A NOVEL CONTACTLESS SENSOR FOR HELICOPTER BLADE MOTION IN-FLIGHT MEASUREMENTS

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Abstract

This paper presents the comprehensive approach followed to design, implement and test an innovative sensor system aimed at the in-flight estimation of the helicopter main rotor state. This activity represents a fundamental step of MANOEUVRES, a project carried on in the framework of Clean Sky Green Rotorcraft 5 research programme, which is aimed at developing an integrated system capable of informing the pilot of the real-time noise generation and of suggesting possible corrective actions for low-noise maneuvering. The main rotor state is one of the most impacting factors on the helicopter noise generation, and cannot be measured with conventional rotorcraft instrumentation. The stereoscopic vision-based measurement system described in this paper overcomes this limitation, allowing the running estimation of the main rotor blade attitude in terms of lag, flap and pitch angles. Furthermore, such a sensor system could allow the implementation of enhanced attitude control laws based on rotor state feedback. The full development process of the sensor system, mounted on the main rotor head is presented, up to the flight trials on board an AgustaWestland AW139 prototype helicopter.

1. INTRODUCTION

A fundamental output of the CleanSky project MANOEUVRES (Manoeuvring Noise Evaluation Using Validated Rotor State Estimation Systems) is represented by the design, development and testing of an innovative measurement system for the real-time acquisition of the motion of a helicopter main rotor blade. In fact, the MANOEUVRES project was carried out as a 32-month activity, ended in May, 2016, with the aim of delivering new solutions for rotorcraft in-flight noise monitoring [1][2]. To this end, a methodology to estimate the acoustic impact in real time has been developed, which integrates several components in order to finally present a synthetic noise index to the pilot through a dedicated cockpit instrument, the Pilot Acoustic Indicator [3][4]. Among these components, a major role is played by the availability of real-time accurate measurements of the main rotor blades flapping. This motion can be related to the rotor tip-path-plane (TPP) angle of attack, which in turn is one of the main parameters governing rotorcraft noise emission, along with helicopter advance ratio and thrust coefficient [5].

This paper deals with the development and testing of a new generation contactless sensor for in-flight main rotor blade attitude estimation. Such a sensor, integrated in the helicopter Flight Control System, could also be an enabler for the adoption of Rotor State Feedback (RSF) control strategies to improve rotorcraft performances while reducing pilot workload [6][7].

2. THE MANOEUVRES PROJECT

The MANOEUVRES project, framed within the Green RotorCraft (GRC) Integrated Technology Demonstrator of the European Union Clean Sky Joint Technology Initiative, represents an effort aimed at providing innovative solutions for rotorcraft noise reduction. It has been launched in response to a Clean Sky Call-for-Proposals issued by Leonardo Helicopters [8], and won by a consortium led by Politecnico di Milano University, together with University of Roma Tre, Vicoter snc and Logic spa.

The main goal of the project consists in delivering an integrated package of technologies and tools to support rotorcraft pilots in flying low-noise terminal procedures, with the aim of minimizing the acoustic impact on overflown communities.

The MANOEUVRES solution is based on an integrated system capable of informing the pilot of the instantaneous acoustic emission, through a new

Human-Machine Interface, called Pilot Acoustic Indicator (PAI). This device consists in a cockpit display showing a synthetic representation of the noise footprint extracted from a pre-calculated database of hemispherical acoustic distributions [4]. The database is parameterized by three quantities, the vehicle advance ratio (μ), the main rotor thrust coefficient (C_T), and the main rotor tip-path plane angle of attack (*TPP-AOA)*, which represent the main factors affecting rotor noise generation.

Since two of the three above mentioned parameters (C_T and TPP-AOA) are not currently available inflight on standard helicopters, a fundamental outcome of the MANOEUVRES project is a main rotor blade attitude measurement system, capable of real-time estimation of the main rotor TPP orientation with respect to the fuselage. This, according to the approach presented in [9], can be used to estimate the main rotor TPP orientation with respect to the airspeed vector, *i.e.* the TPP angle of attack, as well as the thrust coefficient.

The schematic of the MANOEUVRES project activities, from the main rotor blade attitude measurement to the noise information conveyed to the pilot through the PAI, is shown in Figure 1.

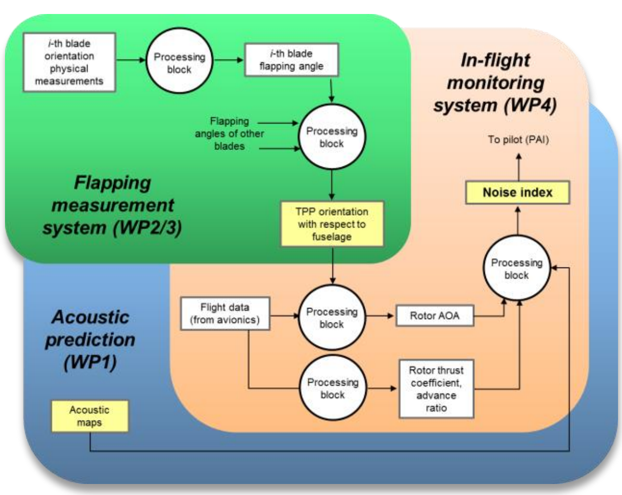

Figure 1: Schematic of MANOEUVRES program activities.

In the following sections the sensor design and development process will be described, briefly recalling the technology selection and preliminary development phases, recently presented in Refs. [10][11][12], and presenting new results of in-flight final demonstration on board an AgustaWestland AW139 prototype helicopter.

