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Magnetic Stress Gages for Torque and Load Monitoring in Rotorcraft

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Abstract

The noncontact, reusable torque and stress gages discussed in this paper address the need for enhanced torque measurement capability for main and tail rotorshafts, as well as for convenient stress/load monitoring at critical locations for diagnostic and health monitoring purposes. Results of static tests at JENTEK and full-scale dynamic tests at Boeing are described. This paper also describes the Magnetic Stress Gage and how it overcomes many of the stated limitations of other stress measurement methods based on magnetic permeability. This is achieved by using a multidirectional, model-based approach to remove the effects of hysteresis, temperature, material property variation, stray magnetic fields, and other interferences. This method also offers the capability to monitor stress, with a reusable gage, through paint and with limited or no surface preparation. These capabilities are enabled by: (1) the MWM® (Meandering Winding Magnetometer) design, (2) a rapid model-based multivariate inverse method, and (3) unique parallel architecture impedance instrumentation (patents issued and pending).

INTRODUCTION

The United States Army currently has a goal to transition its fleet of aircraft to a Condition Based Maintenance (CBM) approach. This effort consists of transforming reactive, usage-based maintenance into proactive, evidence-based maintenance. In order to successfully make this transition, there is a critical need for a practical and accurate torque measurement system at the main and tail rotor drives. This in turn will enable more accurate prediction of remaining service life for critical components.

At present, the torque seen at the main and tail rotors can be calculated by measuring torque output at the engine, assuming certain losses, and estimating the load share between rotors. In conventional, as well as tandem rotor helicopters, conservative (worst-case) loads at the rotors are used to evaluate component life because the exact torque split varies depending on flight regime. Accurate torque measurement systems placed at the rotor heads, supplemented with an existing health and usage monitoring system (HUMS) will improve prediction of the remaining life of rotor components. This creates an opportunity for real-time torque level monitoring in order to better assess the remaining fatigue life of the dynamic components in the drive system of all current and future Army rotorcraft.

The JENTEK Magnetic Stress Gage System for Torque and Load Monitoring in Rotorcraft is a technology that has the potential to fulfill the Army's need for an accurate, noncontact torque and load monitoring solution. If proven successful, this torque measurement system will enable parts to be removed based on actual fatigue/load cycles rather than assumed flight loads; furthermore, this will allow parts to remain in service for a larger fraction of their actual fatigue life, resulting in reduced operational costs and improved aircraft availability.

This paper introduces the JENTEK Quadri-Directional Magnetic Stress Gage (QD-MSG™) and describes its application as a noncontact torque gage for rotating shafts. The QD-MSG is formed from a stack of four Meandering Winding Magnetometer (MWM®) sensors [1-8]. When located in close proximity to a rotating shaft, the thin, conformable MWM sensors each provide simultaneous measurement of the magnetic permeability of the shaft material (in one direction) and the proximity of the MWM winding plane to the surface of the shaft. Thus, the four sensors, as described in the following, provide magnetic permeability measurements in four different directions, simultaneously (0, 90, +45, and –45 degrees). This is necessary to both correct for interferences (e.g., hysteresis and temperature variations) and to enable measurement of bending and axial loads, in addition to torque. Also, the proximity measurements can be used for vibration monitoring.

This paper first describes the MWM sensor construct. Then the Grid Method used to rapidly convert the MWM impedance measurements into magnetic permeability and lift-off (proximity) is described. This is followed by a detailed description of the QD-MSG. Then results are presented for static and dynamic tests demonstrating the QD-MSG capability to measure (1) torque for a static shaft, (2) torque for a rotating shaft, and (3) torque and bending loads in a multi-mode static test.

The QD-MSG can also be used as a reusable strain gage. This includes capability to monitor stress in steel components through paint and even through non-magnetizable metallic coatings without surface preparation, and with no need for mechanical load transfer to the sensor. Stress measurements in non-magnetizable components with a magnetizable coating are also possible.

