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WHITE PAPER

How Electrification is Changing Aircraft Testing

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Advances in electric propulsion create new possibilities for new structural geometries. All aircrafts require testing for structural integrity before they can be considered flightworthy, but these new geometries require even more attention. Similarly, the new propulsion methods need to be characterized and optimized for flightworthiness and maximize range. This paper will look at the importance of ground vibration testing and why it should be considered when developing the electric propulsion systems.

WHAT IS GVT AND WHY IS IT NECESSARY?

Ground Vibration Test (GVT) is the process used to determine information such as the damping, stiffness, natural frequencies, and mode shapes inherent to the dynamic response of a structure or aircraft. GVT is a crucial step in the development of a new aircraft as flutter analysis relies on the results of this test to aid in the prediction of flutter critical speeds. This data is needed for the aircraft's flight safety and to be considered flightworthy.

WHAT IS "FLUTTER" AND WHY DO WE CARE?

There are two main types of flutter, classical and whirl. Classical flutter is an instability in the aircraft wings which originates from aerodynamic, inertial, and elastic forces. Whirl flutter is an instability that occurs within specific conditions, which involves the stiffness of the supporting the nacelle structure and the aerodynamic and inertial effects of a rotating propeller.

Classical flutter is sensitive to the construction of the aircraft, where the response of flutter comes from the oscillation of the wings and various control surfaces. These oscillations can be in the form of bending and/or torsion of fixed surfaces like the wings and fuselage along with torsion and/or rotation of the control surfaces like ailerons, rudder, flaps, and elevator.

Whirl flutter is sensitive to the structural damping and the stiffness between the attachment of the motor to the wing. This type of flutter instability becomes more critical when its frequencies align with the structural modes of the aircraft. Both types of flutter can cause unwanted vibrations in the aircraft which can result in passenger, discomfort, fatigue, structural damage, or catastrophic failure.

IS A GVT MANDATORY?

Yes, a GVT is mandatory for the certification of new aircraft and existing aircraft that have undergone a major reconstruction or modification.
See FAA and DoD regulations below.

FAA – 14 CFR § 25.629 Aeroelastic stability requirements
(a) General. The aeroelastic stability evaluations required under this section include flutter, divergence, control reversal and any undue loss of stability and control because of structural deformation. The aeroelastic evaluation must include whirl modes associated with any propeller or rotating device that contributes significant dynamic forces. Compliance with this section must be shown by analyses, wind tunnel tests, ground vibration tests, flight tests, or other means found necessary by the Administrator.

DoD – MIL-HDBK-516C Airworthiness Certification Criteria
(2 examples)

Section 5.2 Structural Dynamics
Sub-section 5.2.1 Aeroelastic Design – general
Method of Compliance (Navy): Verification methods of the JSSG and MIL-A-8870 include analyses (e.g., flutter, mechanical and torsional stability), component level test (e.g., mass property verification, stiffness, force-velocity, free-play and rigidity of flight control system and surfaces), wind tunnel tests, ground test (e.g., ground vibration tests, whirl tests, torsional stability, mechanical stability), pre-flight correlations to ground test results, flight test, inspection and review of documentation. Compliance is shown for each combination of configurations at all critical gross weight, center of gravity, lift, payload, and environmental condition specified.

Section 6.2 Vehicle Control Functions (VCF)
Sub-section 6.2.1.1 Functional Criteria
Method of Compliance: Verification methods include analysis, test, demonstration, simulation, inspection, and review of documentation. Modeling and simulation are used to analyze and evaluate the VCF architecture. Testing of the VCF includes, but is not limited to component development, qualification, and Failure Modes and Effects Tests (FMET) or failure modes testing. System Integration Laboratory (SIL), Vehicle Integration Facility (VIF), and hardware in the loop (also known as Iron Bird (IB)) are used to verify and validate integration of VCF with all other subsystems. The primary focus of SIL, VIF and hardware in the loop testing is to evaluate the operation of VCF under normal and failed states. FMET, or failure modes testing, is a particularly critical part of system level testing. Prior to first flight, Ground Vibration Testing (GVT), Structural Mode Interaction (SMI), Electromagnetic interference (EMI), and on aircraft ground testing are completed to demonstrate safe operation of the VCF under all natural and induced environments.

WHY ARE GVTS SO IMPORTANT ON EVTOL VEHICLES?