3. DESIGN REQUIREMENTS AND SENSOR DEVELOPMENT

3.1. Design requirements

The primary aim of the measurement system is the accurate estimation of the main rotor blade flapping motion. However, lead-lag, flap and pitch blade motions are coupled, so the need to develop a new sensor system capable of measuring the three blade motions was clear from the beginning of the project. Furthermore, such a sensor system would not only generate an input for the real-time noise estimation algorithm, but can also be an enabler for the adoption of Rotor-State-Feedback control laws and can be beneficial for helicopter developmental flight testing as well. This represents a further motivation to seek an accurate measurement of all the three blade angles.

A wide variety of contactless technologies were thus considered, in an effort to achieve high system durability and intrinsic flexibility of application, in view of a light and reliable system, possibly applicable to different main and tail rotor configurations.

The basic requirements for sensor system performance were defined at the beginning of the MANOEUVRES project, involving metrological performance necessary for accurate noise prediction; they are shown in Table 1 in terms of bandwidth, accuracy, and range.

Bandwidth	0 – 10 Hz (minimum) 0 – 25 Hz (desired)
Accuracy	0.5 deg (minimum) 0.1 deg (required)
Range	lead-lag: (-13.5, 10.3) deg flap: (-6.0, 18.0) deg pitch: (-22.0, 20.0) deg

Table 1: Measurement system performance requirements.

As a baseline for requirement definition, the main rotor blade attitude measurement system currently in use in Leonardo Helicopters Experimental Operations department has been adopted. This is an experimental system based on potentiometers and Rotary Variable Differential Transformers (RVDT) [13].

Further to system performance, several additional requirements were considered, concerning various aspects of functionality, geometry and mass characteristics, environmental suitability, reliability, safety, testability, and maintainability, with the aim of designing a system with a clear potential for future airworthiness certification. Finally, a particular attention has been devoted to vibratory loads, according to standard criteria and test procedures described in the RTCA/D0160 document [14], both in terms of sensor system suitability and measurement accuracy as well.

3.2. Selection of sensor technology and concept design

3.2.1 Candidate technologies review

The considerations mentioned in the previous section led to pre-select a number of contactless solutions, which appeared to provide the potential to satisfy all requests, to be installed on the fuselage and/or on the main rotor (Table 2).

N.	Technology	Installation
1	Capacitive	On rotor
2	Ultrasonic	On rotor
3	Eddy current	On rotor
4	Hall effect	On rotor
5	Magneto-inductive	On rotor
6	1-D and 2-D laser triangulation	On rotor On fuselage
7	Time-of-flight laser	On rotor On fuselage
8	Vision systems	On rotor On fuselage

Table 2: Preliminary technology selection

Initially, all sensor types were considered for possible installation on the rotor, while the fuselage-mounted solution posed more stringent limitations in terms of measurement range: only types 6-8 were pre-selected as capable of targeting main rotor blades from the helicopter airframe.

At a first stage in the technology review, types 1–5 were considered sub-optimal due to their potentially high sensitivity to environmental conditions (*e.g.* presence of dirt, moisture, water, air turbulence). Furthermore, some of the sensor types (such as eddy current, Hall effect and magneto-inductive) typically display short measuring ranges and strong non-linearity, which makes difficult to measure a tri-dimensional, large amplitude motion. The time-of-flight laser systems were also discarded because of their relatively low sampling frequency.

This preliminary assessment allowed to choose types 6 (1-D and 2-D laser triangulation) and 8 (vision systems) as the most promising for candidate rotor state measurement system concepts.

3.2.2 Sensor concept design

Based on the sensor technologies selected above, 9 different concepts of possible measurement systems have been devised, listed in Table 3. In some cases (*i.e.* R3, R5, R6) the systems are based on the same technology, but the target and/or the sensor location are different; this impact strongly on the requirements of sensor size, weight and measurement range.

ID	Sensor type	Position / target
F1	Single point laser	Fuselage to blade
F2	2-D laser	Fuselage to blade
F3	Vision-based single camera	Fuselage to blade
R1	Single point laser	Hub top to blade root
R2	2-D laser	Hub top to blade root
R3	Vision-based single camera	Hub top to blade root
R4	Vision-based stereoscopy	Hub top to blade root
R5	Vision-based single camera	Hub top to blade tip
R6	Vision-based single camera	Hub side to blade root

Table 3: Sensor concepts evaluated.

Since all the concepts considered were potentially suitable for the targeted application, a method was needed to evaluate them against multiple objectives and to identify the most suitable solutions. This was chosen as the Analytic Hierarchy Process (AHP) [15], a theory of measurement through pairwise comparisons developed in support of decision-making processes involving many tangibles and intangibles that need to be traded off.

The parameters which have been adopted to rank the sensor concepts can be grouped into the following four classes:

- weight, cost and helicopter requirements;
- technical challenge;
- technical capability;
- road to commercial exploitation.

The evaluation against each parameter has been jointly performed by Leonardo Helicopters specialists and MANOEUVRES partners, in order to merge industrial experience and knowledge of leading edge sensor technologies.

Following the assessment process (the final ranking is shown in Figure 2), it can be noticed that none of the fuselage-mounted solutions excels. Despite the ease of installation, if compared to the rotor-mounted concepts, these solutions show a strong penalty in terms of frequency bandwidth: to identify the n/rev (*i.e.* n times per revolution) component of a blade angular motion, at least ($2n + 1$) sensors are needed. This implies that 7 sensors are needed to estimate the blade flapping up to the 3/rev harmonic, which is fairly unpractical. On the contrary, for all rotor-based solutions, a single sensor can acquire as many harmonic components of blade motion as allowed by the available sampling rate.

