Analysing the effects of integration on the Noise from Electric Aircraft Motors

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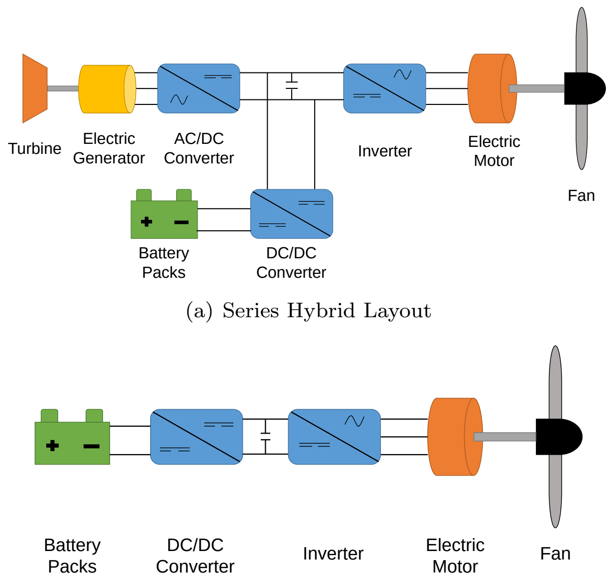
Introduction

The aviation industry accounts for 2.5% of the worlds total CO_2 emissions, plus other non-CO_2 emissions [1]. The amount of emissions produced will only increase as air transport returns and surpasses the traffic levels before the pandemic. To reduce the emissions of air travel, the concepts of an All-Electric Aircraft, Hybrid Electric Aircraft, and More Electric Aircraft are under investigation. In order to perform the electrification of the aircraft, electric machines are implemented into the powertrain or used for subsystems. A More Electric Aircraft uses the electrical machine to generate electricity or drive the electric, hydraulic and pneumatic systems that were previously powered by the turbine [2]. For an electric motor in the powertrain, the requirements determine whether it is classified as a hybrid or all-electric powertrain [3]. A hybrid powertrain integrates the electric motor while keeping the turbine. The initial way to differentiate a hybrid architecture type would be the use of a battery pack. Turboelectric powertrains do not use a battery pack, having all energy supplied by the turbine while a hybrid-electric powertrain includes a battery pack to provide energy as well. Hybrid-electric powertrains can also be split into further categories: Series, Parallel, or Series-Parallel. Series uses the turbine to drive an electric generator, which powers the electric motor and provides energy to batteries as well, as shown in Figure 1(a). Parallel has the turbine and electric motor on the same shaft to drive the fan or propeller individually or together while a Series-Parallel is able to perform a combination of the other two layouts. An All-Electric powertrain has the fan directly powered by the electric motor, enabling the removal of the turbine, depicted in Figure 1(b). This would be the only powertrain layout capable of zero emissions, however a major limitation is current battery technology and weight increases [4]. For large transcontinental aircraft, the amount of batteries required would render the rest of the plane inoperable for passenger transport. However, regional planes would be able to use the current technology to implement more efficient systems.

Having electric motors would reduce the carbon emissions emitted but another source of pollution would need to be considered, which is noise and vibration. The common noise sources in the turbine propulsion system from a traditional combustion aircraft is the jet, fan, turbine, compressor, and combustor [5]. The noise created has the greatest effect at or nearby airports due to the high concentration of people. Two major airports, Heathrow in London, England and Schiphol in Amsterdam, have



(a) Series Hybrid Layout

(b) All Electric Layout

Figure 1: Two different propulsion system architectures. Based on [3].

an annual cost of 179.5 and 86 millions Euros in order to reduce noise nuisance, respectively [6]. Since noise has a large impact on the environment and costs, noise reduction techniques and technology has been prioritized. Current engine noise reduction solutions include developing better noise prediction models, active noise control, chevron nozzles, forward-swept fans, higher bypass ratios, scarf inlets, and swept/leaned stators [7]. While some of these technologies could be adapted and used with the implementation of electric motors, any noise and vibration not reduced needs to be analysed.