Electric Vertical Takeoff and Landing (eVTOL) aircrafts have radical, or non-conventional designs where they may have multiple motors on each wing. The motors can rotate vertically for takeoff and then rotate horizontally for forward motion. Because of the numerous motors on the wings, the structural characteristics of the aircraft are different from conventional designs (which have no motors or have one or two motors on the wings). The added mass and distribution of these motors will cause the wing bending and torsion modes to be lower in frequency than a conventionally designed aircraft. The aircraft also has motors that rotate vertically and horizontally which are more susceptible to whirl flutter. For efficiency reasons the aircrafts are designed to have motors which are propeller based to make taking-off and landing easier. Most of these motors have an RPM range with a frequency content that matches the frequency of the structural modes of the aircraft, which could make these aircraft very sensitive to flutter. If a flutter mode is excited to long the aircraft could incur a catastrophic failure.

Figure 1: Example of an electric aircraft with distributed propulsion

Figure 2: Example of electric vertical takeoff and landing

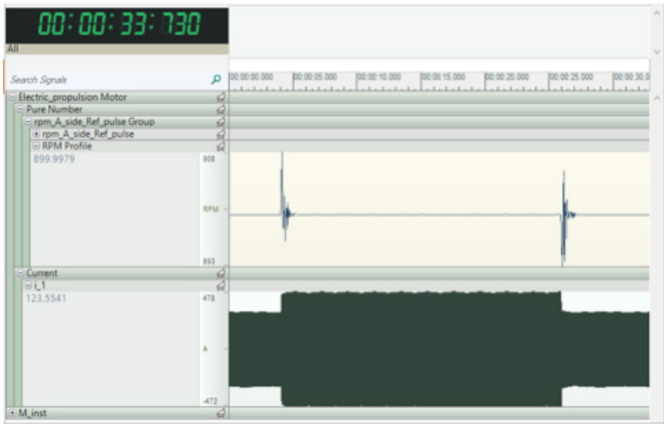

Figure 3: Time domain data

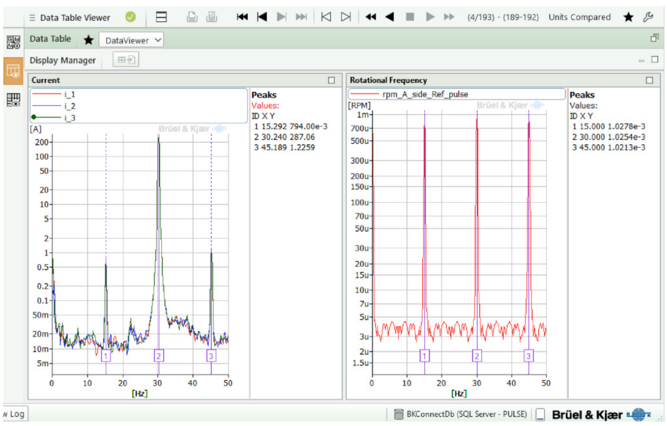

Figure 4: Frequency domain data

HOW CAN ELECTRIC MOTORS EXCITE MODES OF THE AIRCRAFT?

The typical RPM of electric motors, used on these aircraft, range from 500rpm to 1500rpm. The fundamental frequency of the RPM range is ~8Hz to 25Hz, which is the approximate range of the structural modes of an aircraft. Along with the rotation of the motors, we have the excitation coming from the motors electrical switching frequency. Figure 3 shows an example of the fundamental frequency of a four-pole motor is at 30Hz with side lobes at 15Hz and 45Hz. Since this is a four-pole motor the current fundamental frequency is twice the RPM's fundamental frequency (see figure 4).

Torque ripple is a torsional vibration in the motor shaft caused by construction, excitation, and is proportional to speed. Since the frequency of the current and RPM is in the range of the structural modes of an aircraft, torque ripple can also be a form of structural excitation, especially if the torque has a transient in it. As seen in figure 6, the frequency of the torque ripple can be in the range of the aircraft wing and fuselage bending modes .

Because of the increased number of excitations, eVTOL aircrafts are more susceptible to flutter which makes a GVT even more critical than conventional aircraft.