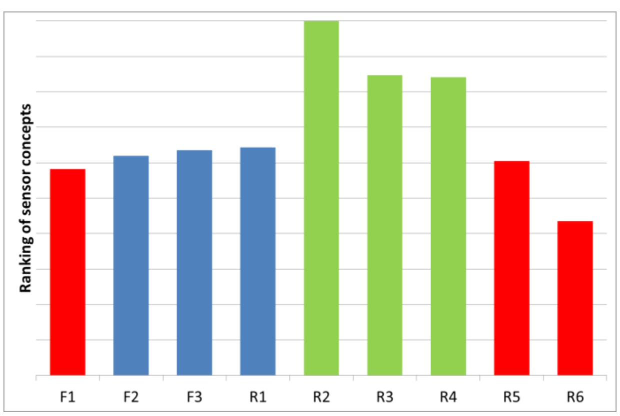

Figure 2: AHP ranking for candidate sensor concepts.

Among the rotor-based solutions, the single point laser (R1) showed some criticalities in estimating the 3-D coupled motions of the blades, the camera targeting the blade root (R5) could not fulfil the challenging dimensional requirements, while the camera targeting the blade tip (R6) showed strong penalties in terms of measurement accuracy.

Finally, the candidate concepts which have been selected for further development and testing are the 2-D laser scanner (R2) and two vision systems: a single camera solution (R3) and a stereo camera (R4) solution. The measurement target is, for all of them, the tension link, *i.e.* the main rotor part, integral with the blade root, which holds the blade to the rotor hub (Figure 3). The sensors are conceived to point the target from above, being installed in the main rotor beanie, a “hat-shaped” structure normally mounted on the rotor head for aerodynamic optimization purposes.

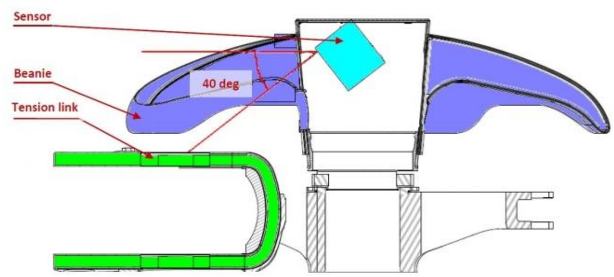

Figure 3: Schematic of possible sensor installation in the AW139 Main Rotor beanie.

3.3. Preliminary development and testing

The second phase of the study begun with the full-scale prototypal implementations of the three solutions selected, in order to assess their capabilities and allow the final choice of the definitive system.

The experimental campaign performed was structured on three types of tests:

- “Type I” tests were aimed at the verification of the ability of the prototype measuring systems to measure in realistic operating conditions with respect to vibrations;
- “Type II” tests were aimed at the assessment of the measurement accuracy;
- “Type III” tests were aimed at the validation of the functionality and safety under realistic centrifugal loads coupled with structural vibrations.

Type I tests employed electro-mechanical shakers fed with vibration spectra reproducing the operational vibration level measured in flight on an AgustaWestland AW139 main rotor hub (Figure 4).

The three systems correctly performed continuous operations, while acquisition and data transfer were not affected by sustained vibration levels.

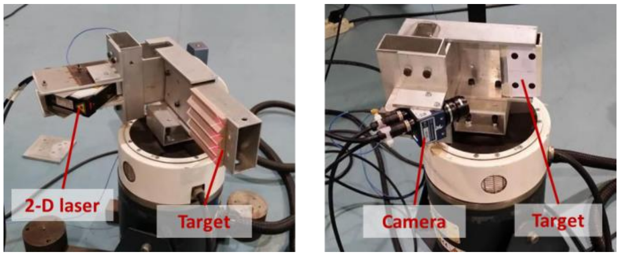

Figure 4: Vibration test rig at Politecnico di Milano laboratories.

Type II tests were performed on two different rigs, with different test methods: first, a quasi-static rig, specifically developed by the MANOEUVRES consortium using AW139 helicopter components for hub and blade root was employed for pure flapping simulation, flapping being the most important blade motion for noise-oriented TPP estimation as well as RSF applications. Secondly, a highly complex, non-rotating rig available at the Leonardo Helicopters laboratories was used to impose fully coupled blade motions, including specific time histories provided by flight test data of an AgustaWestland AW139 helicopter.

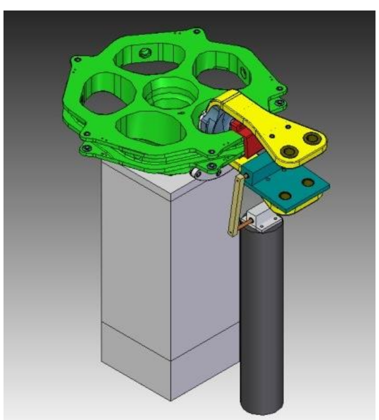

Figure 5: Model of pure flapping rig for Type II tests.

Finally, in Type III tests, a A109MKII ironbird, *i.e.* a highly representative rotating rig, available at Politecnico di Milano laboratories, was employed (Figure 6). This equipment is basically a helicopter fuselage complete with the original transmission gearbox ad a simplified rotor head, driven by electric motors and capable of reproducing the AW139 main rotor speed. Also in this case the three systems correctly performed continuous operations with no loss of data.

Figure 6: The A109MKII ironbird used for Type III tests at the Politecnico di Milano laboratories.

3.4. Test results and sensor concept selection

The in-depth experimental analysis described above allowed to confirm that the performance of all the three systems were compliant in terms of frequency bandwidth and range.

On the contrary, the accuracy was found to be different among the three systems, especially when tested on the fully coupled blade motion rig. In particular, while the vision-based systems showed accuracy for angle static (mean) values and first harmonic components compliant with the mandatory requirements (0.5 deg), the 2-D laser sensor revealed some weaknesses. Table 4 reports the maximum discrepancies between the angles estimated by the systems under tests and the values measured by the rig control system, among all Type II tests. The stereoscopic vision-based system showed the highest accuracy, even achieving the demanding desired accuracy requirement of 0.1 deg (see Table 1) for the first harmonic (*i.e.* the cyclic components which, in the case of flapping, contribute to define the TPP orientation).

