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Fundamental recommendations for the design configuration of rotor shafts for use in electric motors and generators

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Abstract

This paper presents a real case study of a generator that successfully passed testing in one environment; although, the rotor shaft failed mechanically when the testing environment had been customized. So, to design a robust rotor shaft, major factors that affect the life time of the rotor shaft should be addressed and considered. These major factors which are addressed in this paper are fundamental geometry driven stress concentration factors, fretting driven fatigue stress concentration effects and vibration natural frequency. Finite elements analysis and extensive mechanical vibration tests were used to achieve a robust shaft design.

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Keywords: Rotor Vibration, Critical Speed, Fretting Fatigue, Notch Effect, Finite Element Analysis;

1. Introduction

The Rotor Shaft is generally considered the fundamental structure within an electric motor or generator. The shaft dimensions are principally controlled by the electromagnetic design and consequently, the material selection (for this component) is an important part of the design process. The material chosen should have sufficient strength and toughness to resist failure when subjected to the flight and vibration loads existing at the extreme edges of the flight envelope expected, operational and vibration loading as a result of a combination of geometrical stress concentrations and fretting fatigue.

Modern airplanes are entering the era of the 'More Electric Aircraft' and eventually the 'All Electric Aircraft'. To achieve these historic milestones in aviation requires high-power/lightweight motors and generators which operate at relatively high rotational speed, which increases the probability of rotor dynamics problems. It has been found that under certain conditions a rotor may precess about the bearing centre at a speed below the operating speed. Such motion is termed as non-synchronous, and is due to self-induced vibration (Newkirk and Lewis, [9]). Self-induced

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vibrations are caused by forces controlled by the motion itself as opposed to forced vibration which is a function of only time (Boeker and Sternlicht, [3]). Such whirling motion may be caused by external factors such as internal damping (Gunter, [5]), hydrodynamic forces in fixed geometry journal bearings (Reddi and Trumpler, [11]), or oil seals (Kirk and Miller, [7]). However, further work on the rotor dynamic stability was discussed in details in a case study that was presented by De Choudhury [4]. De Choudhury has discussed the capability of how the use of an analytical tools in diagnosing the rotor instability as well as solving the problem.

This work is a design case study of a rotor shaft for an aircraft electric generator. The generator in question was based on an existing and successful design and it was intended to supply the same generator - with a minimum of design changes - for a similar application on a different aircraft. So, this article addresses the phenomena of using of the same rotor in two different operational environments.

Although the existing design had been fully qualified and has been operating reliably in service, the main shaft in the new generator failed (mechanically) on three successive vibration qualification test attempts using a new vibration test procedure. The vibration spectrum required for this generator application; a combination of random and sinusoidal input, follows an alternative format (paragraph 8.8 RTCA/DO-160D [12]) for the new generator to that which is specified for the existing generator application (MIL-STD- 810-D Method 514.3 [8]).

The location of failure was the same on all three tests; at the root of the fillet radius (area of stress concentration) that blends between the main shaft diameters that accommodates the rotor and the rotor location abutment shoulder.

The unintentional interference between the shaft fillet and the rotor (too small a clearance chamfer on the rotor) further increased the notch effect (stress concentration factor) at the root of the fillet radius on two of the failures. This notch effect had already been identified and removed by configuration change and incorporated into the third test specimen, which also proceeded to fail. Finite Elements analysis was implemented to study the effect of the configuration changes (reducing the stress concentration factor) on the resultant stress.

Fretting was witnessed on all three shafts at the interface between the shaft and the rotor wound assembly.

This paper demonstrates the expected operational loads to which the rotor shaft in a generator would be subject to and how each of these loads contributes to the failure of the rotor shaft. It would also introduce the effect of the bearing pre load on the rotor shaft vibration. Fretting fatigue due to the clearance fit of the corepack to the rotor shaft has been investigated in order to establish the causes of the failure. This analysis did lead into robust and fundamental recommendations to overcome the failure of the rotor shaft; and hence to demonstrate compliance with the loading and vibration test specification of the revised generator configuration. These recommendations would be justified and discussed in detail in this paper.

2. Rotors loads

The rotor shaft is usually subjected to a combination of loads which are generated from manufacturing, assembly (interference or clearance fits), centrifugal rotational inertia, transmitted torque, thermal loads, end loads and vibration loads. These loads are discussed below:

- Centrifugal or rotational inertia loads: this load is the most significant load on the rotor shaft and the corepack assembly. Structurally, the corepack assembly is probably best thought of as a set of spinning weights. From this load the stress in a thin rotor shaft is given by

  $$\sigma = \rho\, \omega^2\, r^2/g \qquad (1)$$

  where σ is the hoop stress, ρ is the density ω is the rotational speed, r the radius of gyration and g is the gravity. So, from this equation it can be noticed that the stress varies as the square of the rotor rotational speed and the radius of gyration. In this case study; the maximum operational rotational speed was greater in the second operational environment (17040 RPM) compared with the first environment (15800 RPM).
- Torque load: Torque is transmitted from the gear box to the generator by way of the rotor shaft splines. Radial loads are introduced due to the wedge action of the spline teeth, so the rotor shaft is subjected to hoop tension under the action of transmitted torque.
- Thermal load: the generator is required to operate in hot and cold environments, and as the rotor assembly is constructed from different materials, consideration must be given to how these materials interact in these different environments. Different materials have different thermal expansion; therefore the rotor shaft would be under radial compression stress whilst other rotor parts (corepack) would be under tensile stress.