The MWM® and MWM®-Array technology is more commonly known for its use in coating characterization [9-11], cold work quality assessment [12], and crack detection [13-15]. For example, the MWM-Array engine inspection team received the 2007 FAA-ATA "Better-Way" award for automated inspection of engine disk slots and blade dovetails. This paper introduces a new realm for the MWM as a real-time, on-board sensor.

MWM Sensors

The MWM sensor construct is shown in Figure 1. Figure 1(a) provides a schematic and Figure 1(b) shows an actual sensor.

The MWM was designed to provide absolute property measurements (e.g., electrical conductivity and magnetic permeability for metals), without calibration standards, using a model-based inverse method [16-19]. The MWM sensor consists of a meandering primary winding (a modified, patented, winding construct [20]) for creating the magnetic field and two series-connected secondary windings located on opposite sides of the primary for sensing the response [21].

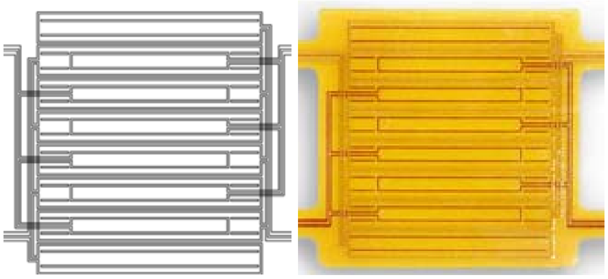

(a) (b)

Figure 1. (a) MWM schematic, (b) MWM FS33 sensor.

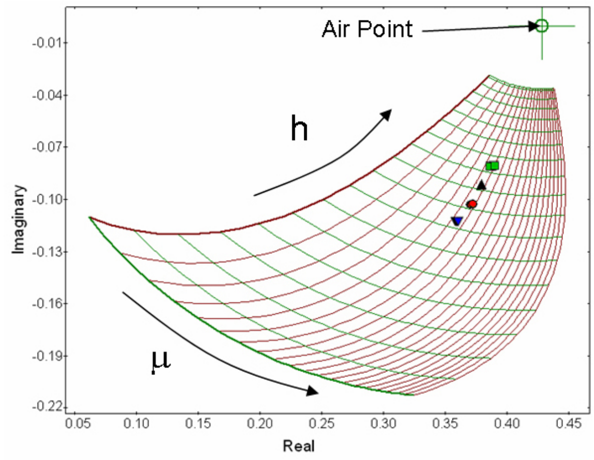
The MWM and MWM-Array sensors were designed to permit the sensor response to be accurately modeled, dramatically reducing calibration requirements (as described in ASTM Standard E2338-04, titled "*Characterization of Coatings Using Conformable Eddy-Current Sensors without Coating Reference Standards*" [22]).

Grid Methods

The Grid Methods use precomputed databases of sensor responses to represent the MWM field interactions with the rotorshaft (or other materials under test). In this paper we will limit our discussion to two-unknown methods for magnetic permeability and lift-off measurement using measurement grids. However, these methods have been used for three unknowns (Lattices) and four or more unknowns (Hypercubes). For example, as a reusable strain gage, the MSG will require correcting for metallic and nonmetallic coatings. This capability has been described in previous papers [9-11, 17, 22, 23].

Figure 2 shows a measurement grid for a two-unknown permeability/lift-off measurement. The measurement grid is generated using a model of the MWM field interactions with the neighboring material. The model used for this purpose was developed in the 1980s and refined over the years to enable extremely accurate representation of the MWM field interactions. The grid is generated once (off-line) and stored as a precomputed database for access by the GridStation® software. To generate the grid, all combinations of lift-off and magnetic permeability over the dynamic range of interest are input into the MWM models to compute the corresponding grid points. The visualization in Figure 2 includes lines of constant lift-off (h) and lines of constant magnetic permeability (μ). **Calibration of the MWM in both tests described below was performed at the Air Point (Air Calibration)** using the methods described in ASTM Standard 2338-04.