Measurement system	Maximum estimation error	
	On mean value	On 1st harmonic
2-D laser	0.72 deg	0.89 deg
Single camera	0.15 deg	0.35 deg
Stereo camera	0.15 deg	0.09 deg

Table 4: Results of sensors accuracy test campaign.

Indeed, the stereoscopic vision-based system exhibits remarkably higher performance with respect to the other candidate solutions, and was therefore selected as the concept to be brought to maturity in the final phase of the project.

Furthermore, the results appear really promising when compared to those recently presented in Ref. [16], which describes a device capable of measuring the blade attitude by means of an array of Anisotropic Magnetoresitive (AMR) sensors on the main rotor hub. The results of simplified conditions tests of that system, not involving fully coupled blade motions, show an accuracy of 1.0 deg in lag, 0.3 deg in flap, and over 1.0 deg in pitch.

4. FINAL DEVELOPMENT AND TESTING

Following the final selection, an additional development phase has been carried out in order to integrate the stereoscopic measurement system on an AW139 main rotor head, *ad hoc* customized. This phase involved various steps, which will be described in Section 4.1:

i. Optimization of sensor system geometry;
ii. Structural installation design and verification;
iii. Design of electrical power supply and data transmission systems, including interfaces with the slipring to electrically connect the helicopter fuselage to the main rotor system and *vice versa*;
iv. Safety analysis and flight clearance.

After completion of this phase, the integrated rotor state measurement system was installed on board an instrumented AgustaWestland AW139 helicopter and subjected to ground and flight testing, as detailed in Section 4.2.

4.1. Integrated system detailed design

4.1.1 Measurement system description

The selected solution for the in-flight testing is composed by (see Figure 7):

- 2 smart cameras, arranged in stereo configuration;
- A LED-based lighting device;
- A camera conditioning unit, to trigger cameras acquisition and light flashing, and to collect cameras output;
- A trigger generator, based on main rotor revolution, and power adapter;
- The Leonardo Helicopters experimental blade attitude sensor, used as a baseline;
- One tri-axial accelerometer per camera, for vibration monitoring;
- A slipring;
- Flight Test Instrumentation for data acquisition and recording;
- A dedicated laptop for camera management.

The smart cameras selected are provided with embedded electronics capable of identifying the position of a certain number of geometric features (*'blobs'*) in the image and to provide in output such positions, instead of a video streaming. This allowed to significantly reduce the data bandwidth requirement for the slipring.

The sampling frequency was selected synchronous to the main rotor speed, 7 times per revolution (*i.e.* ~35 Hz, given the 300 rpm nominal main rotor speed). This allows to maximize the *n/rev* harmonic components information, while minimizing the required sampling frequency, thus the amount of data to be elaborated.

The camera frame rate was led by a trigger generator, driven by the main rotor azimuthal position.

