Measurement of Windage Losses and Temperature Distribution for a High Speed Composite Rotor in a Stator Assembly at Low Air Pressures

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Abstract

With the advancements in composite technology several innovative applications present themselves that involve high-speed composite rotors spinning in a stator assembly. As rotational speeds and rotor tip speeds increase, these rotors must operate in low air pressure environments to minimize windage losses and thermal effects of at high speed for long durations. Accurately predicting this windage loss for a specific geometry and operating conditions is very important for a proper design. Several analysis tools are available to aid designers in predicting this rotational windage loss. It is also very important to know the relative heat distribution that is seen by the rotor and stator from this windage loss. Analysis tools to date do not have a coupled link that calculates windage loss and a resultant thermal distribution to the rotor and stator surfaces.

This paper presents the design and fabrication of a test setup to measure the total windage loss and temperature distribution from a high-speed composite rotor in a stator structure. Rotor speeds up to 40,000 rpm and rotor tip speeds up to 900 m/sec with pressure ranges from 0.1 Torr to 10 Torr were operating parameters during the testing. The paper will also present experimental data obtained during the testing. Experimental data obtained during the testing will be used to evaluate new analysis methods for predicting the windage loss and thermal distribution in new high-speed rotor applications.

Introduction

The Center for Electromechanics at The University of Texas at Austin (CEM-UT) is a research facility that does a wide range of research associated with pulsed power generation and energy storage systems. One specific area of research that has observed an increase in interest in recent years is energy storage using high-speed composite flywheels. High strength composites have revolutionized flywheel designs and have allowed for smaller and lighter wheels than those made of metal. Some examples of applications that are presently being researched at CEM-UT include flywheel battery systems for power generation for space applications, as well as flywheel battery designs for a transit bus and a locomotive platform to improve fuel efficiency and reduce air

pollution. Others include small systems for uninterruptable power supplies for computer systems and slightly larger UPS systems for industrial use. Larger flywheel systems could also possibly be used for utility grid load leveling during peak use periods.

Any specific flywheel design, whether it is a UPS system that runs at a constant speed waiting for a loss of power or a flywheel battery device with a defined operating speed range, has windage drag losses imparted to the rotor. Many flywheel systems can be designed to operate in high enough vacuum levels that windage losses are not a concern. However, not all applications for high speed composite rotors can operate in these vacuum ranges so windage losses are extremely important [1]. This windage loss or drag on the rotor manifests itself as heat input to the rotor and stator. Even relatively small thermal energy input from windage losses can create temperature problems for a flywheel system. Composites in general have a much lower thermal conductivity than metals. These flywheel systems are also designed to operate in vacuum environments to minimize windage drag; therefore limiting heat transfer from conduction and convection. The combination of reduced thermal conductivity and minimal heat removal to its surroundings can cause these flywheel designs to reach critical temperatures that can limit the flywheel's safe operating life or worse, cause a flywheel failure. The magnitude of these windage losses is primarily a function of the specific rotor and stator geometry, the air gap between the rotor and stator, the pressure and temperature of the gas within the air gap, and the rotor tip speed. The first challenge for a flywheel designer is to be able to accurately predict the total windage losses imparted to the flywheel for a given set of operating parameters [2]. Once the total loss is calculated, the next challenge is to determine where this loss or thermal input is seen within the rotor/stator assembly.

Windage Test Hardware and Data Collection

The windage test hardware shown in figure 1 consists of two major components: a composite rotor and a stator assembly. The rotor used for this testing was a graphite composite rotor that had been fabricated and used for previous spin testing research at CEM-UT. The 11.9 cm (4.7 inch) long rotor is fabricated in a manner that results in the outer diameter being tapered with a 0.063 cm/cm (.025 in/in) taper per side. The outer diameter of the rotor is approximately 43.2 cm (17 inch). The composite rotor (fig. 2), consisting of eight individual preloaded composite rings, is approximately 14 cm (5.5 inches) radial thick and is pressed and epoxy bonded onto a titanium alloy (Ti6Al4V) center hub. This titanium hub has a stub shaft on each end that is 3.8 cm (1.50 inch) long and 5 cm (2.0 inch) diameter. Finally, the rotor is fitted with a .95 cm (.375 inch) diameter by 20.3 cm (8 inch) long, high-strength, steel quill shaft for

connection to the drive turbine during spin testing. The maximum operating speed for this rotor is 40,000 rpm (900 m/sec) with a peak operating temperature of 93 C (200 F). Peak allowable strain for the composite outer banding is 1% at 40,000 rpm. The outer diameter surface of the rotor was lightly abraded or buffed to remove the slightly shiny surface caused by the thin neat resin epoxy layer on the surface of the rotor. This buffed matte finish was required to minimize reflections and facilitate using infrared sensors to monitor the rotor surface temperature.

