AN OPTICAL ON-LINE BENDING MOMENT MEASUREMENT SYSTEM FOR THE EC 135 ROTOR MAST

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Abstract

The main rotor mast of the Eurocopter EC 135 helicopter is equipped with a Mast Moment Measurement System (MMS) to monitor the bending moments induced into the rotor hub by the rotor system. Currently, a traditional measurement system with strain gauges bonded into the rotor mast is used. This paper introduces a design for a non-contact and low-maintenance optical Mast Moment Measurement System based on a laser and photosensitive detector configuration. The mast moment is derived from the displacement of the rotor head, which is determined from the position of an incident laser beam on the active surface of a Position Sensitive Detector (PSD). All active components of the system can be accessed from the ends of the rotor mast for simple and cost-efficient installation and repair. The optical system has a high accuracy, and is not adversely affected by dynamic loading. An overview of the EC 135 rotor system and a description of the current MMS are given, followed by an outline of the optical system and its advantages. The paper concludes with a discussion of test results obtained in a ground-based fatigue test of an EC 135 rotor mast. The results show that the optical system matches the performance of a strain gauge-based system, with the additional advantage of supplying loading data in all phases of the mast rotation.

1. INTRODUCTION

The EC 135 is a modern twin engine multi-role light helicopter, which was developed by Eurocopter starting in 1991/92 and has been in service since its type certification in 1996 [1]. Currently the fleet consists of over 800 helicopters, making the EC 135 one of the most successful helicopters of its class. The EC 135 is a successor of the MBB Bo 105, and features a number of advanced technologies, including a high proportion of composites in the fuselage, a vibration absorption system between the transmission and the fuselage, and a Fenestron low-noise antitorque system developed by Eurocopter France.

A defining feature is the unique Bearingless Main Rotor (BMR) consisting of composite rotor blades bolted directly to the main rotor mast, as seen in Fig. 1. The core of the rotor blades is an elastic Flexbeam made of glass fiber reinforced plastic (GFRP). Flapping, lead-lag, and torsional movements are made possible by elastic deformation of the Flexbeam [2]. The blade root is tailored to have discrete virtual flapping and lead-lag hinges. The BMR system has significantly fewer parts than conventional fully articulated rotor systems, and accordingly is lighter, easier to maintain, and less costly.

In comparison to a fully articulated rotor, a BMR system induces higher bending moments into the rotor hub. This is due to the increased flexural stiffness in the blade neck, which results in a larger offset *a* of the virtual flapping hinge, as shown in Fig. 2. The minimum offset distance is limited by the rotor design along with the requirement for a high strength and stiffness in the blade root. The stiffer rotor system leads to a higher steering sensitivity of the helicopter.

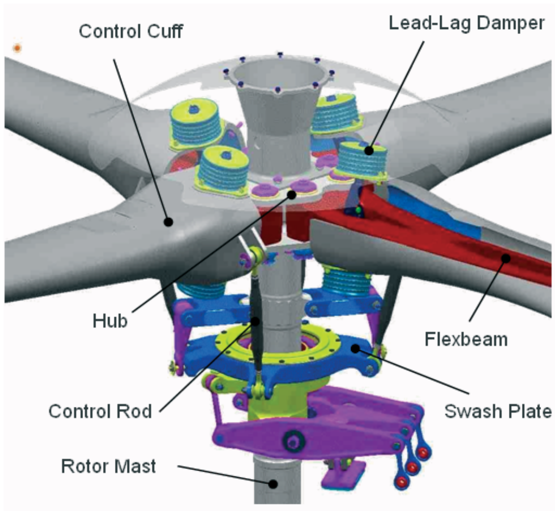

FIG. 1. Bearingless Main Rotor system of the EC 135 including rotor mast with integrated hub and rotor blades with Flexbeam.

The main rotor mast is the connecting element between the rotor system and the helicopter fuselage, and is essential to the aircraft functionality and safety. Aside from the lifting force at the hub, the rotor mast also transfers the torque from the transmission to the rotor system. Additionally, harmonic vibrations originating from aerodynamic and mechanical forces in the rotor system are superimposed on the hub forces and transmitted to the fuselage via the mast and transmission. To ensure the structural integrity of the rotor system, a permanently installed Mast Moment Measurement System (MMS) is integrated into the rotor mast, to monitor exceedances of predefined mast moment limits. The MMS is primarily required for flapping moment monitoring during slope operations on steep slopes. In normal flight operations, the mast moment level is uncritical.

