A New Framework for Rotorcraft In-flight Noise Monitoring

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ABSTRACT

An original approach to the in-flight noise monitoring of maneuvering rotorcraft was recently pursued, developing the fundamental ingredients that allow estimating the acoustic emission in real time and presenting a convenient information of such emission to the pilot. This is obtained through a new cockpit instrument, the Pilot Acoustic Indicator, which is supported by a noise estimation algorithm that exploits offline, accurate acoustic predictions, runtime available parameters from the avionic bus, and an observation method that provides the values of non-directly-measurable parameters, such as the main rotor angle of attack. The observer uses the measurements of the main rotor blade angles, which are achieved by a new contactless measurement system based on stereo vision. These technologies and tools have been fully developed and tested in either highly representative, or real operating conditions. The paper describes the complete framework, its main components and the related results, and sketches possible activities towards a complete implementation on board current or future production rotorcraft.

KEYWORDS: *rotorcraft noise, noise abatement, noise monitoring, low-noise procedures, blade attitude sensor*

1 INTRODUCTION

The present paper offers a comprehensive review of the work performed while setting up a methodology and the habilitating technologies and tools for a novel approach to rotorcraft in-flight monitoring of emitted noise, and sketches a few ideas for future steps.
Radiated noise stands as one of the biggest hindrances in performing rotorcraft operations, as these are typically carried out at low altitudes and impact significantly on the overflown human and natural environment. On the other hand, the peculiarity of some of the mission tasks performed by helicopters and tiltrotors is such that, even considering the rapid pace of the diffusion of unmanned rotary-wing vehicles for aerial work applications, it makes their usage inevitable and therefore inspires continuous development and optimization. Therefore, an important research topic in recent years is represented by noise reduction strategies. Basically, four approaches are investigated:

1. Vehicle design for low noise (e.g., blade aerodynamic design).
2. Active control for emitted noise abatement (e.g. higher harmonic pitch control).
3. Flight procedure design for low noise (e.g. steep descent profiles).
4. In-flight monitoring to allow noise-alleviating actions by the pilot.

The last approach is of interest here, being the main focus of the MANOEUVRES (Manoeuvring Noise Evaluation Using Validated Rotor State Estimation Systems) project, carried out in response to the Clean Sky GRC5 Call for Proposal SP1-JTI-CS-2013-01 "Innovative measurement and monitoring system for accurate on-board acoustic predictions during rotorcraft approaches and departures". The project was developed by a consortium composed by Politecnico di Milano, Università Roma Tre, Vicoter (a small engineering company skilled in structural dynamics and testing) and Logic (a leading avionics company), in close cooperation with Leonardo Helicopters (LH).
Within the Clean Sky Joint Technology Initiative, the Green Rotorcraft (GRC) Integrated Technology Demonstrator was concerned with multiple applied research actions for sustainability and environmental friendliness of rotorcraft. In particular, the GRC5 "Environment friendly flight paths" sub-project was strongly concerned in the achievement of one of the ACARE environmental objectives for 2020, i.e. the reduction of the noise perceived on ground by 10 EPNdB or halving the noise footprint area by 50%.

2 THE MANOEUVRES FRAMEWORK

Therefore, in the MANOEUVRES project, a feasible noise-abatement approach based on in-flight monitoring of the emitted acoustic radiation was conceived, for possible integration on current and future production helicopters [1–3]. This approach is intended to deliver methodologies and practical tools that concur to provide a synthetic, intuitive noise information to the pilot in real-time, allowing him the possibility to adopt suitable actions to maintain or reduce the vehicle's acoustic impact while following a given trajectory. Special attention has been given to terminal operations, and therefore to maneuvers such as decelerations and descents performed in the approach to landing. In this approach, actual vehicle characteristics (weight, configuration) and operating conditions are taken into account through their combined effects on some direct measurements, including elements of the kinematic state of the rotorcraft and its main rotor (MR). Based on this, a complex algorithm invoking relatively simple numerical modelling – fit for real-time computation needs – allows to estimate the noise emission and to relate it to specified thresholds.