The purpose of the stator structure in the windage spin test is to provide a close boundary surface to generate the windage “drag” or loss on the composite rotor. The main stator structure is a carbon steel tube, .95 cm (0.375 in.) thick wall, with a bolt flange on each end. The bore of the steel tube is machined with a .063 cm/cm (0.025 inch/inch) taper to match the taper of the rotor. Immediately inside the steel tube is a hoop-wound G-10 composite liner with an approximately 1.0 cm (0.400 in.) wall thickness. This G-10 liner is machined to have a line-to-line fit with the I.D. of the steel tube. The I.D. of the G-10 liner tube is also machined with a .063 cm/cm (0.025 inch/inch) taper, again to match the taper on the rotor OD. The ID of the liner is also sized so that it provides a .25 cm (0.1 inch) radial air gap when the rotor is at peak speed (40,000 rpm). The G-10 liner provided a composite boundary on the stator I.D. to get representative heat flow into a composite layer. The ends of the stator structure are closed by bolting on a .95 cm (0.375 in.) thick 6061-T6 aluminum plate. Both aluminum cover plates have a .31 cm (0.125 inch) thick G-10 sheet bonded to their inside surface to provide a composite material for windage loss heat rejection to the end cover plates. The top aluminum plate has a short aluminum extension ring and a thin G-10 thermal barrier ring attached at its center. These two rings are hollow to allow the quill shaft to pass through. Attached to the top of the G-10 thermal barrier ring is a reaction torque sensor, Teledyne Engineering® model #5228. The purpose of the reaction torque sensor is to provide a real time measurement of the windage drag on the rotor by measuring the torque imparted on the stator assembly; i.e. the torque on the stator is equal to the torque on the rotor [3]. The entire stator structure hangs from the spin pit lid via a steel mounting plate. The bottom of the stator also has a short aluminum cap, which serves several functions. First, it extends the stator structure around the bottom stub shaft so pressure in the stator can be controlled. Second, it provides a radial “stop” for the rotor so if the rotor whirls during spin up, the composite rotor is kept from impacting the composite stator liner.

Sensor Details

An important aspect of obtaining good temperature data during the windage testing was the type of sensors used and the manner in which these sensors were mounted. Standard type-K thermocouples were used to record temperature data within the stator structure and infrared devices were used to monitor rotor surface temperatures.

The goal was to provide a reasonable number of temperature measurements to provide a reliable and comprehensive picture of the temperature distribution and yet not have the sensors themselves affect the recorded data due to their presence in the assembly.

The type-K thermocouples used in the stator assembly (Omega #C01-K) were a thin junction design mounted to a small thin plastic tab. These were designed to be epoxy bonded to a test surface. The stator had these thin thermocouples at several locations: the inner diameter surface of the G-10 liner the outer diameter surface of the G-10 liner and the outer diameter surface of the steel housing. There were two sets of three thermocouples each attached to the liner inner surface. One thermocouple aligned with the rotor axial centerline, and one to either side to measure the stator temperatures that aligned with the rotors top and bottom corners (fig. 3). The two sets of liner I.D. thermocouples were positioned 180 degrees apart and intended as a redundant measurement. The thermocouples on the liner O.D. surface (fig.3) were positioned to be immediately behind and inline with the liner I.D. thermocouples. The liner O.D. thermocouples also had the same two sets of three as a redundant measurement. There were only three thermocouples on the steel housing O.D. and these three were also aligned with one set of G-10 liner thermocouples (fig. 3). The thermocouples in the G-10 liner were imbedded in .076 cm (.030 in.) deep pockets machined into the G-10. The thermocouple pockets illustrated in figure 3 are drawn as a deeper pocket for clarity in the drawing. The purpose of mounting the thermocouples in these recessed pockets was to provide a smooth surface in the stator I.D. and not disrupt flow patterns in the air gap between the rotor and stator and also maintain a smooth surface on the liner O.D. to keep a true line-to-line fit to the steel housing. The thermocouples were first bonded in place using Loctite® instant adhesive #495. This adhesive maintains 50% of its bond strength at 100 C. After the thermocouples were fixed in their pockets, the pockets were filled with Loctite® Hysol 9396A epoxy resin. The epoxy was allowed to cure and then it was handed sanded smooth to provide a uniform surface profile at the thermocouple locations. It should be noted that these surface temperature measurements were not truly on the surface, but actually about .05 cm (.020 inch) below the surface. The pockets were .076 cm (.030 inch) deep and the thermocouples are approximately .025 cm (0.01 inch) thick. This thin epoxy layer was modeled and accounted for during the FEA thermal analysis that was performed after the spin testing. The three thermocouples on the steel O.D. were just bonded to the outer surface and not set into shallow pockets.