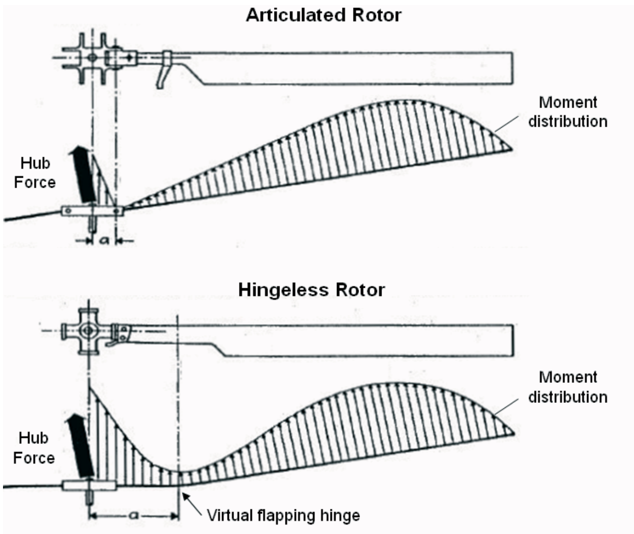

FIG. 2. Bending moment distribution in flapping plane and hub force for articulated and hingeless rotor blade.

2. MAST MOMENT MEASUREMENT WITH STRAIN GAUGES

The current Mast Moment Measurement System (MMS) of the EC 135 derives the mast moment from a strain measurement with strain gauges within the rotor mast. The same approach is used in the EC 135's predecessors, the BO 105 and the BK 117, which also feature hingeless rotor systems [3], [4]. Two pairs of parallel strain gauges are bonded into the upper region of the rotor mast on opposing sides, Fig. 3. The strain gauge contacts are wired in a Wheatstone Strain Gauge Bridge (SGB) soldered into the mast.

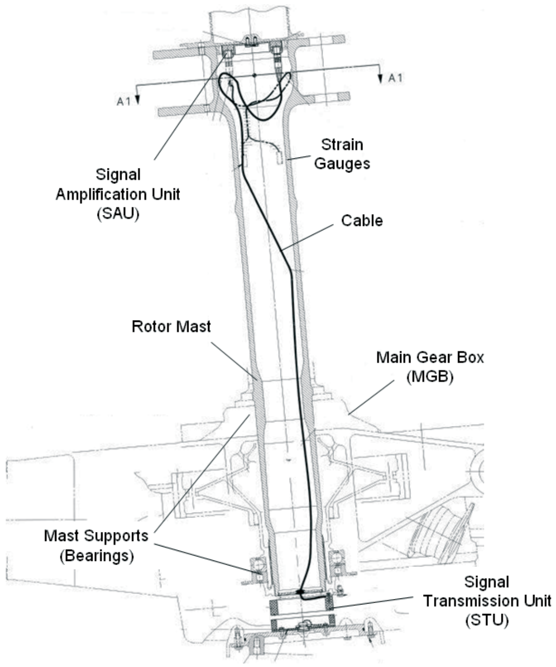

FIG. 3. Rotor mast and transmission with installed Mast Moment Measurement System (MMS) in sectional view.

The SGB signals are fed into a Signal Amplification Unit (SAU) mounted in the top of the mast, under the hub cap support. From the SAU, a cable leads to the lower end of the mast, to the rotor ring of the Signal Transmission Unit (STU). The opposite stator antenna is attached to the gearbox cover. A cable then leads to a Signal Processing Unit (SPU), mounted inside the helicopter fuselage, and on to the Cockpit Display System (CDS).