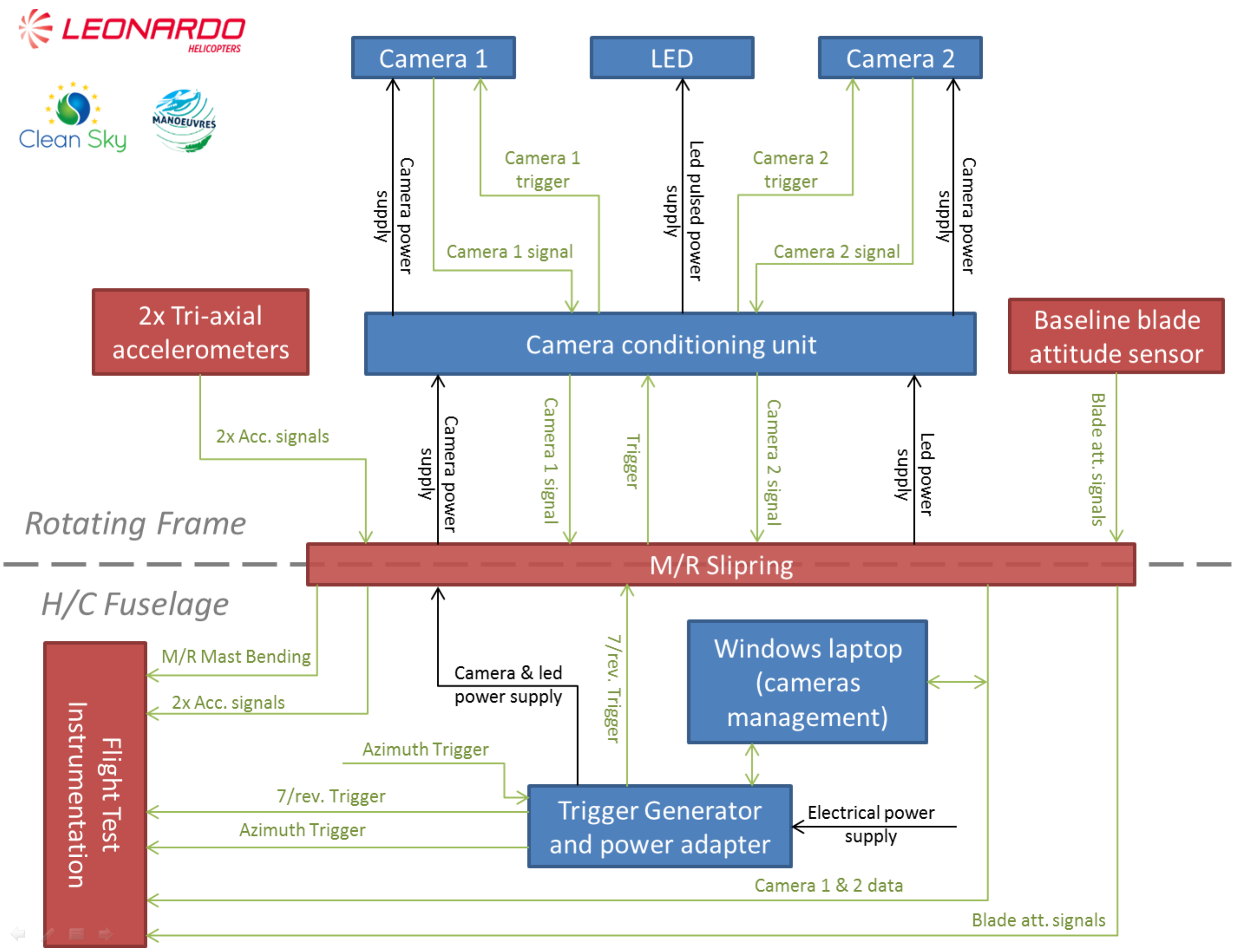

Figure 7: Schematic of stereo-cameras system installation on helicopter main rotor head.

4.1.2 Structural installation

Two cameras, the lighting device and the conditioning unit had to be installed on the main rotor head, as close as possible to the optimal position for measurement, and not too far from the rotation axis in order to limit the centrifugal force loads. It has been decided to host the system in an experimental main rotor beanie, capable of providing the required structural support and some degree of environmental protection to the sensor system. Furthermore, two masses were installed on the beanie opposite to the cameras for beanie balancing purposes (Figure 8 and 9).

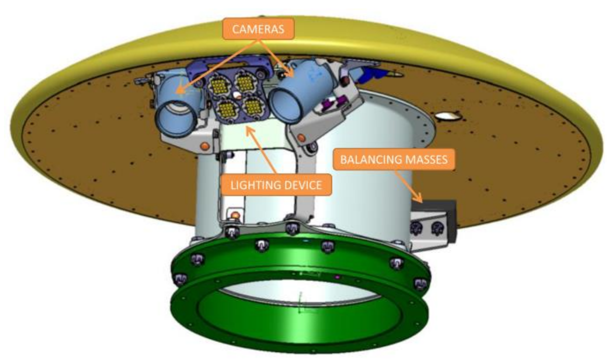

Figure 8: Blade attitude sensor system installation.

Figure 9: AW139 main rotor beanie instrumented with the final sensor system.

The fully instrumented beanie has been carefully assessed for structural static and dynamic behavior by Finite Element analysis (Figure 10). After a first iteration, minor modifications were introduced in order to get a safer and more stable installation, minimizing the vibration level imposed to the cameras. In fact, camera vibrations are not only a source of possible sensor damage, but may also contribute to reduce the measurement accuracy.

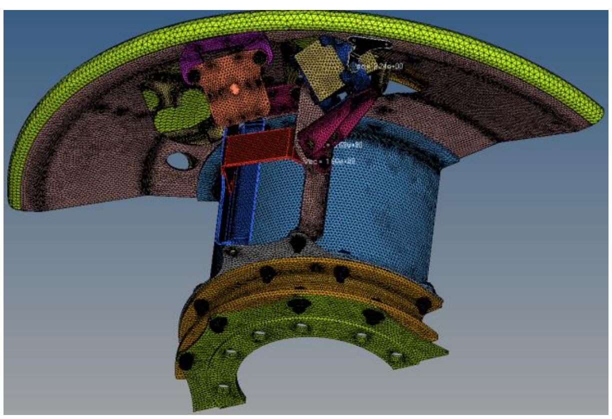

Figure 10: Finite Element model of AW139 intrumented Main Rotor beanie.

4.1.3 Laboratory testing for flight clearance

The sensor system was designed tacking into account most of the certification requirements. However, as the aim of the prototypal device developed in the MANOEUVRES project was to provide a technology demonstrator, it includes some components that are not qualified for airborne installation. Further tests were thus needed to get a flight clearance for the assembly, and were performed at Politecnico di Milano laboratories.

A MIMO (Multi-Input – Multi-Output) impact modal test with 7 uni-axial and 7 tri-axial accelerometers and rowing hammer technique has been performed to derive the integrated system modal characteristics. Further tests were performed on specific components, to collect data related to local modes of the supports, cameras, balancing masses and lighting device. The test results confirmed the absence of resonances close to the dominant *n*/rev. frequencies.

Subsequently, the three types of test described in Section 3.3 were performed on the final assembly to assess both safety and performance characteristics.

- Vibration tests: electro-mechanical shaker tests with vibration spectra comparable with operational ones in the most demanding flight conditions, were performed in vertical, radial and tangential directions (Figure 11). Operational vibration amplitude was also increased by a suitable safety factor. Each test had a continuous duration of 5 minutes (30 minutes in total).
- Rotation tests: the complete sensor system assembly was installed on the A109MKII ironbird for centrifugal testing at a 360 rpm speed (20% higher that AW139 main rotor speed).
- Sunlight sensitivity tests: the A109MKII setup was completed with a simulated "Sun" tested in 3 positions. The influence of sunlight was very low:
  - "Sun" in the upper position (45 deg with respect to the rotor plan): no data loss;
  - "Sun" in the equatorial position: 1/1000 data loss;
  - "Sun" in the lower position (parallel to the camera axis): 1 point per revolution lost.

At the end of each test, tightening of all the screws, structural integrity (absence of cracks and missing parts), unchanged position of the optical assembly (lenses, cameras, lighting device), and functionality of the measurement system were carefully checked.

Figure 11: Vibration tests of final sensor system configuration at Politecnico di Milano.