The thermocouples that were used to measure the end-face temperatures in the stator endplates were mounted in the same manor; shallow pockets on the inner surfaces with an epoxy fill and smoothed surface. The outer thermocouples were once again just bonded to the cover plate outer surfaces and inline with the inner thermocouples. There were two thermocouples on each of the top and bottom cover plates. The inner one positioned at about 1/3 the rotor radius and the outer one positioned at about 2/3 the rotor radius. These measurements were taken at just one angular position so no redundant set of data was obtained.

Five infrared sensors (Omega #OS36-K-140F) were used to measure the rotor surface temperatures during the windage spin testing. Three were positioned to measure the rotor O.D. surface and one on each end face of the rotor. As with the stator thermocouples, one infrared sensor was placed to measure the rotor axial centerline and one on each end to measure the corner temperatures of the rotor (fig. 4). These infrared sensors are approximately 1.27 cm (.50 inch) in diameter and 4.4 cm (1.75 inch) long. These infrared sensors are calibrated to a target with an emissivity of 0.9 with an accuracy of +/- 2% of nominal range. The stator housing was bored at these five locations and fitted with an aluminum holder to hold the IR sensors in place. The IR sensors were positioned to be flush with the G-10 liner I.D. and then held in place with a set screw in the aluminum housing.

The windage test assembly was also equipped with a set of six vacuum pressure transducers (MKS Instruments Baratron Absolute Capacitance Manometers Type 722A) to monitor the pressure within the rotor/stator air gap during the spin testing. Because the spin testing was to be performed at three different vacuum levels (0.1, 1.0, and 10 Torr), it was desired to measure the pressure distribution in the assembly at these different test pressures. These pressure transducers had a range of 0.1 Torr to 20 Torr with a full scale voltage output of 10 VDC at 20 Torr. This provided a transducer that measured specifically in the range of pressures for the spin testing. There were two pressure transducers evenly spaced along the rotor axial length measuring the pressure in the actual rotor/stator air gap. There were also two transducers on each of the stator cover plates located at approximately 1/3 and 2/3 of the rotor radius respectively. A single pressure transducer was also attached to the outside of the stator to measure the spin pit pressure. The pressure transducer manufacturer data showed that these devices are sensitive to temperature changes (0.008% of F.S./C). Because these transducers were to be mounted to the stator which was assumed to heat up during the spin testing, a low

thermal conductivity plastic mounting bracket was used to attach the transducers to the stator (fig. 5). This mounting bracket had a small diameter hole through the middle of it to expose the transducer to the stator bore. To insure that the pressure data was reliable and not affected by temperature changes, a type-K thermocouple was attached to the casing of each pressure transducer to monitor temperature during a test. Inspection of the data after the testing showed that the thermal insulation worked well and the pressure transducer temperatures did not vary more than a degree or two during a test.

Sensor Calibration

Before the actual spin testing was done, the various sensors were calibrated to verify that the data acquisition system was working properly and the sensor outputs were reliable. Several different calibration setups were used to check the temperature sensors, the pressure sensors, and finally the reaction torque sensor.

The temperature sensors were checked and calibrated by heating the entire stator assembly in the oven to approximately 70 C (160 F). All the thermocouple channels were recorded and compared to other channels measuring similar points within the stator assembly. All thermocouples showed to be working well and within 1 to 2 degrees C of similar measurement points (fig. 6). For presentation clarity, only two of the recorded stator temperatures are shown. The infrared sensors were in place in the stator assembly during the oven heating cycle. With the stator assembly at 70 C (160 F), the stator was removed from the oven and the room temperature rotor was positioned within the stator assembly as it would be during a spin test. This was done to provide a temperature differential between the rotor and stator surfaces that may be present during a spin test. The stator slowly cooled and the rotor slowly heated up. With the rotor now in place, the infrared sensors now measured a rotor surface temperature for verification. Before placing the rotor in the stator assembly, two type-K thermocouples were affixed to the rotor O.D. surface. These two thermocouples provided a reference temperature for comparing to the infrared sensor output. It was observed that the infrared sensors output also remained within 1 to 2 degrees C of the reference thermocouples on the rotor OD (fig. 6). This calibration testing did not account for the potential effects of a surface boundary layer on the surface of the spinning rotor that may affect the infrared sensor accuracy. These infrared sensors were recommended by the spin test facility where they had been used before with good results.