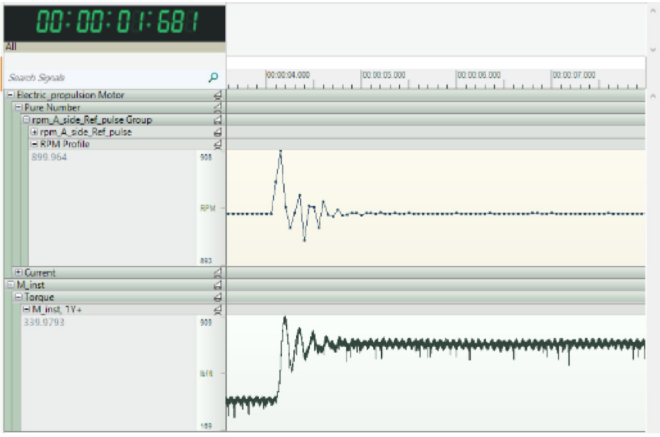

Figure 5: Transient in the Torque and RPM time data

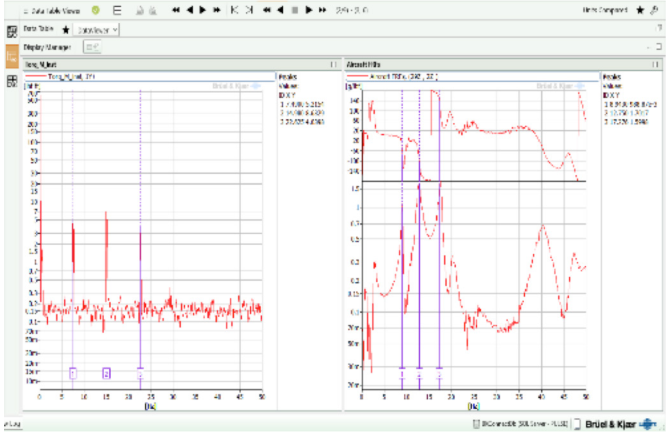

Figure 6: Frequency content of Torque data compared to an FRF on aircraft from artificial excitation

EXCITATION SOURCES IN ELECTRIC MOTORS

Using an electric motor for propulsion creates a variety of unique challenges to an electric aircraft including weight, distributed propulsion, and energy storage. To combat the weight of energy storage, and to maximize the range of the vehicle, it is beneficial to make motors as light, small, and efficient as possible. Through design choices in both the motor and inverter, lighter machines can be created with higher efficiency, but as a result create potential sources of vibration from mechanical and electrical sources.

One technique to reduce weight is to use less back iron during the motor construction. This will reduce the weight of the machine but lower the machine's inductance. The lowered inductance makes it harder for the machine to filter out the high frequencies of the inverter and results in a current with a high ripple and harmonic content (figure 8). The current ripple will often result in torque ripple and torsional vibrations which can couple resonances to the aerostructure resulting in classical flutter or pass frequency content onto the blades resulting in whirl flutter.