H2Electra

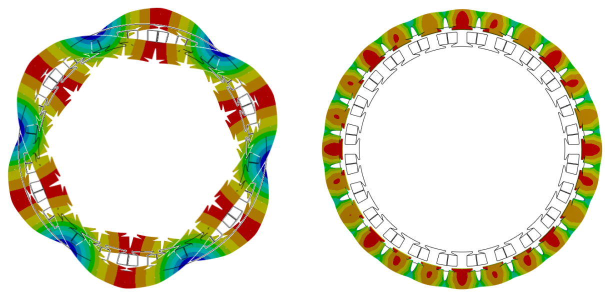
The H2Electra is a project of the German Aerospace Center to create an hydrogen based electrified regional aircraft and the basis aircraft for this project [8]. Its size would be comparable to the 78 passenger plane ATR72 and would have a payload of 6 tonnes, which can be broken down into 50 passengers and 1 tonne of cargo. To power the all electric aircraft, two possible propulsion system types could be used: a partially fuselage-integrated or nacelle-integrated propulsion system. The nacelle-integrated propulsion system would have one nacelle on each wing, containing the electric motor, gearbox, fuel cell, and power electronics. The hydrogen tank would be located in the fuselage and the batteries located in the wing. The partially fuselage-integrated propulsion system would have 6 nacelles, three on each wing. The nacelles would be smaller, as they would have electric motors with less power and only a gearbox and inverter, along with the other required systems. The rest of the components required for the propulsion system would be found in the fuselage, such as the hydrogen tank, fuel cell, batteries, and the power electronics. Although both propulsion system types have advantages and disadvantages, the main goal is to build a working All Electric Aircraft.

Background

The introduction of electric motors into the propulsion system brings many new challenges and problems that need to be solved. One problem that needs to be understood and limited is the noise and vibration created by the system. To keep the plane as safe as possible and comfortable for all people inside and around, all potential sources have to be determined and analysed.

For an All Electric Aircraft, noise and vibration sources are found all around the plane. While these sources should not be ignored, there is a much larger unknown with the use of an electric motor. As the electric motor will be implemented into the nacelle with other components, that will be the area of focus. There are four categories that noise from an electrical machine can be divided into: aerodynamic, electronic, magnetic, and mechanical [9]. Electronic noise is caused by harmonics in supply voltages that are not perfectly sinusoidal. Aerodynamic noise is caused by fans being used for forced air cooling of the electric motor. Magnetic noise takes place inside of the electric motor, caused by radial forces travelling through the air gap and acting on the stator and rotor. Mechanical noise is caused by bearings. While all sources of noise can be present, magnetic noise inside the air gap due to the radial forces acting on the stator will have the largest effect. Not only does the electric motor need to be considered, but also how its noise and vibration changes when interacting with other components. A component undergoing constant vibration is able pass the vibration to other components, amplifying its effects and radiating noise into the far field.

To analyse the noise and vibration, a structural modal analysis is performed on the desired component. Modal analysis involves having a computer model of the component or system and using a computer software to perform the analysis. No forces are applied to the component or structure for a modal analysis. The purpose is to determine the modes of the component as well as their related natural frequencies. A structure has many modes, therefore many natural frequencies, with each frequency corresponding to a different mode shape. Mode shapes are the form that the structure takes at that natural frequency. The characteristics of a mode is determined by the shape of the structure, material properties and boundary conditions. Often the notation (m,n) is used to indicate half the number of nodes in the circumferential and axial directions. In the context of this work, only the nodes in the circumferential direction are considered.



(a) (b)

Figure 2: a) Mode $m = 3$ of a Stator with winding. b) Mode $m = 0$ of a Stator with winding. Undeformed shape with black outline.

Figure 2(a) shows the mode $m = 3$ of a stator with winding. The black outline shows the original shape and the coloured portion shows the (deformed) mode shape. The intersection between the two triangles in the blue region is the node. It is also important to note that both triangles are part of the same mode as the natural frequency causes the component to transform back and forth between triangles. Mode $m = 0$, also known as the breathing mode, has no nodes. As seen in Figure 2(b), the entire ring becomes larger and shrinks, having no points of zero motion. To perform a modal analysis, the model is uploaded, then the materials is chosen. Some material properties are required, such as density, Poisson's ratio and Young's Modulus. Then a mesh of the model can be generated. For the mesh, the smaller the individual elements are, a more precise result is generated, however more time and processing power is required. After generating the mesh, the software can be run to find the natural frequencies of the model. A further analysis of the model is possible to determine the mode shapes for its corresponding natural frequency.

Analysis

In order to analyse the noise generated by electric aircraft motors, four stages of the integration were chosen. A four stage analysis allows for a comparison of natural frequencies to understand how integration affects the natural frequencies and mode shapes. The first component analysed will be the electric motor's stator. The stator is made of Vacoflux 48 and has 24 slots. The next stage will be of the stator and winding, where copper windings will be placed in the slots. The third stage will be the whole electric motor. It consists of magnets, rotor, rotor band, shaft components, stator and winding as well as the casing. In the final step, the motor was mounted inside the nacelle. The nacelle was designed for the partially fuselage-integrated propulsion system of the H2Electra. A propeller and cowling were used on the nacelle, however their role was to act as a guide for the size and have not been included in the analysis. Inside the nacelle, a frame was built to hold the electric motor, along with the other components required in the propulsion system. Those components, the gearbox and inverter, were added to the nacelle just for mass purposes. The different stages