The pressure transducers were calibrated by testing them in a vacuum chamber at CEM-UT. The transducers were tested with their respective mounting hardware to verify that this mounting design did not affect the transducer measurement. One transducer was put into the vacuum chamber with no mounting hardware for comparison to those with mounting hardware. A different vacuum transducer was attached to the chamber for comparison to the windage test transducers. As the pressure dropped in the chamber, the transducers started giving an output just above 20 Torr and the output of all the transducers agreed well with the chamber reference pressure. The pressure dropped to approximately 3 Torr before the small roughing pump could not get the vacuum to go any lower. All the transducers agreed well to this pressure and there was no difference observed between the transducers with mounting hardware and the one without mounting hardware. All the pressure data channels recorded during this test, when plotted on the same graph, lay exactly on top of each other. This suggests these transducers were calibrated well at the factory and their outputs are tightly controlled to give reliable data.

The reaction torque sensor (58 kg-cm or 50 in-lb peak) was also tested to verify its manufacturer calibration data. The torque sensor was rigidly mounted to an aluminum block, which was held in a vice. A 15.2 cm (6 inch) long aluminum torque arm was attached to the opposite end of the torque sensor. A small 12 kg (25 lb) digital load cell was used to apply a measured force at a precise moment arm length and load the torque sensor in torsion. A set of varied torque values was applied to the torque sensor and the torque sensor's voltage output recorded. This output data was scaled using the vendor calibration information and all applied torque values matched within < 5% of measured torques.

Spin Testing

The actual spin testing was done at Test Devices Inc. in Hudson, Ma. during a one week schedule. Figure 7 shows the windage test hardware installed in the spin pit at Test Devices. These tests varied in peak rpm, time at speed, and operating pressure. Please refer to Table 1 for a test plan summary that describes the tests conducted. The test plan was set up to provide data at a lower rpm (15 krpm, 340 m/sec) to provide low speed windage data and run tests for a longer duration to perhaps more closely approach a steady state temperature condition. Several tests were also run at an intermediate speed (27,600 rpm, 620 m/sec) to provide additional windage data for future comparison to windage loss predictions in this speed range. And finally, several tests were run at higher

speed (40,000 rpm, 900 m/sec) to provide loss data at high tip speeds for use in a wide variety of potential flywheel applications. In general, the testing performed at each speed level involved a separate test at each of the three pressure levels of interest; 0.1, 1.0, and 10 Torr respectively. The actual order of the tests conducted seems to be out of order and confusing. The test plan was set up in this manner to get the most efficient use of the testing time at Test Devices. After each test, the spin pit was opened and the assembly was cooled to bring the rotor and stator temperatures back to approximately room temperature before the next test could be conducted. The stator was cooled by blowing several fans across the assembly. The rotor cooling was aided by connecting a small plastic tube to the bottom center of the stator and feeding cool nitrogen gas at approximately 4 to 8 C (40 to 45 F) into the rotor cavity inside the stator. This cool nitrogen gas came from the cover vapor from a liquid nitrogen tank at Test Devices. This nitrogen vapor was fed into the assembly at a very low pressure and flow rate. It was just enough cooling to accelerate the process without over chilling the composite rotor. Cooling the rotor and stator after a test took approximately two hours to get it back to room temperature. The test plan was organized to get three tests a day when considering peak speed, time at speed, peak temperatures reached, and time required to cool assembly.

Experimental Results

This paper presents four sets of data from the windage testing. The data presented represents the three different speed ranges and three pressure ranges of interest. It should be noted that the data plots illustrate only a few of the 58 channels of data recorded during each test. For clarity of data comparisons, the same data channels were plotted for each of the four data sets presented.

Figures 8a and 8b contain data from the 15,000 rpm, 10 Torr test. Figure 8a shows the rotor speed data along with the several of the stator and rotor temperature measurements. Note the sharp rise in temperatures as the rotor is accelerated and also that the stator temperature rises slightly faster early in the test, and then the rotor temperature rise is a slightly steeper slope later in the test. At the end of the test, the stator and rotor temperatures were beginning to equalize. The data also shows the temperature differential through the G-10 liner wall and stator steel housing. Figure 8b illustrates the measured torque data and two pressure data channels. Note the torque data trace tracking exactly with the speed data profile. The pit pressure shown is the actual

vacuum level in the spin pit and the rotor/stator gap pressure was measured in the 0.25 cm (.1 inch) gap between the rotor OD and the stator ID. There was a slight rise observed in the measured gap pressure as the rotor accelerated. This is believed to be caused by a centrifugal “pumping effect” from the high-speed rotor.

