excellent agreement with experimental data. 3d AC magnetic solves have been implemented to ascertain electrical characteristics and compared experimental results, the inductance was found to be sufficiently well predicted. AC affects of resistance will require further refinement to the models including stranding of the conductors to probe skin and proximity effects. Transient 2D solves have been implemented and found to agree well with analytic models and literature values.

Further work will be to refine the AC magnetic models and validate the loss and rotordynamic models with experimental results from the upcoming dynamic test rig.

9. Acknowledgments and conflicts of interest

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