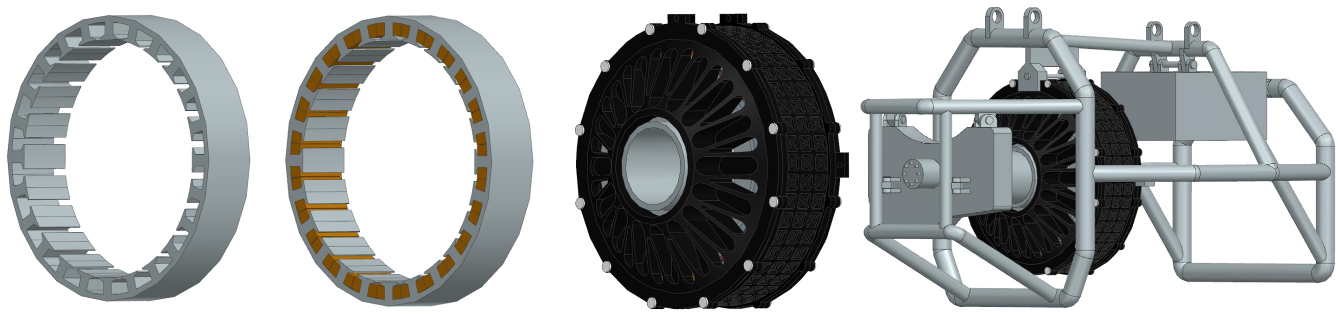


Figure 3: Different model stages of the electric machine and its integration into the frame. From left to right: Stator only, stator with winding, complete machine, machine integrated into the frame. The end wiring has been omitted.

are shown in Figure 3.

Prior to performing the final modal analysis, a mesh sensitivity analysis was performed to ensure that the discretization was fine enough and the results were accurate. Simulated using ANSYS Academic 2023, the mesh analysis pictured in Figure 4 was done with the stator only. Meshes of different sizes were tested, observing the change in frequency for all modes. The frequency was normalized by dividing all outputted frequency values by the accurate frequency value, determined when the frequency values had changes of less then 0.1 Hz. Using the results from all modes, it was seen that meshes with a number of elements less 8500 saw a significant decrease in accuracy. The most accurate frequencies were archived with an amount of elements greater than $20e3$. While an element amount of greater than $90e3$ can be used, the resulting frequency is nearly identical while the computation time took much longer. In this case, a very large amount of elements would not yield a large enough benefit to be worthwhile.

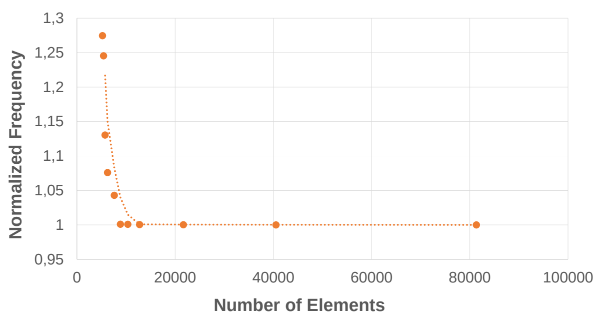


Figure 4: Mesh sensitivity analysis of the stator's mode 6. Frequency normalized by the accurate frequency value.

Results

A modal analysis has been performed on the different model stages including: stator, stator and winding, electric motor and integrated model. Modes 0, 2, 3, 4, 5 and 6 of each model were examined. The results showed that all stages of integration had these modes appear in the solution, so a comparison of the frequencies for each mode is possible. The modes were most clearly seen in the stator, stator and winding, and the electric motor. Although the integrated component didn't have a full cylindrical shape, the modes were still visible. Taking a closer look at the components, the stator had its first mode (Mode $m = 2$) appear at 114 Hz, the lowest recorded. Each following mode of the stator increased in frequency, with Mode $m = 0$ having the largest frequency at 2865 Hz, with a fairly large increase from Mode $m = 6$.

The next step in the integration was the stator and winding. The theoretical understanding would assume that the frequencies would be larger as the windings would add mass and stiffness to the structure. These results were also supported by the modal analysis of the stator and winding. The natural frequency of Mode $m = 2$ was 154 Hz, slightly higher than the stator's natural frequency. The next modes also had larger frequencies with the difference in frequency between the two components increasing. The one exception was Mode $m = 0$, where the frequency decreased to 2478 Hz.