Figure 4 shows the voltage signal from the SGB. Due to the rotation of the rotor mast, the SGB signal is periodic, reaching a maximum whenever the strain gauge measurement axis coincides with the direction of the mast moment. The strain in the rotor mast is approximately proportional to the applied mast moment. The sensitivity of the SGB is calibrated with a reference moment, so that the output voltage of the system corresponding to the mast moment Limit Load is 10V. The SGB signal amplitude, determined by halving the peak to peak voltage ΔU, then relates to the maximum voltage U_{max} as the present mast moment M to the limit moment M_{limit}:

$$\frac{\Delta U/2}{U_{max}} = \frac{M}{M_{limit}} \tag{1}$$

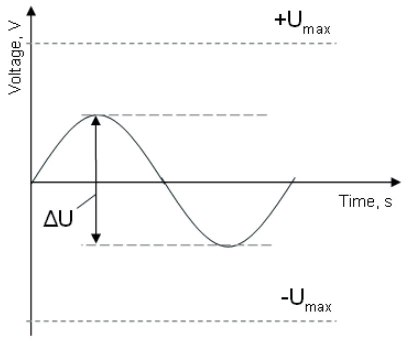

FIG. 4. Sinusoidal voltage signal from the Strain Gauge Bridge (SGB).

An overview of the signal flow in the MMS is given in Fig. 5. In the SAU the SGB signal is amplified and converted into a frequency modulated RF signal. This signal is then wirelessly transmitted in the passive STU and fed into the SPU. In the SPU the signal is converted back into a voltage signal, peak to peak demodulated, and scaled to a ± 10 V output signal. The mast moment is displayed in the cockpit on a linear scale indicating the percentage of the current moment relative to the limit moment. A caution indication is given beyond 50% of the limit moment, and a warning indication above approximately 80%. If the warning level is exceeded, a counter registers the time spent in the warning region, and a log book entry is made. An exceedance may lead to maintenance actions on the transmission and rotor system.

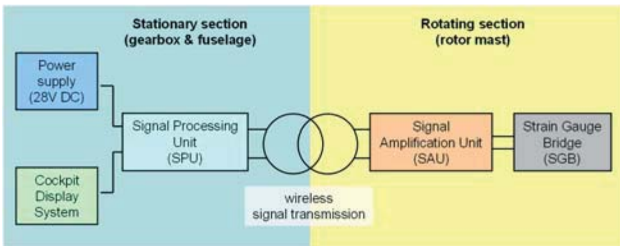

FIG. 5. Signal flow chart of the EC 135 Mast Moment Measurement System (MMS).

The application of a SGB is a traditional and straightforward approach to moment measurement on a steel shaft, however, this method has some disadvantages when used long-term on the inside of a dynamically loaded rotor mast. The bonding of the strain gauges onto the inside surface of the mast is an elaborate process. A special tool is needed to position the strain gauges, and the adhesive must be hardened in a hot bonding process in an oven. This requires that the rotor system be dismantled and the mast removed for repairs to the SGB. Small irregularities that naturally occur in the bonding process, such as particle inclusions and slight off-axis positioning, require that the SGB is calibrated before use with a reference moment, which is simulated with weights hanging from a bending beam attached to the rotor mast. The calibration includes soldering additional resistors onto the SGB, which is done by hand in a disadvantageous position. During flight operations, the SGB and the bonding are submitted to highly dynamic loading which can lead to fatigue damage. Considering the installation effort described above, repairs to a failed SGB are costly and time intensive. These drawbacks were the motivation for the development of a new low-maintenance mast moment system.

3. OPTICAL MAST MOMENT MEASUREMENT SYSTEM

A number of requirements and boundary conditions needed to be considered for a new Mast Moment Measurement System (MMS) design. First, a high overall reliability of the system is demanded. Since a weak point of the SGB-based system is the dynamically loaded bonding between the strain gauges and rotor mast, a non-contact measurement method is preferred. Second, installation and repair of the system must be simple and cost-efficient. Therefore all components of the system should be accessible and removable from above or below the rotor mast, without requiring removal of the mast from the transmission. Third, the system must be insensitive to the demanding environmental conditions present in the transmission and vicinity. These include high temperatures up to 110°C (transmission oil), an oil mist within the transmission, possible condensation, electromagnetic interference, and severe mechanical vibrations. Fourth, a redesigned MMS should integrate well with the existing structure and avionics system, to permit a retrofit on existing helicopters, and to keep the development effort low. Finally, system costs and development costs must be acceptable, to encourage development within Eurocopter and to make the alternative system attractive for customers.