Figures 9a and 9b present data from the 27,600 rpm, 1 Torr windage test. This data is very similar to the data in figures 8a and 8b. The temperatures rise sharply during rotor acceleration and again the stator temperatures rise sharper early in the test and the rotor temperatures rise quicker as the test proceeds. Note that the temperatures during this test rose approximately 50 C in 2000 seconds and the temperatures only rose about 30 C in the same 2000 seconds in figure 8a. The temperature distribution through the liner wall and steel housing is also more pronounced in figure 9a. Figure 9b illustrates the measured torque data along with the pit and air gap pressures during the test. It is again observed that the torque data tracks well with rotor speed and the rotor “pumping effect” is also very evident in the gap pressure data.

Figures 10a and 10b present data from the 40,000 rpm, 0.1 Torr test. These figures again present the same data, but for a shorter test duration. The test had to be stopped due to the peak temperatures in the rotor and stator approaching preset limits. The steeper rise in stator temperatures is very evident in this data and due to the short test duration, the rotor temperature rise catching up to the stator temperature was not observed. Note also that the stator temperatures rose approximately 70 C in only about 600 seconds. Figure 10b illustrated the torque and representative pressure data for this high-speed windage test.

The final set of data presented is for a long duration test at 15,000 rpm and 0.1 Torr. The goal of this long duration windage test was to observe if the stator and rotor temperatures approached a steady-state condition. The rotor was held at 15,000 rpm for approximately five hours before terminating the test. Figure 11a shows the stator and rotor temperature data and it can be seen that the temperatures were still rising significantly. An interesting observation is that the rotor and stator temperatures match well early in the test and then the rotor temperatures actually rise slightly above the stator temperatures and remain this way for the remainder of the test. Figure 11b presents some interesting torque data. The measured stator torque has a slow but steady rise during this test. It is believed that this was caused by a differential thermal growth of the rotor and stator. This differential growth would cause the air gap between the stator and rotor to

change slightly as the assembly heats up. The slight rise in torque suggests the air gap decreased slightly during the long duration test.

Conclusions

The windage loss test hardware designed and built at CEM-UT has successfully measured the total windage loss and temperature distributions for a high-speed composite rotor spinning in a stator assembly. A test plan was implemented to provide future flywheel system designers with empirical loss and temperature data for three speed ranges and three operating pressure levels. This broad range of data will be useful for a wide variety of potential flywheel applications. The data collected will be used as benchmark data for development of empirical models to predict total loss and operating temperatures for high-speed flywheel systems and other rotating equipment.

References

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- [2] H.P. Liu, M.D. Werst, J.J. Hahne, "Prediction of Windage Losses of an Enclosed High Speed Composite Rotor in Low Air Pressure Environments," Submitted to *The 2003 ASME Summer Heat Transfer Conference*, Las Vegas, Nevada, July 2003
- [3] This reference was copied from a text book and sent to CEM from Test Devices. I have not received this reference info yet. Will put in when I receive. Should be able to clear paper without this info.

Fig. 1 Cross section of windage test assembly

Fig. 2 Composite rotor used in windage testing

Fig. 3 Thermocouple installation in stator assembly

Fig. 7 Windage test hardware installed at Test Devices

Test #	Peak Speed (rpm)	Rotor tip speed (m/sec)	Spin Pit Pressure (Torr)	Comments
1	10,000	225	0.1	System Checkout
2	10,000	225	0.1	System Checkout
3	27,600	620	1	
4	15,000	340	1	
5	15,000	340	10	
6	27,600	620	10	
7	27,600	620	0.1	
8	15,000	340	0.1	
9	27,600	620	10	
10	15,000	340	0.1	Long Duration Test
11	40,000	900	0.1	
12	40,000	900	1	

Table 1. Windage Spin Testing test plan

Fig. 8a 15,000 rpm, 10 Torr temperature data

Fig. 8b 15,000 rpm, 10 Torr Torque and pressure data

Fig. 9a 27,600 rpm, 1 Torr temperature data

Fig. 9b 27,600 rpm, 1 Torr Torque and pressure data

Fig. 10a 40,000 rpm, 0.1 Torr temperature data

Fig. 10b 40,000 rpm, 0.1 Torr Torque and pressure data

Fig. 11a Long duration test temperature data

Fig. 11b Long duration test torque and pressure data