In-Situ Monitoring of the Brush/Rotor Interface in a Homopolar Motor with Acoustic Emission

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Abstract

Homopolar motors have been proposed as an alternative propulsion means for ships. Such motors operate in a very harsh and demanding environment, making in-situ diagnostics and fault-monitoring systems a key issue for extended operation. In a typical homopolar motor, several thousand brushes are used, which are all in sliding contact with a copper rotor at a velocity of about 10 m/s. Wear and degradation of the brush and rotor are key issues that need to be understood in order to design a reliable motor. In this investigation, acoustic emission transducers were used to study the characteristics of the brush/rotor interface of a homopolar motor as a function of speed, load, materials, and other design parameters. The AE sensors were directly coupled to the brush in the homopolar motor test rig, and data were obtained over extended periods of time. The sensor signal demonstrated good sensitivity to brush/rotor contact conditions, brush contact load, and motor current polarity. The results show that AE is well suited for in-situ monitoring of the brush and rotor conditions.

1. INTRODUCTION

Homopolar motors have been proposed as an alternative means of propulsion for ships, due to their high efficiency, high power density, and quiet operation. The basic principle of operation is shown in figure 1, where a high current is applied to a conductive rotor within a magnetic field. A net torque T is imparted on the rotor according to equation 1,

$$T = (BxI)r \qquad [1]$$

where B is the magnetic field, I is the current, and r is the radius of the rotor.

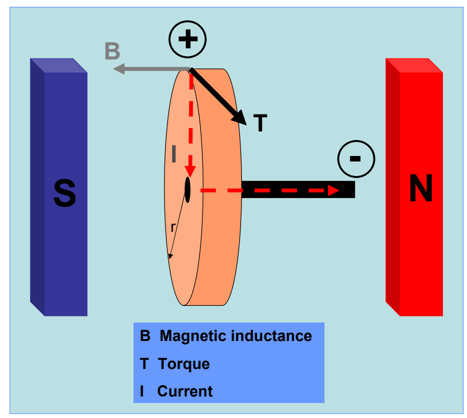

Figure 1 Schematic of homopolar motor

Since homopolar motors are likely to operate under harsh conditions, and are expected to operate for over 15 years, wear occurring at the brush/rotor interface becomes a significant issue. Another issue of concern is the difference in wear rate between the positive and negative polarity-brushes, with positive polarity brushes demonstrating a tenfold increase in wear rate over negative polarity brushes. Homopolar motors operate in a hermetically sealed environment that makes it challenging to monitor operational parameters, such as the brush and rotor condition and brush wear rates. This investigation discusses the usage of integrated sensors (acoustic emission, in particular) to monitor the status of a homopolar motor in an in-situ fashion.

1.1. Acoustic Emission as a diagnostics tool.

Acoustic emission (AE) is related to transient elastic stress waves generated during elastic and plastic deformation of materials under load. AE is a useful technique to monitor sliding interfaces, and has been demonstrated as having good sensitivity to detecting a number of tribological phenomena, such as friction and wear. The root-mean-square (RMS) of the AE signal is a useful signal processing technique, expressed as

$$V_{RMS} = \left[\frac{1}{\Delta t} \int_0^{\Delta t} V^2(t) dt \right]^{1/2} \qquad [2]$$

where Δt is the time interval over which the signal is collected, and V(t) is the recorded signal. The RMS of the AE signal is representative of the energy content of the signal, and has been consistently demonstrated as a reliable measure of the energy consumption taking place at sliding interfaces (Kannatey-Asibu, 1981). In several review papers, AE RMS was demonstrated as being proportional to the power consumption and overall material removal rate in manufacturing processes (Lee, 2004, 2006). Previous work (Talke, 1998) has also established the sensitivity of AE to tribological conditions at the head/disk interface in hard drive systems.