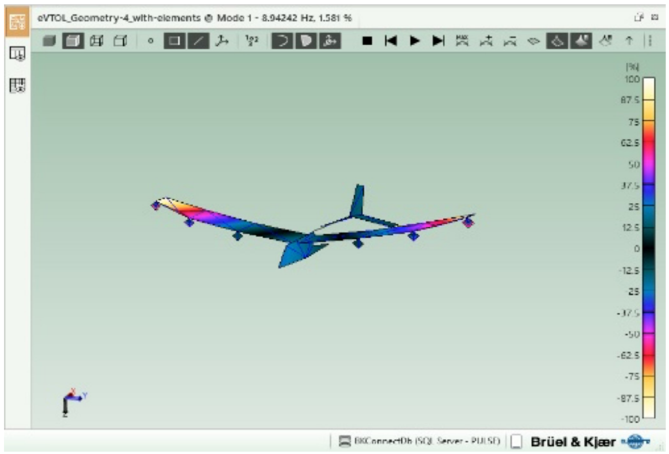

Figure 7: First wing bending mode 8.9 hz

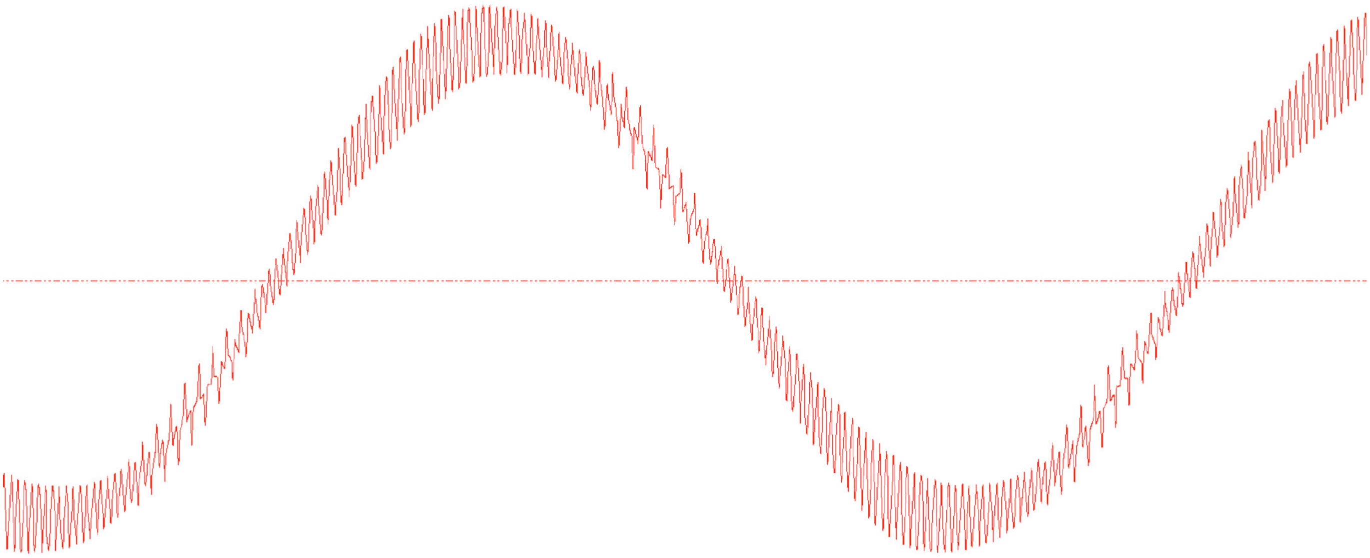

Figure 8: Current signature with large current ripple

To reduce the amount of current ripple and the size of other passive filters in the powertrain you will need to push the switching frequency of the inverter to very high levels. The passive filters can be large and contribute to the overall weight of the system. The switches in the inverter also have an associated loss every time the switch turns on or off, so higher switching frequencies will result in additional losses. Again, there is an engineering tradeoff between switching frequency and efficiency. It is possible to increase the switching frequency to regulate the size of passives and their associated current ripple, but the impact will sacrifice efficiency. For this reason, it is important to measure their vibration, torque ripple, current ripple, and efficiency on a single test to optimize their system for the tasks that need to be executed.

There is also an option to incorporate a gearbox into their electric machine design. Machines will typically be more efficient at higher speeds and lower torques but need to operate at the propeller speed. If it is possible to have lower machine losses than the additional loss of adding a gear box, you can incorporate a gear box to achieve higher efficiencies at the appropriate speed. The gearbox can have the downside of amplifying any torsional vibrations caused by the machine and adding their own element of gear chatter. Torque ripple through a gearbox can be seen in figure 9. This is another element that needs to be considered when designing a motor.

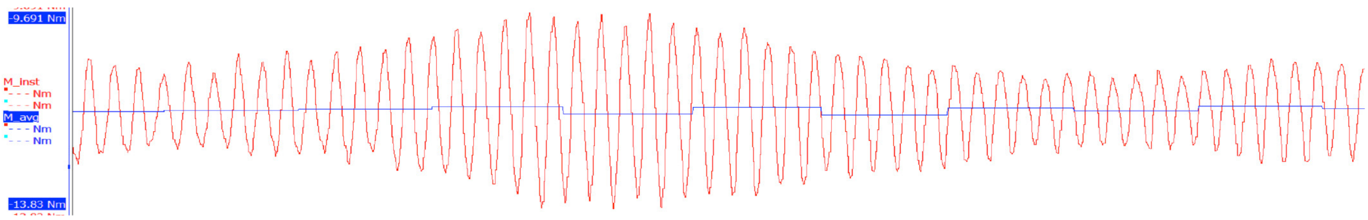

Figure 9: Torque ripple through a gear box compared with average torque

TESTING ELECTRIC MOTORS FOR ELECTRIC AIRCRAFT

GVT testing may seem vastly different from propulsion testing, but with novel aircraft designs that often includes many motors, the structural and propulsion teams will need to communicate more frequently. When developing and calibrating the powertrain system, it is necessary to maximize the efficiency of a system for a given design, while minimizing and avoiding any vibrations that the motor may cause.