To perform a permeability/lift-off measurement, first the real and imaginary parts of the complex transinductance (impedance/$j\omega$) are measured, at an instant in time, using a parallel architecture impedance instrument with 37 parallel channels.



$$\text{Transinductance} = \frac{V_2}{j\omega i_1} = \text{Re}\left(\frac{V_2}{j\omega i_1}\right) + j\ \text{Im}\left(\frac{V_2}{j\omega i_1}\right)$$

Figure 2. Measurement Grid for lift-off and magnetic permeability at one applied frequency $f = \omega/2\pi$.

As described later, the 37 channels in the instrument enable simultaneous monitoring of nine QD-MSGs with four MWM sensors (channels) each. Then, the GridStation software performs a nonlinear search through the two-dimensional database (Measurement Grid) to provide simultaneous estimates of the lift-off and magnetic permeability.

The Quadri-Directional Magnetic Stress Gage

The Quadri-Directional Magnetic Stress Gage (QD-MSG) (Figure 3) is a stack of four MWM sensors, with axes of sensitivity in four different directions, 0°, 90°, +45° and –45°. The layout, orientation, secondary element size, and other geometrical properties are designed in a way that makes the sensing elements of one sensor insensitive to the magnetic fields generated by the primary windings of the other three sensors. This permits measurement of directional properties, such as conductivity or permeability, in four directions simultaneously and, although each sensor has a different lift-off, the differences are known and can be accounted for by using the Grid Methods.

As described in the following, arrays of these sensors (shown in Figure 4) have been used to demonstrate noncontact torque measurement capability on an unmodified main rotor shaft in a test cell at Boeing Rotorcraft Division.

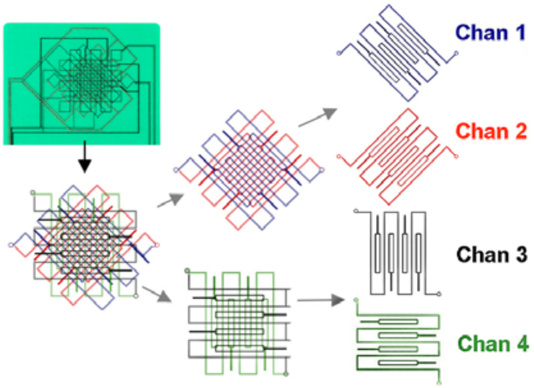


Figure 3. The Quadri-Directional Magnetic Stress Gage (QD-MSG™) is a stack of four directional MWMs that permits simultaneous stress measurement at –45°, 0°, +45° and 90°. This permits determination of axial and bending loads, as well as torque.

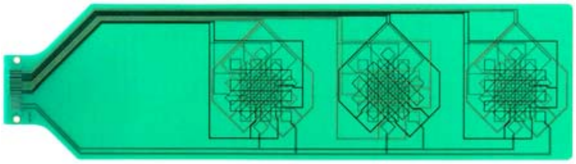


Figure 4. An array of three QD-MSG sensors used for the main rotor shaft noncontact torque measurement demonstration. Patents pending.

Static Torque and Bending Load Demonstration

A simple static test stand (Figure 5) was fabricated for initial demonstrations of capability. Using this test stand, torsion and bending loads can be applied simultaneously. As shown in the figure, an array of QD-MSG sensors is wrapped around the circumference of the hollow model shaft. Here, the sensors are in contact with the shaft, for convenience; while in the rotating shaft tests described in the next section, there is an air gap between the sensors and the shaft. To verify performance and establish the correlation of the magnetic permeability with stress, strain gages were located near one of the three QD-MSG sensors of the array at one circumferential position.

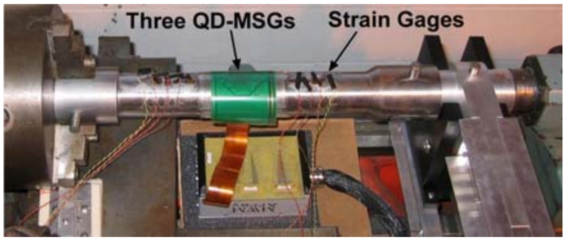


Figure 5. Simple static test stand for torque and bending loads.