The chosen conceptual design configuration shown in Fig. 6 is based on a displacement measurement of the rotor head with a laser – photodetector configuration. A laser is placed at the lower end of the mast and aligned with the rotor axis. At the upper end, a Position Sensitive Detector (PSD) registers the position of the incident light beam on its surface. If a bending moment is applied to the hub, it causes a deformation of the mast, in which case the PSD moves relative to the laser beam, and the laser point moves on the detector surface.

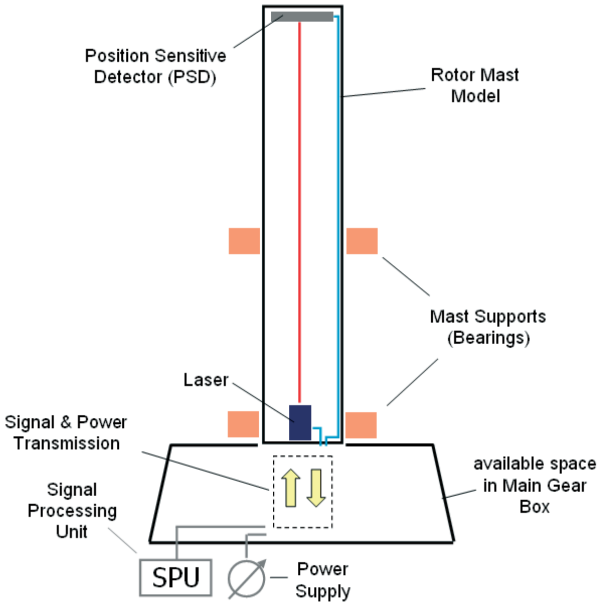

FIG. 6. Model configuration of optical measurement system including laser and Position Sensitive Detector (PSD).

The displacement of the rotor head relative to its support bearings is approximately proportional to the applied mast moment and can be determined analytically via beam theory, numerically, or by experimental calibration. In the case of a quasi-stationary displacement of the rotor head in flight, the laser beam describes a circle on the detector surface, as shown in Fig. 7.

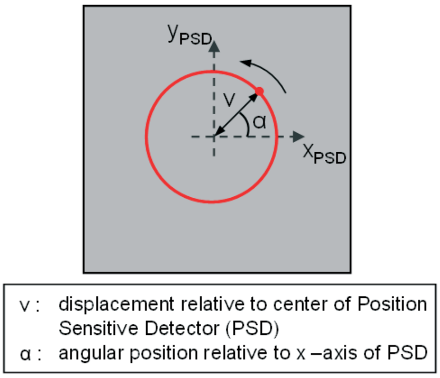

FIG. 7. Path of laser point on detector surface.

With a 2D-PSD, the momentary position of the light point is given in x- and y- coordinates, which are both given as sinusoidal voltage signals. From this data, the displacement v, which corresponds to the radius of the circle, can be determined with Eq. (2), and the momentary angular position α with Eq. (3).

$$\text{(2)} \quad \mathrm{v} = \sqrt{x_{PSD}^2 + y_{PSD}^2}$$

$$\text{(3)} \quad \alpha = \arctan\left(\frac{y_{PSD}}{x_{PSD}}\right)$$

The proposed configuration has a number of advantages. All active components are contained within the rotor mast, so the mast can be sealed, to isolate the components from oil and moisture. As specified, the components can be accessed from the ends of the mast. The optical measurement setup with a laser and analog photo detector is fast and allows a high measurement resolution (micrometer range). Also, the required signal processing and signal transmission is very similar to that already available, so the existing electronics can be adapted with minor modifications.

4. SYSTEM CONFIGURATION

The sensor in the optical measurement system is a Position Sensitive Detector (PSD). In principle the PSD is a semiconductor diode that produces an analog photocurrent proportional to the intensity of incident light on the detector surface [5]. The photocurrent is subdivided to two electrodes at the edges of the active area, referred to as the resistance length L_x, in proportion to the distance of the centroid of the beam from the electrodes. Figure 8 shows a schematic diagram of a one-dimensional PSD.