1.2. Sources of AE in the homopolar motor.

At the brush/rotor interface, AE is generated through the elastic perturbation of the brush fibers as they interact with the surface of the rotor. It has been proposed that the fibers buckle elastically in a "chaotic random" motion that cannot be easily predicted. Simulation work by Moon (1987) has shown that the first several resonant frequencies of the buckling brush fibers can approach the kHz regime. As these elastic waves propagate along the fiber length and into the brush housing, both constructive and destructive interference can take place between adjacent waves, causing the signal to shift further. The waves are finally detected by an AE sensor directly attached to the brush housing (see Figure 2).

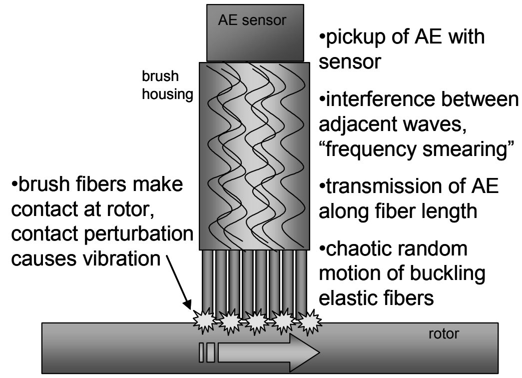

Figure 2 AE Sources at the Brush/Rotor Interface

2. EXPERIMENTAL SETUP

A schematic of the homopolar motor test rig and data acquisition system is shown in Figures 4 and 5. The test rig is designed to simulate the mechanical contact between brush and rotor and allow integration of other sensor systems. A magnetic field is not present, and the rotor is driven by a belt-driven motor. A hand-wound copper brush (AWG 34) is loaded with a dead weight onto a copper disc rotating at ~1500 RPM (~15 m/s surface velocity). A fiber optic probe is used to measure vertical brush position and wear rate, while an AE sensor is mounted directly to the brush housing. A laser Doppler vibrometer (LDV) was also used to measure lateral brush motion in some of the experiments. All sensor signals were monitored in real-time at 2.5 MHz with a commercially-available PC DAQ system, and the collected signals were analyzed with MATLAB.

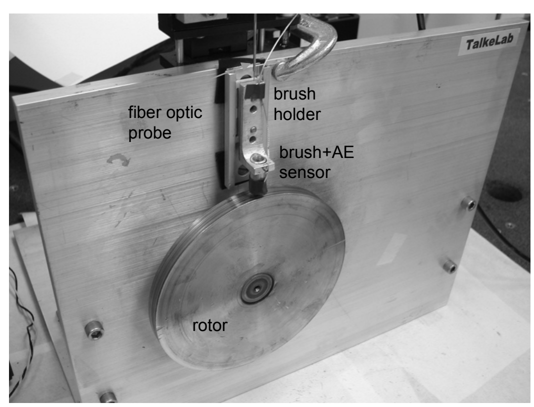

Figure 3 Homopolar Motor Test Rig

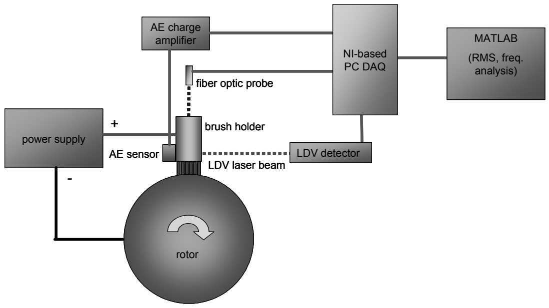

Figure 4 Schematic of homopolor motor with DAQ system

A high-current power supply (50 A maximum) was used to apply both positive and negative current to the brushes to simulate the current densities (up to 160 A/cm^2) typically found in homopolar motors.

3. IN-SITU MONITORING OF THE HOMOPOLAR MOTOR BRUSH INTERFACE

3.1. Difference in AE sources at the brush/rotor interface.

Experiments were conducted to investigate the dependence of AE on the type of contact at the brush/rotor interface. The AE signal was collected from a single brush in contact with the rotor, a single fiber protruding outwards by 1 mm from the brush surface, and a solid copper pin (7/16" diameter). The spectral densities of all three AE signals are shown in Figure 5.