Furthermore, a new rig has been assembled at Politecnico di Milano laboratories with a stationary instrumented beanie and target fixed on a 7-d.o.f. robotic arm (Figure 12). This new rig was designed for accuracy test of the sensor system in its final configuration, spanning the full angular envelope of interest. The results confirmed the satisfactory accuracy levels previously achieved.

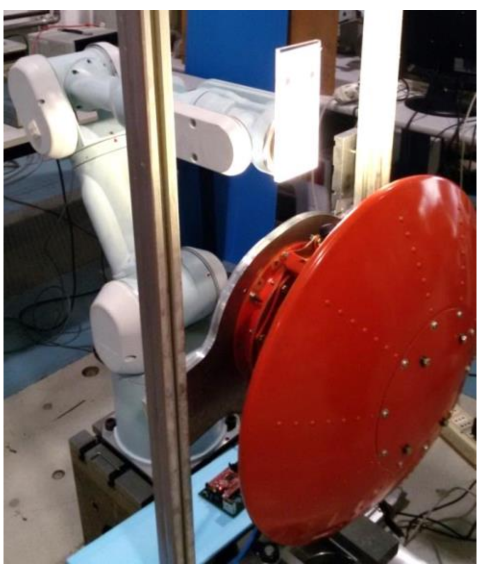

Figure 12: Accuracy tests using a 7 d.o.f robotic arm at Politecnico di Milano.

The positive completion of the test campaign allowed the sensor system to obtain the flight clearance and therefore the green light for dedicated AW139 flight tests.

4.2. Flight demonstration trials

The main goals of the final demonstration on board of the AgustaWestland AW139 prototype helicopter (Figure 13) were the following:

1. Check the ability of the sensor system to operate correctly and safely when integrated on board, both on ground and in flight; this implies the verification of correct operations of cameras, LED lighting device, and trigger generator/distributor, including two-way signal transmission through the slipring.
2. Check the ability of the measurement system to provide blade attitude estimation when integrated on board.
3. Correlate the blade angles measurements with those simultaneously acquired by the baseline Leonardo Helicopters system [13].
4. Provide lessons learned, useful guidance and recommendations for further developments of the main rotor blade attitude measurement system and its on-board integration.

Additionally, the effects of vibration levels have been verified and any possible interaction between the installed system and pilot operations have been assessed.

4.2.1 Test Matrix

The test matrix included the following 4 phases:

- Test Phase A – On ground system check and calibration.
- Test Phase B – On ground test conditions with combinations of main rotor collective and cyclic pitch as allowed by the ground manoeuvring envelope.
- Test Phase C – Steady-state flight tests.
- Test Phase D – Steady-state, approach and dynamic manoeuvring flight tests.

These phases were considered in order to provide an adequate build-up approach to the final demonstration, in view of a correct step-by-step verification of the expected system operational characteristics and of an optimal mitigation of possible inconveniences and difficulties during the full process.

Test Phases A and B have been conducted with the helicopter on ground. In particular, Test Phase A included the preliminary functional check and the system calibration with rotorcraft engines shut off, while Test Phase B includes engine-on acquisitions of the blade motion.

Test Phases C and D involved in-flight operations, with acquisitions along the full duration of the mission. In particular, Test Phase C includes take-off, hover, climb to test altitude, 15 steady-state conditions from low to maximum speed, and normal approach and landing. In Test Phase D, take-off and climb, 2 steady-state conditions, and 18 dynamic manoeuvring test conditions were performed, including final steep approach and landing.

At the end of each test sequence, the structural integrity of the installation has been verified, as well as the correct data acquisition, before proceeding to the following phase. Furthermore, a camera status indicator was constantly checked on-board by the Flight Test Engineer, in order to trig a test abort procedure in case of persisting data loss, which could also be an indication of system structural failure.

4.2.2 Troubleshooting

Initial experiences during Test Phase A with the sensor system led to some difficulties in continuous, effective image acquisition due to the difference in lighting conditions compared to the laboratory trials. Therefore, a local modification of the target was carried out, as well as the optimization of camera parameters (optical and software).

After these modifications, the image acquisition was proven to be generally continuous and effective. However, to fully decouple system performance assessment and sunlight-related problems, minimizing the risk of data loss or bad data acquisition, Test Phase D was scheduled to be performed at dusk.

4.3. Flight Test Results

The integrated main rotor blade attitude measurement system performed correctly and continuously during the flight test campaign. During the full duration of the test sequence, both on ground and in flight, the system accomplished the acquisition of the blade position without showing any malfunction, either hardware or software.

In addition, during the full duration of the flight operations (over 3 hours), the baseline measurement system for blade motion acquisition operated continuously, providing a useful reference for data analysis.

Figure 13: AgustaWestland AW139 prototype helicopter during rotor state measurement system flight test campaign.

A total of 64 flight conditions have been acquired, as described in Section 4.2.1. While an extensive and accurate analysis on the whole amount of data is still in progress, three records related to different flight conditions will be shown in the present paper, representative of the full envelope investigated: a steady level flight (record No. 6), a steady descending flight (record No. 7) and a steady deceleration during a descent (record No. 18). Helicopter airspeed and altitude of the selected records are shown in Figure 14 and 15.

Data from the record No. 6 will be analyzed and presented into details in section 4.3.1, as an example of sensor system performance. Then, data of the three records considered will be presented in aggregated and synthetic form (section 4.3.2).

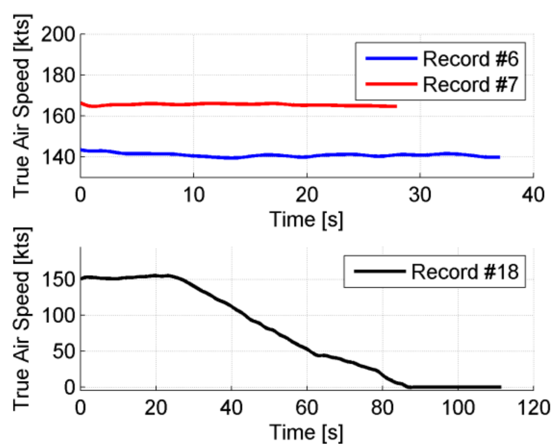

Figure 14: Helicopter airspeed in the selected records.