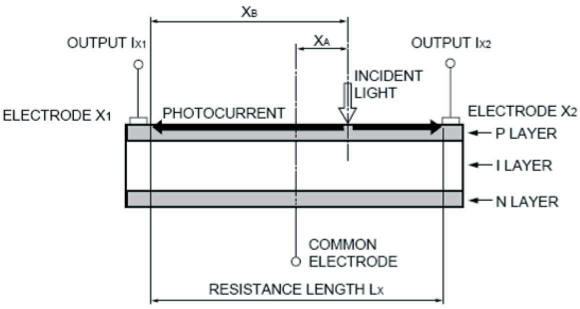

FIG. 8. Schematic of a Position Sensitive Detector (PSD) showing flow of photocurrent to electrodes.
(Image courtesy of Hamamatsu Corporation)

The position of the light spot X_A relative to the resistance length L_x can be calculated from the output currents I_{x1} and I_{x2} according to Eq. (4). A two-dimensional PSD has a 2-D active area, and a second pair of orthogonally oriented electrodes to measure the photocurrent in the y-direction. The y-coordinate is calculated analogous to Eq. (4).

(4) $$\frac{X_A}{L_x/2} = \frac{I_{x2} - I_{x1}}{I_{x1} + I_{x2}}$$

Several manufacturers offer circuit boards with analog circuit elements to add, subtract and divide the detector currents to determine the light beam's relative position according to the above equation. The output is a common voltage signal with a range of ±10 V. The accuracy of the position detection depends primarily on the PSD non-linearity, which is in the range of 0.3 % to 0.8 % for a standard 2-D PSD, and the non-linearity of the signal amplification circuit, which can be tuned to ± 0.1 %. At the outer edges of the PSD, the linearity decreases slightly, so a PSD with a sufficiently large active area must be selected.

As a light source, a laser diode with an output of approximately 1 mW is sufficient. The laser diode produces a monochromatic light beam with a Gaussian intensity distribution. The diode can be integrated in a housing with a collimating lens and a drive circuit, as shown in Fig. 9, for easy positioning and alignment. Alternatively, the laser beam can be coupled into a glass fiber, which allows the laser diode and its circuits to be placed outside environmentally demanding areas, particularly areas with high temperatures.

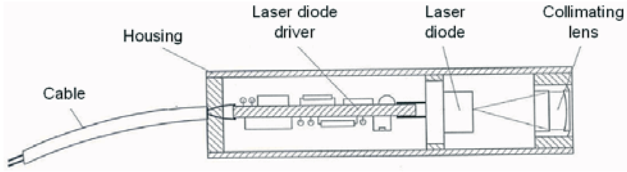

FIG. 9. Schematic of laser module including drive circuit, laser diode and collimating lens.
(Image courtesy of Laser Components GmbH)

Figure 10 shows an example for the positioning of a laser module in the lower end of the rotor mast. The inner surface of the rotor mast is used to align the laser mount, ensuring that the laser beam coincides with the axis of rotation. The retaining ring, which secures the nut, is modified to hold an o-ring, to seal off the mast. After removal of the gearbox cover, all components of the Mast Moment Measurement System can be removed along with the retaining ring. The PSD can be integrated into the Signal Amplification Unit (SAU) at the upper end of the rotor mast. The sensitivity of the system, relating the output signal to the beam displacement on the detector surface, can be adjusted outside of the rotor mast, before installation. This can significantly simplify the calibration process.