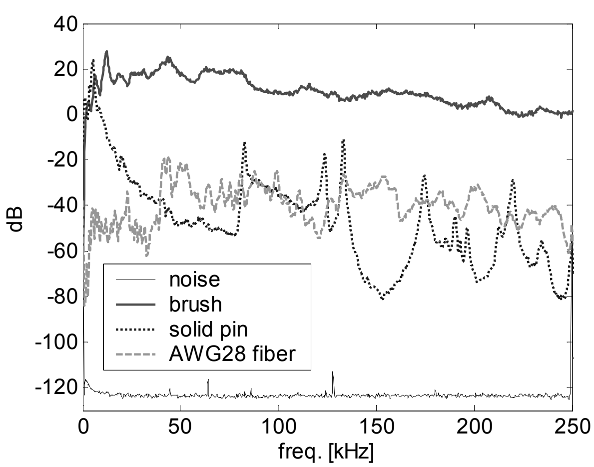

Figure 5 Frequency distribution for different AE sources

We observe a clear difference in the frequency distribution from the three AE sources. The AE signal for the full fiber brush demonstrates a flat frequency response (similar to white noise) over the range of 0-250 kHz. The single fiber also demonstrates a similar flat frequency response, although at a signal level roughly two orders of magnitude lower than that of the full fiber brush. However, the solid pin shows a significantly different frequency distribution, with the presence of several characteristic peaks that are likely associated with harmonics of the pin/rotor system. We postulate that the frequency distribution for the full brush consists of the combination of AE events from hundreds of individual fibers, yielding a flat white noise distribution similar to that of a single fiber, but of greater amplitude.

3.2. Dependency of AE signal on brush type.

Figure 6 shows the spectral density of the AE signal taken from three hand-wound brushes of differing wire gauges (AWG28: 300 micron diameter, AWG 34: 150 micron diameter, AWG 40: 70 micron diameter), with the AE spectral envelope showing a unique signature for each brush type. As the wire diameter used in the brushes increases, the amount of elastic energy stored and released within the fibers during contact with the rotor increases. This is reflected in the increase in collected AE signal for each brush.

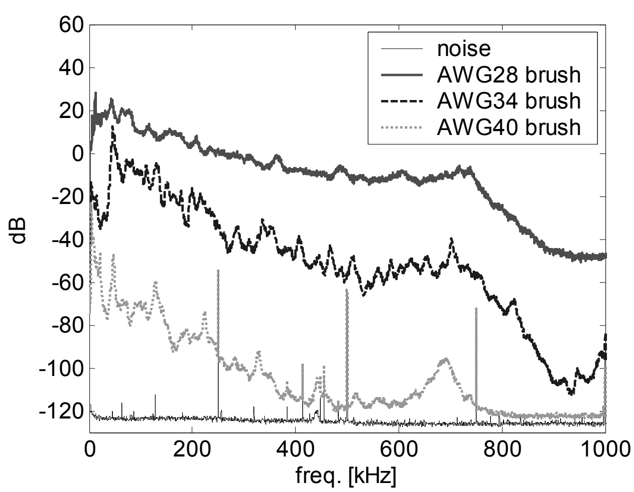

Figure 6 AE Spectral density variation with brush type

3.3. Short-term brush contact monitoring.

Figure 6 shows the results from a basic test demonstrating the capability of AE to monitor specific phenomena at the brush/rotor interface. First, the brush was lifted from the rotor, and only a background noise signal was observed. Then, the brush was placed in contact with the rotor with a nominal load of about 3 N, and an appreciable increase in the AE RMS signal was observed, demonstrating the usefulness of AE for brush contact monitoring. Next, the brush was lifted up, and the AE RMS signal dropped back to the background noise level. The brush was dropped onto the rotor, and a spike in the AE signal was observed. An additional 1 N and 5 N load was applied, and an increase in the AE RMS signal was observed in both cases. We believe this increase in AE signal is due to the increase in contact area between the brush and rotor. The brush was then hit twice with a hard object, and two corresponding peaks in the AE signal were seen. Finally, the brush was lifted off the rotor, and the AE RMS signal drops back to the background noise level. Each physical phenomenon is manifested as a different level of AE RMS amplitude, corresponding to a difference in energy consumption at the brush/rotor interface for each case.