This results in many test stands for powertrain performance also being equipped with many accelerometers. When optimizing the efficiency of the powertrain it is important to also monitor for vibrations that will affect the structures and propellers of the aircraft. Measuring both systems will ensure a faster development time and increase communication between groups. An example of combined measurements can be seen in figure 10 where two single accelerometers, a triaxial accelerometer, torque, speed, and current are all displayed on the same screen so that the motor control team can see how control type effects vibration. You can note an increase in Single_acc_2 when the control of the currents becomes less stable.

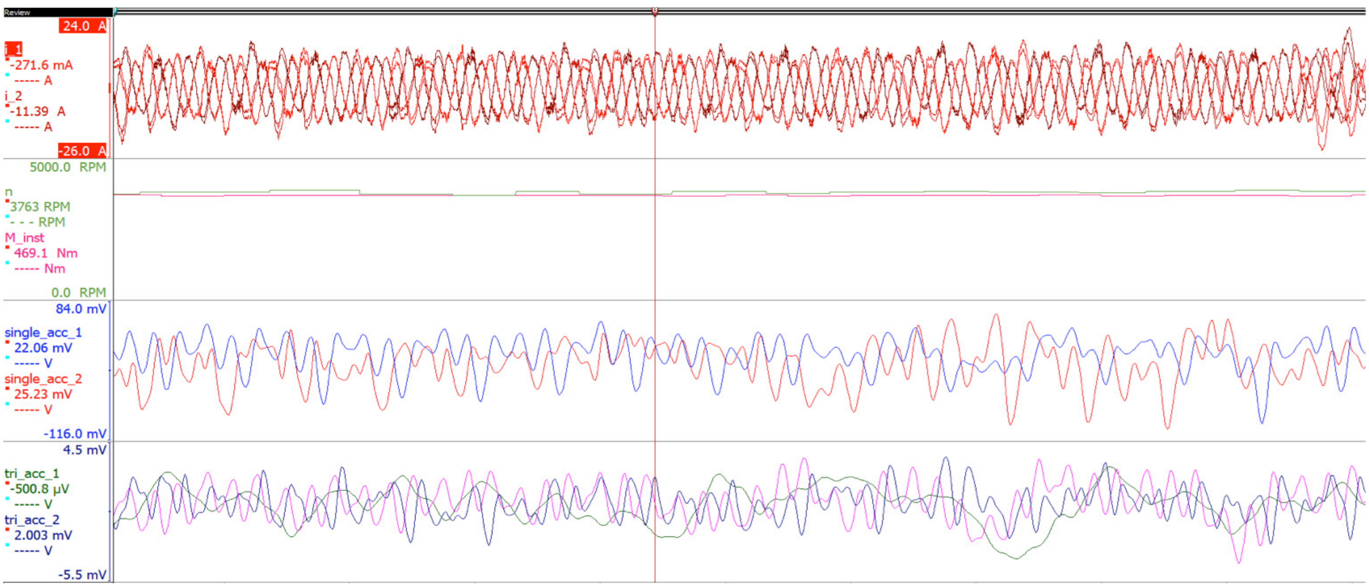

Figure 10: Measurement of electrical and vibration signals in a single powertrain test.

Electrical and structural measurements will need to be evaluated. When doing a system level powertrain test, where all the motors in a system are operating, engineers will often check for electrical resonances, electrical faults, and vibrations through the structures. System level tests will often take place on the wing or structure so that measurements can be made, like a GVT. Again, the propulsion team can electrically change the system control to avoid modes or vibrations.

CONCLUSION

Electric aircraft and the associated novel architectures will create many new opportunities for traveling, but these aircraft need follow a rigorous certification process to ensure safety. GVT is one of the key metrics for safety testing in aircraft to determine its structural airworthiness. The new structures are made possible by new propulsion methods and fuel sources that create issue of increased weight and limited range. The new propulsion systems also have a variety of structural excitation modes that can be altered by the powertrain control methodology. There are often engineering tradeoffs between vehicle range and vibration that control engineers will need to make. For this reason, structural and powertrain testing cannot be done independently. Information on powertrain excitation modes, and structural excitation modes need to be measured and communicated between groups.

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