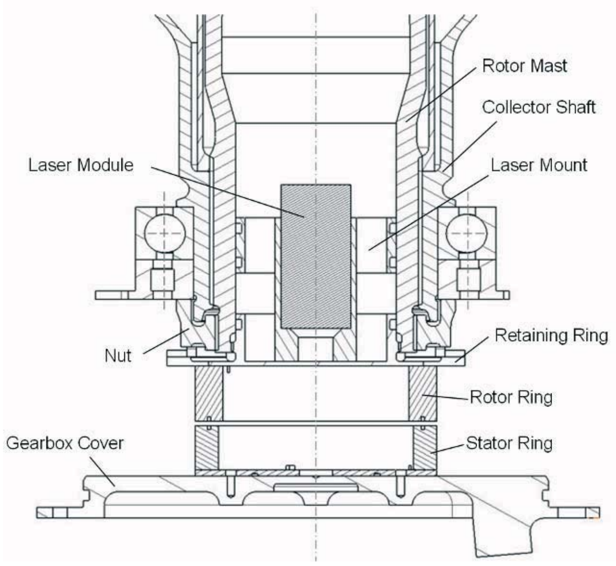

FIG. 10. Sectional view of the EC 135 transmission including laser module installed in laser mount.

Both the x- and y- signals of the photosensitive detector are sinusoidal, with a frequency equaling that of the rotor rotation. As such, they are similar to the SGB signal and require similar signal processing. Alternatively, the displacement can be calculated digitally or electronically according to Eq. (2). The modifications to the electronics mainly involve integrating the circuitry for the position calculation into the SAU, and adjusting the power output of the Signal Processing Unit (SPU) to power the laser and supply the PSD with a bias voltage of approximately 5 V. The signal flow in the proposed system in the rotating section is shown in Fig. 11.

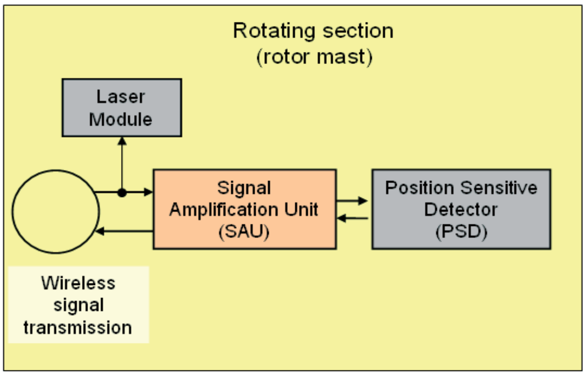

FIG. 11. Signal flow chart of optical system in rotating section.

The optical system allows considerable savings in the installation and repair process. In particular, the time and cost intensive warm bonding of the strain gauges and, in case of repair, the removal of the rotor mast, can be dispensed with. These savings compensate the higher component costs. A strain gauge costs only a few euros, whereas a robust laser module with a high-temperature laser diode costs several hundred euros, and a photodetector with an active area of 20 mm x 20 mm is priced at approximately 1000 euros.

5. EXPERIMENTAL VALIDATION

The optical Mast Moment Measurement System (MMS) described above is currently being tested in simplified configurations at Eurocopter. A recent experiment involved the installation of a laser and Position Sensitive Detector (PSD) according to the configuration in Fig. 6 into a rotor mast during a mast fatigue test. The mast is fixed in a mount, and hydraulic cylinders are used to simulate the operational loads, including hub moment, mast torque, and centrifugal blade forces, as shown in Fig. 12. Normally, the mast moment direction is quasi-stationary while the mast rotates, whereas in this test the rotor mast remains stationary, and the loads are applied circumferentially. A wireless signal transmission for the MMS signals is not needed in this case, and cables from the laser and PSD can be fed out of the top of the rotor mast to external data acquisition and data processing equipment.

Aside from the optical sensor, a Strain Gauge Bridge (SGB) is also bonded to the outside of the mast at a distance of 445 mm from the rotor head to measure the mast bending moment. In addition, a pair of linear cable extension transducers is used to measure the horizontal displacement of the rotor head. Therefore, three sets of data can be compared to evaluate the performance of the optical system.

Figure 13 shows the peak to peak demodulated amplitude signals of the strain gauge and the y-electrode of the PSD over a period of 2200 load cycles. Both signals are sinusoidal in the time domain. The signals are scaled to indicate a moment in kNm, based on a calibration procedure in which a pure hub moment is applied, resulting in a constant mast moment distribution from the rotor head to the upper mast support. Also shown is the displacement signal from the linear transducer, scaled in mm on the right axis. As can be seen, all three signals have very similar progressions, reflecting instationary changes in loading and accordingly displacement and mast moment amplitude. The optical and strain gauge signals are slightly offset, due to a linear moment distribution over the shaft during test operation caused by residual lateral forces from the horizontal cylinders. The ratio of the optical signal to the displacement signal has a variance of only 7E-04 over the shown range of load cycles, as compared to 11E-04 for the SGB signal, indicating that the optical system is slightly more accurate.