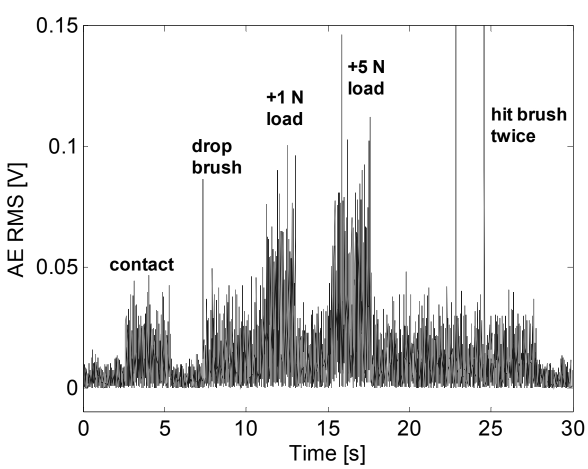

Figure 7 Brush contact monitoring with AE RMS signal.

3.4. Operational Parameter Monitoring.

A full factorial test of the dependency of AE signal with brush pressure and current density was conducted. The motor was continuously run at a surface velocity of 15 m/sec, with the application of current densities ranging from 0-160 A/cm^2, and brush pressure ranging from 0-138 kPa.

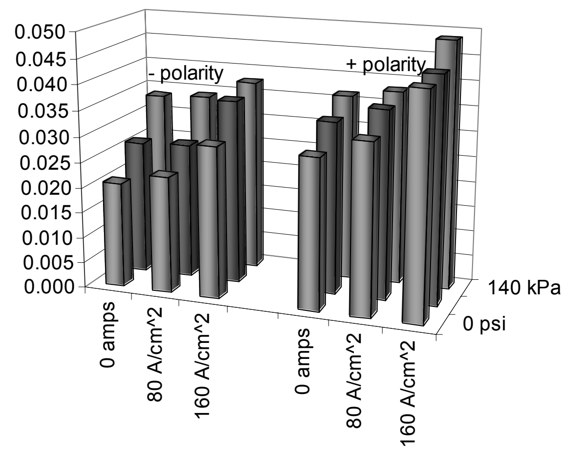

Figure 8 AE RMS values for full-factorial parameter testing on full-scale test rig.

Of particular interest is the increase in AE RMS as the brush pressure increases. This can be explained by the increase in contact area at the brush/rotor interface. As brush pressure increases, the total area of contact between brush and rotor also increases, hence increasing the number of AE events taking place at the fiber tips, and the total energy consumption at the interface. This increase in energy is reflected in the overall increase in AE signal amplitude. Also, as current density increases, the AE signal tends to increase, which reflects the higher wear rate found in the brush at higher current densities. An order-of-magnitude increase in wear rate has been observed for positive-polarity (electron-receiving) brushes, compared to that of negative-polarity ones. A possible explanation is that in many high power-density systems, such as arc welding or EDM, the cathode (electron-receiving) side typically has higher operating temperatures than the anode, with as much as 70% of the total generated heat of the system being at the cathode, and the remaining 30% at the anode (Lincoln, 1994), which can contribute to the accelerated wear of the positive-polarity brush. The increase in AE RMS for positive-polarity brushes over that over the negative-polarity brushes reflects the increase in wear rate.

3.5. Long-term brush wear monitoring.

To demonstrate the long-term monitoring capability of AE, an extended test was conducted. The brush was operated under nominal conditions without current (15 m/s surface velocity, 12 kPa pressure). Figure 9 shows the overall wear of the brush over a 4 hour time span, with an average non-dimensionalized wear rate of 3E-10.