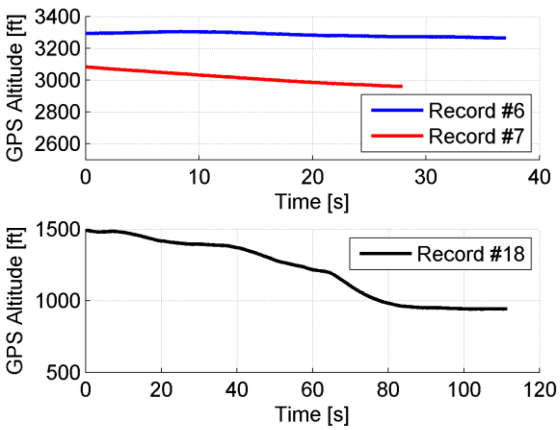

Figure 15: Helicopter GPS altitude in the selected records.

4.3.1 Detailed analysis of record No. 6

Lag, flap and pitch estimations from the blade attitude measurement system have been acquired with a sampling frequency synchronous with the helicopter main rotor, at 7 samples per revolution. On the other hand, estimations from the baseline sensor are sampled at the constant frequency of 512 Hz. This implies that while it is fairly straightforward to compare the two estimations in the frequency domain, data need some pre-processing for a time-domain comparison. The stereo camera sensor system data have been re-sampled after the acquisition to match the 512 Hz sampling frequency of the concurrent system. The results of this comparison are presented in the Figure 16 to 18, where a short time frame is shown to enhance the possibility to appreciate the wave form.

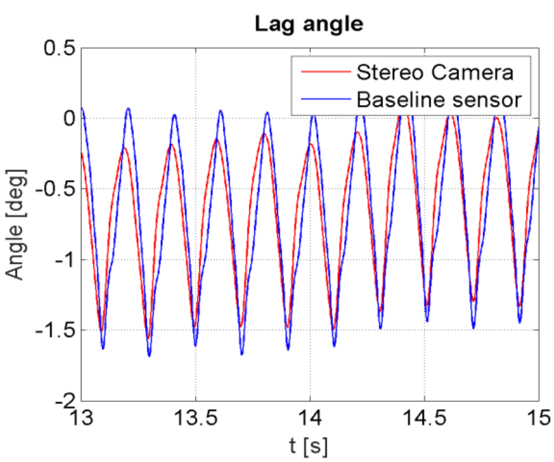

Figure 16: Main rotor lag angle comparison.

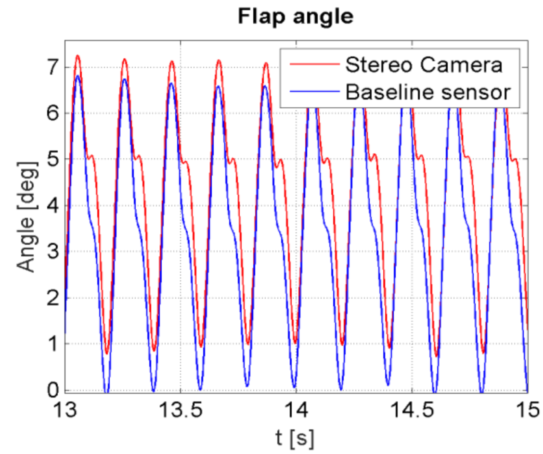

Figure 17: Main rotor flap angle comparison.

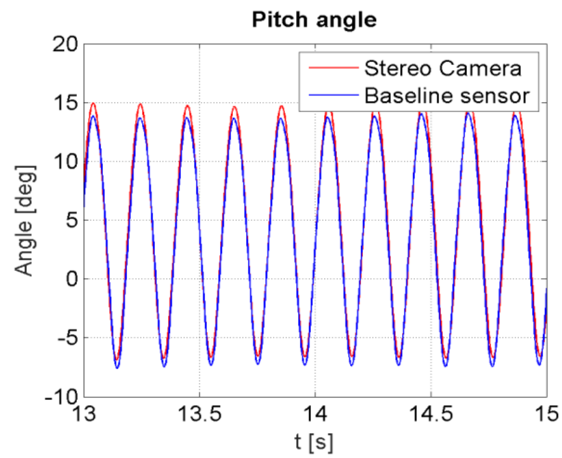

Figure 18: Main rotor pitch angle comparison.

It can be seen that some differences, generally limited, can be observed between the two sets of quantities.

An analysis was performed to characterize the discrepancy in the static values (*i.e.* mean values) for the three angles. Figure 19 shows the trends of the lag, flap and pitch angles mean values, highlighting a remarkable affinity between the average values of the mean angles of lag, which amounts roughly to -0.05 degrees. Also the values for pitch are significantly close, with a discrepancy of approximately 0.56 deg. The flap values appear as those which show the highest difference, amounting to about 0.92 deg.

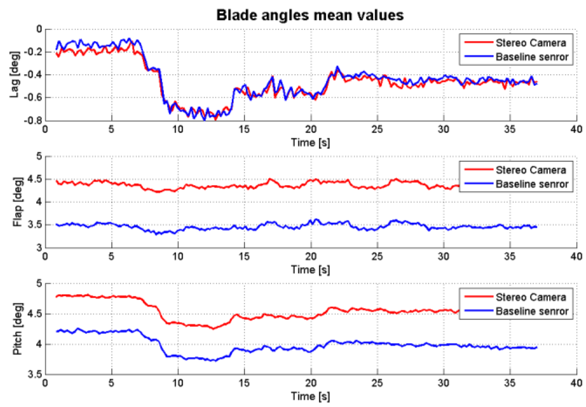

Figure 19: Trends of the static values of lag, flap and pitch angles.