The SGB sensors as applied in the fatigue test and in the serial MMS can only measure bending moments around one spatial axis, giving a one-dimensional, sinusoidal output signal. A 2D-PSD, however, can supply load data throughout the entire range of the mast motion, as shown in Fig. 14. Though not essential to on-line moment monitoring, the 2-D signal provides more detailed information on the mast loading. It can be seen that a circumferential loading with a nearly constant magnitude

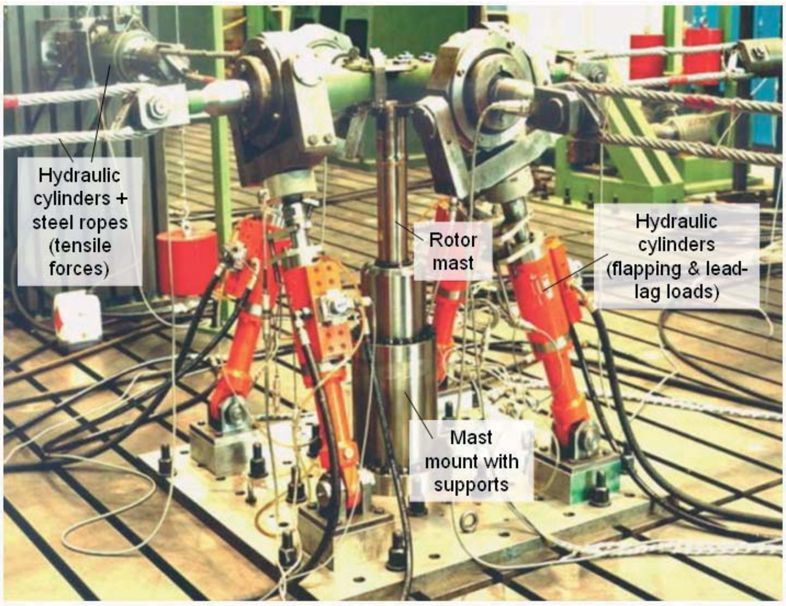

FIG. 12. Rotor mast fatigue test configuration including hydraulic cylinders for load generation.