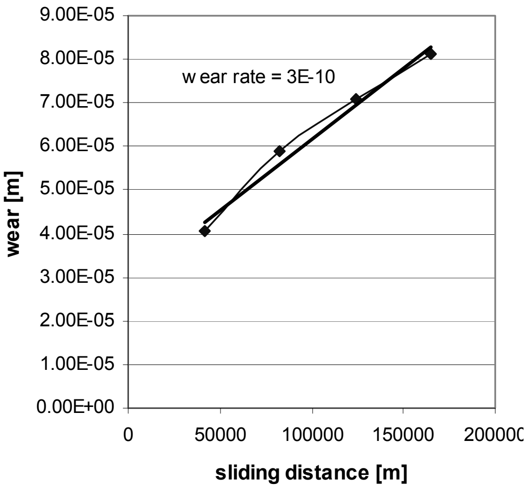

Figure 9 Overall brush wear vs. sliding distance.

Figure 10 shows the real-time acquired AE RMS signal and calculated wear rate for the same 4 hour time span. After an initial wear-in period, the overall non-dimensional wear rate stabilizes at approximately 2E-10. In this particular case, the AE RMS level scales with the wear rate. This can be used as a means of long-term monitoring of the overall conditions of the motor. A baseline in AE signal can been established during continuous steady-state operation, and large variation in the signal can serve as a means of fault-monitoring and on-line diagnostics of the brush/rotor interface.

Another series of experiments was conducted to correlate the AE RMS to wear rates under different operating conditions of the motor. A baseline wear rate and AE RMS signal were acquired under nominal operating conditions (no current, 15 m/sec surface velocity, 12 kPa pressure) over a period of 4 hours. A force was applied to the brush, increasing the pressure to 34 kPa. A large increase in the wear rate was found, but a less appreciable increase in the AE signal was seen. The force was removed, and a 70 A/cm^2 positive current density was applied to the brush. Both the AE RMS and wear rates showed a considerable increase. Decreasing the current density to 30 A/cm^2 also resulted in a slight decrease in the AE RMS and wear rate. Finally, to investigate the effect of polarity on the brushes, the power supply leads were reversed, making the brush the negative (electron-giving) end. A reduction in both AE RMS and wear rate was seen, which is consistent with previous observations of lower wear rate in negative-polarity brushes.

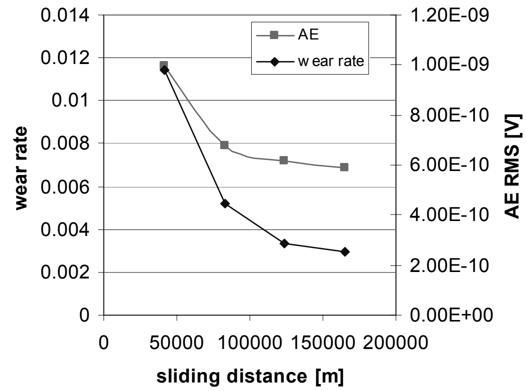

Figure 10 Brush wear-rate monitoring with AE RMS.

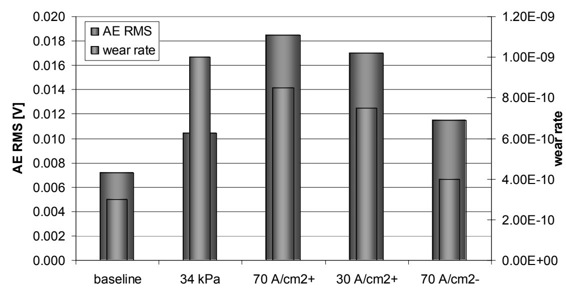

Figure 11 AE RMS and wear rates under different operating conditions.

4. CONCLUSIONS/FUTURE WORK

AE has been demonstrated as an effective tool for in-situ monitoring of a wide range of phenomena taking place in a homopolar motor, including brush condition, motor operating parameters (current density, brush load), and overall brush wear rate. After establishing a baseline for normal motor operation has been established, variation in AE signal can serve as a useful on-line diagnostics tool, such as monitoring brush wear rate.

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