Figure 6 shows the response of three MWM sensors, which are in three different orientations (axial, i.e. 0°, 45°, and –45°) in a single QD-MSG with varying applied stresses, as measured by the strain gages. The fourth orientation is used for hysteresis correction, as described later. The stresses are applied by a combination of torsion and bending in the simple static test stand, shown in Figure 5. A portion of the data from the first test (Figure 6, left) was used as a calibration set to develop the hysteresis correction.

In Figure 6, data from three different channels, i.e., different MWM sensors in different orientations. Many different combinations of torsion and bending loads were applied to create a variety of multi-directional stress states. The linear correlation was obtained for both bi-directional and uni-directional loading schemes, and the calibration and hysteresis corrections are portable.

The plot on the right of Figure 6 shows data from the second static test taken weeks after the first test, but with the same hysteresis correction (derived from the first test). In the second test, the same calibration was initially loaded and then corrected using the no-load state as a reference (a method for avoiding this no-load recalibration is under development). Each sensor response is plotted against the stresses acting in a direction consistent with the direction of measured permeability that is normal to that sensor's orientation.

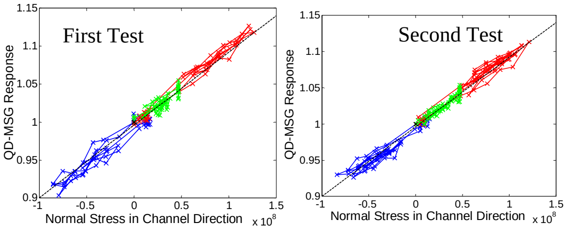


Figure 6. Corrected QD-MSG response vs. stresses caused by multi-axial loading. Data taken on different days share the same initial calibration and hysteresis correction factors.

This figure demonstrates several important features: (1) the hysteresis correction is portable over reasonable periods of time, (2) calibration of the MWM sensors in air is sufficient, and (3) the QD-MSG response is linear with stress, even in multi-axial loading.

Dynamic Test at Boeing

Figures 7 and 8 illustrate sensor installation for the noncontact measurement of loads on a rotor shaft using nine QD-MSGs, recently completed under a combination of JENTEK, Boeing, and Army SBIR funding. The arrays were installed on a pre-existing assembly around the rotor shaft (the sleeve in Figure 8). Three sensor strips, each with three QD-MSGs and each covering 1/3 of the full circumference of the shaft were installed. In each of the QD-MSGs, the magnetic permeability, and thus the stress, were measured in four directions: 0°, 90°, 45°, and –45°, as described earlier. The stresses at all nine locations (three sensor strips with three QD-MSGs each) can then be used to determine the torque, bending, and axial loads. Also, each sensor provides an independent proximity measurement that might be used for vibration monitoring.

With the sensor assembly mounted onto the gearbox and the gearbox mounted into the test stand, the setup was run at full speed under a variety of loading conditions. These conditions included torques from 20% to 100% of the maximum design torque, as well as various levels of bending loads and lifting loads.

Figure 7. Nine QD-MSGs (3 QD-MSG-Arrays with 3 QD-MSGs each) mounted to a pre-existing assembly installed around an unmodified main rotor shaft in a test cell at Boeing Rotorcraft.

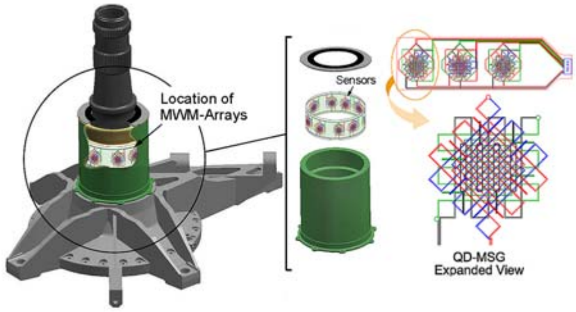


Figure 8. QD-MSG-Array for main rotor shaft torque measurement (figure provided by Boeing and modified by JENTEK Sensors, Inc.).