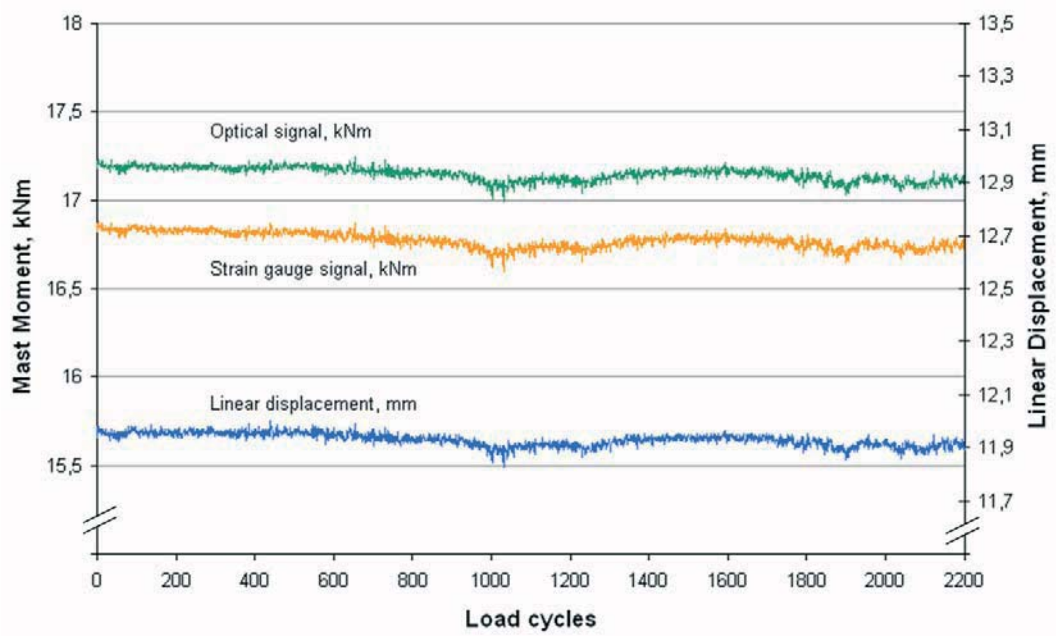

FIG. 13. Mast moment signals from strain gauge and optical sensor, along with linear displacement signal recorded during fatigue testing.

was achieved in the fatigue test. The center offset is again caused by residual lateral forces. The continuous moment measurement also enables the detection of higher harmonic superimposed loads caused by vibrations in the rotor system that are present during flight operations. Overall, the performance of the optical system has met all expectations in initial trials.

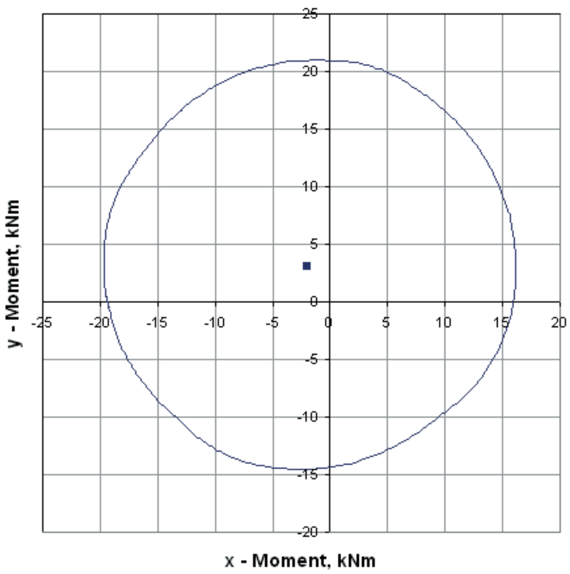

FIG. 14. Two-dimensional mast moment distribution over one load cycle as measured with Position Sensitive Detector (PSD).

6. CONCLUSION

Hingeless main rotor systems as found on the BO 105, BK 117, and EC 145, along with the Bearingless Main Rotor System (BMR) of the EC 135, require a Mast Moment Measurement System (MMS) to monitor the bending moments induced into the rotor mast by the rotor system. The optical MMS using a laser and photosensitive detector positioned at the ends of the rotor mast, as introduced in this paper, is intended to replace a system based on strain gauges. The functionality and accuracy of the design configuration has been successfully demonstrated in initial tests. A major advantage of the system is the easy accessibility of the active components from both ends of the rotor mast, which allows simple and cost efficient installation and repair. The proposed system requires only minimal modifications to structures and electronic equipment, and can be retrofitted on existing helicopters.

For future applications, the sensitivity, high resolution, and 2-D measurement capability of the optical system make the measurement of vibrations in the rotor head possible. In particular, vibrations with a frequency of 4 per revolution, corresponding to the number of rotor blades, can induce bending moments up to 4% of the limit moment, and are therefore well within the range of measurement resolution. Vibration measurements can be used in the Rotor Track and Balance (RTB) process, or for damage identification in the rotor system [6].

Currently, the MMS is used for basic exceedance monitoring. This is a form of usage monitoring, and can be integrated in a more comprehensive Health and Usage Monitoring System (HUMS). By recording the load progression over the duration of a flight, it is possible to derive a load spectrum for the rotor mast, which may be used for fatigue calculations and subsequent prediction of the remaining useful life [7], [8]. Along with other flight parameters, such as velocity, rpm and attitude indications, the load record from the MMS may also be used to reconstruct and evaluate flights for a Helicopter Operations Monitoring Program (HOMP) [9].

The basic design for the measurement system proposed above is currently being adapted to the specific conditions in the gear box at Eurocopter, specifically regarding the high temperatures and electromagnetic interference. The resulting prototype will then be extensively tested and analyzed to determine whether performance, reliability and economic requirements for in-flight operation and serial production can be met.

7. REFERENCES

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