The analysis was extended to include the first two harmonic components of the three angles, by analyzing the spectrum of the two signals and extracting the amplitude of the 1/rev and 2/rev on the same time intervals.

The trend of the discrepancy for the three angles is displayed in Figure 20. Approximately, the lead-lag 1st harmonic amplitude values differ by 0.10 deg, those for flap by 0.25 deg, and those for pitch by 0.50 deg.

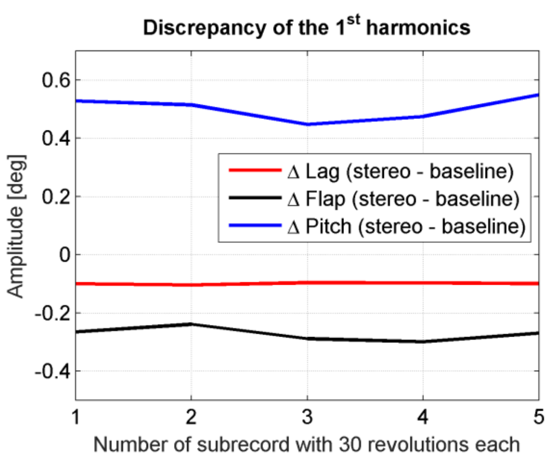

Figure 20: Trend of the discrepancy between 1st harmonic components in record No. 6.

A similar analysis was also carried out for the second harmonic components (Figure 21).

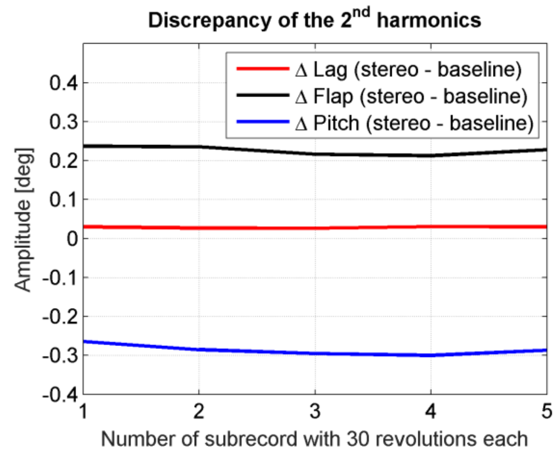

Figure 21: Trend of the discrepancy between 2nd harmonic components in record No. 6.

4.3.2 Synthetic representation of blade attitude data comparison

The analysis presented in the previous Section 4.3.1 has been performed also for records No. 7 and 18, with the aim of comparing the estimations by the new stereo camera sensor system with respect to the baseline sensor. The results are presented in a synthetic and aggregated form in the following Table 5, in terms of average and maximum discrepancy between the two system estimations. The comparison is shown for static (mean) value, first and second harmonic, for the three angles.

		Lag *[deg]*	**Flap *[deg]***	**Pitch *[deg]***
	Max static angle	2,34	4,62	6,65
	Min static angle	-7,04	2,29	-3,70
Static	Max discrepancy	0,40	1,10	1,30
	Avg. discrepancy	0,15	0,97	0,59
1/rev.	Max discrepancy	0,55	0,42	0,93
	Avg. discrepancy	0,10	0,26	0,37
2/rev.	Max discrepancy	0,05	0,36	0,50
	Avg. discrepancy	0,03	0,15	0,17

Table 5: Comparison between the two measurement systems for Records No. 6, 7 and 18.

The results are quite satisfactory, especially considering that come from the first flight trials for a sensor with such an architecture. The discrepancy with respect to the baseline sensor doesn't reflect, generally, the accuracy estimated through the rig tests (see section 3.4, Table 4), but it's fully within the expectations, especially for the first harmonic of flapping angle, the component which mostly impact on noise generation. However, the test rig conditions were significantly different from the flight ones, due to the absence of vibratory, centrifugal and wind loads. Furthermore, it should be noticed that the test rig control system is capable of providing very accurate angles values, which can be used as a term of reference, while a full characterization of the baseline sensor accuracy is not available. A more extensive and detailed analysis of both sensor systems is currently on-going, to provide a more accurate characterization.

5. CONCLUSIONS

Based on the evidence provided in this paper, the final demonstration of the MANOEUVRES main rotor blade attitude measurement system is considered highly successful for the following reasons:

1. The ability of the integrated system to operate correctly and safely when integrated on board, on ground and in flight was fully verified.
2. The measurement system provided valid blade angle measurements when integrated on board, both on ground and in flight.
3. The blade angle measurements were correlated with those simultaneously acquired by the baseline sensor system provided by Leonardo Helicopters.

Concerning the latter point, an analysis of the discrepancy of the measurements obtained by the two measurement systems was carried out. The result of this analysis is satisfactory: the correlation concerning the mean values observed for the lead-lag, flap and pitch blade angles is acceptable (in view of the complexity of the phenomenon being tackled), and the correlation concerning the 1^{st} and 2^{nd} harmonic components for the three angles is even better.

It would be useful to further characterize the accuracy of the baseline sensor system, especially with respect to the impact of possible deviations from the kinematic hypotheses assumed in the calibration algorithm.

Globally, the stereo camera rotor state measurement system appears as a promising candidate for future experimental and, eventually, production applications in which the real-time acquisition of the blade motion is required, such as those targeted in the MANOEUVRES project, *i.e.* emitted noise monitoring and rotor state feedback augmented control laws.

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