Figure 9 shows measured permeability data after temperature correction but prior to hysteresis correction for each of the four MWM channels in one of the QD-MSGs. Figure 10 shows the effect of hysteresis correction on the dynamic test data. Hysteresis effects can be on the order of loading effects. Effective hysteresis correction is vital to providing an accurate measure of load. The hysteresis correction demonstrated here (patents pending) is made possible by the redundancy in the QD-MSG magnetic permeability measurements. By including an extra directional sensor, beyond the three needed to measure torque, bending and axial loads, the correlation in the hysteresis behavior is used to remove the hysteresis effect from the data obtained in the other directions. The result is an essentially linear relationship between the hysteresis-corrected MWM permeability measurements and the stresses in the rotor shaft, and, as a result, between QD-MSG estimated torque and applied torque. This was demonstrated clearly for both the static and dynamic tests. The results shown in Figure 10 demonstrate the portability of the calibration methods.

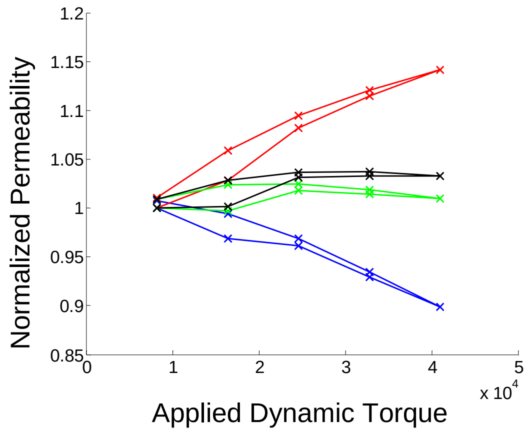


Figure 9. Permeability response in the four directions of a QD-MSG before hysteresis correction, but after temperature correction.

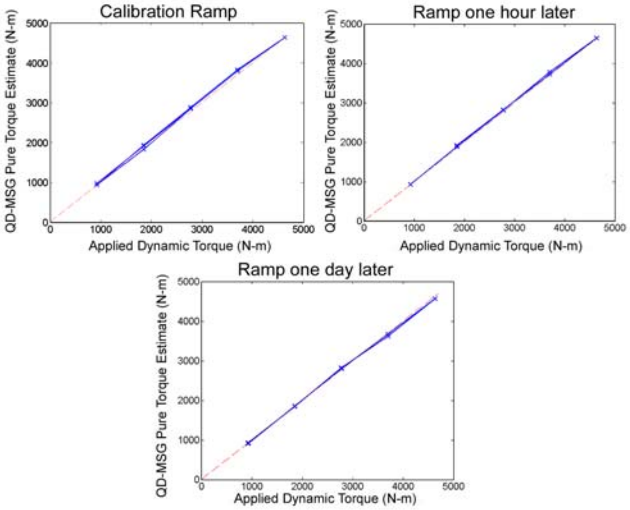


Figure 10. QD-MSG measured torque versus applied torque, after temperature and hysteresis corrections; the data illustrate calibration portability.

SUMMARY

This paper has presented Magnetic Stress Gages and the QD-MSG for noncontact torque, axial and bending load monitoring. This sensor is also suitable for use as a reusable strain gage that can perform measurements through paint or through an air gap with limited, if any, surface preparation. Results of successful static and dynamic testing at JENTEK and Boeing have clearly demonstrated the feasibility of this approach. Ongoing efforts to commercialize this technology are expected to include flight testing in the near future, miniaturization/hardening of electronics, and refinement of real-time and autonomous calibration and data analysis methods. The most significant developments to date are the demonstration of capability to correct for hysteresis and temperature, without modifying the rotor shaft. This should enable relatively low cost retrofitting of legacy fleets as well as application to new aircraft and upgrades.

ACKNOWLEDGEMENTS

The development of the QD-MSG could not have happened without the early contributions of the late Prof. James R. Melcher to the MWM development. His revolutionary MWM design is one key enabler. The authors would also like to acknowledge the many years of funding from JENTEK Sensors, Inc. to develop and commercialize the inverse methods and calibration procedures. Finally, the authors would like to thank Boeing and the U.S. Army for the ongoing funding for the dynamic and static testing of the QD-MSG reported here and for its ongoing adaptation to rotorcraft life management applications.

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