Taking a look at the electric motor, the natural frequencies for all modes increased in a range from approximately 1100 to 1700 Hz. This is easily understood as having many more components increases the overall mass, and the housing adds another value of stiffness. Mode $m = 2$ had the lowest frequency of the electric motor while Mode $m = 0$ had the highest, however the value was only slightly higher than Mode $m = 6$. The Mode $m = 0$ frequency of 3587 Hz was also the highest frequency found in all components. The front and rear covers are connected to the housing at the perimeter, so while the perimeter experiences the mode shape, the rest of the cover is able to reduce the deformation so the center has almost no movement.

The final step was the integration with the nacelle. Looking at the frequencies of the all modes except Mode $m = 0$, the frequency increased for each mode. However, the frequency difference between the integrated and electric motor decreased with the frequency for Mode $m = 6$ being almost identical. Mode $m = 6$ was also the integrated model's highest frequency. While the electric motor didn't have a change in mass, its boundary conditions changed as the mounting to the frame now plays a role. Having locations of restricted movement increased the frequency. The only mode where this was not true

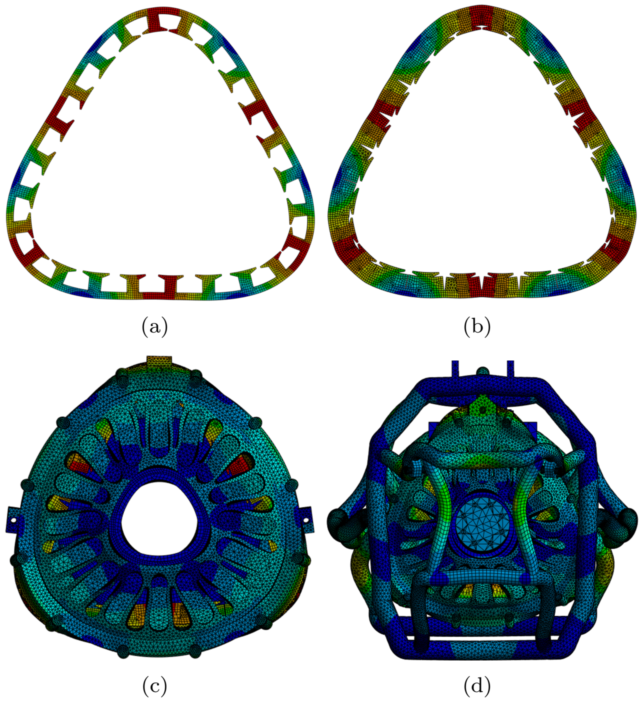


Figure 5: Mode $m = 3$ for the different model stages. a) Stator only, b) stator with winding, c) complete machine, d) machine integrated into the frame.

was Mode $m = 0$, as the frequency decreased from that of the electric motor.

Figures 5(a) to 5(d) show the deformation results of all four models for Mode $m = 3$, whereas Figure 6 shows the determined frequencies for the investigated modes.

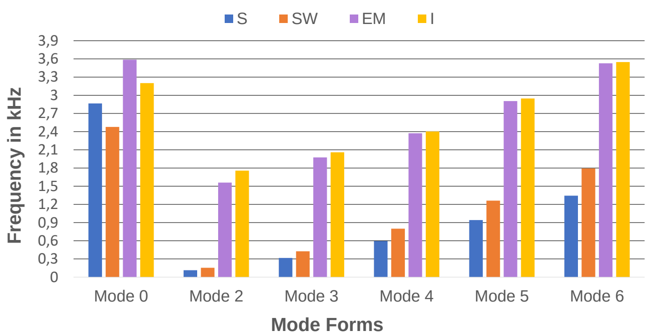


Figure 6: Comparison of Modes 0 to 6 natural frequencies in the different model stages. Stator only (S), Stator with Winding (SW), complete machine (EM), machine integrated into the frame (I).

Conclusion and Next Steps

This paper showed how mode shapes and natural frequencies are affected by the integration of an electrical machine into an frame. It was seen that modes are able to be compared if the structures are similarly shaped as the same mode shape reappears. The natural frequency of modes also usually increases with the integration of more parts as more mass, stiffness and areas of restricted movement are added to the entire structure. Having this information will help in determining the noise (e.g. by performing a harmonic response analysis) by an integrated electrical machine and what influences it may have on the rest of the plane.

The next step for this research would be to validate the results of the stator, stator and winding, and electric motor by testing an actual electric motor. With validated results, the integrated model gains trust and can be used for further developments. The mounting of the electric motor inside the frame could be changed and how the frequency is affected can be determined. An investigation with a further integration would also be possible, where the focus would be on vibrations passed to the wing when the nacelle is mounted on the wing. Other investigations could be of the Mode $m = 0$ and why it doesn't conform to the trends of the other modes.

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