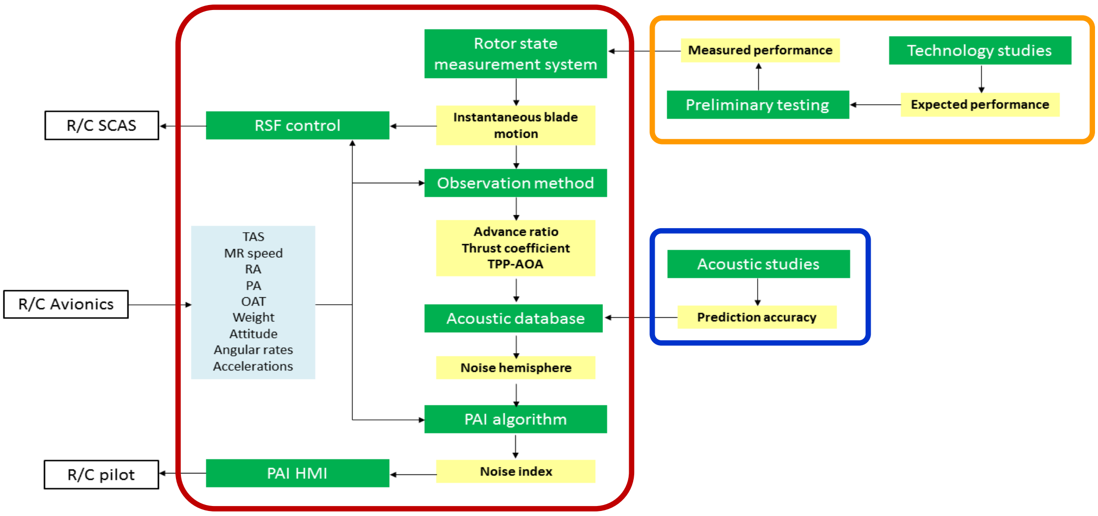


Figure 1: MANOEUVRES integrated concept

The functional scheme of the MANOEUVRES integrated concept is shown in Figure 1. Within the red contour, the components of the noise estimation and indication system are shown: green bpxes identify original elements developed within the MANOEUVRES project, i.e. methods or equipment providing as output the parameters addressed in the yellow boxes. Starting from below, the pilot receives emitted noise information through a new cockpit instrument, the Pilot Acoustic Indicator (PAI), through a dedicated HMI (Human-Machine Interface) [4,5]. The PAI HMI conveniently displays the value of a noise index, which is computed by the PAI algorithm based on of an estimation of the present acoustic emission of the vehicle. This emission is described by a SPL (Sound Pressure Level) distribution over a suitable portion of a spherical surface rigidly connected with the aircraft, retrieved from a pre-calculated database covering the flight envelope of interest (Figure 2).

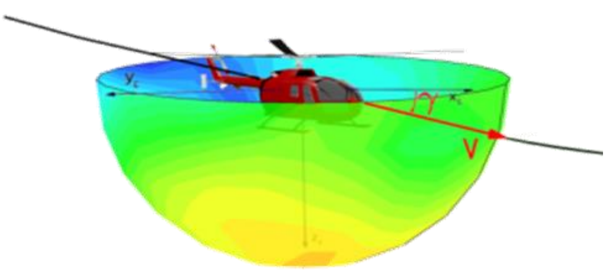


Figure 2: Acoustic (hemi)spherical SPL distribution connected with the vehicle

The database is interrogated by entering the values of three quantities that conveniently parameterize the acoustic phenomenon: the advance ratio, the thrust coefficient, and the angle of attack (AOA) of the tip-path plane (TPP), or TPP-AOA. The first represents the ratio of vehicle translation airspeed on MR rotational speed, the second the MR disk loading, and the third the relative orientation of the MR disk with respect to the vehicle airspeed vector [6].
While the advance ratio is estimated from airspeed and MR speed, effortlessly retrieved from the avionic data bus, the thrust coefficient and even more the TPP-AOA may not be estimated as easily, since a direct measurement of the thrust and of the rotor disc attitude are not normally available on typical production helicopters. In particular, the TPP-AOA can be seen as the result of two relative rotations, one being the orientation of the vehicle with respect to the airspeed vector and the other the orientation of the TPP with respect to the vehicle.
The former may be measured in principle by angle of attack and sideslip vanes placed on an air data boom, but this is not a common equipment on rotorcraft, and may suffer from significant inaccuracy due to the complex aerodynamic field generated by the MR wake and its interaction with the fuselage. For the latter, a measurement of the MR cyclic flapping is needed. Experimental devices are sometimes used by helicopter manufacturer to collect a direct measurement of the blade motion, typically expressed by the three angles of lead-lag, flap and pitch (an example is LH's Movpal system [7]). Although these sensing devices are available, their exploitation is not sufficient for the TPP-AOA estimation, as they only can support the estimation of the TPP angle of incidence with respect to the fuselage. Therefore, an observation method has been developed to take advantage of cyclic flapping measurements to derive an estimation of the thrust coefficient and TPP-AOA, based on an procedure that identifies the coefficient of a linear, airspeed-scheduled model [8,9].
The real-time blade motion parameters can be retrieved through a blade motion sensor such as those cited above. However, these contact-based sensors are prone to significant mechanical fatigue and may be integrated on board production helicopters with some difficulty. Hence, a brand-new rotor state measurement system based on contactless technology was designed and implemented [10,11].
In addition to noise estimation, the availability on board of a direct measurement of the MR blade motion can be beneficial to further applications, including FCS (Flight Control System) augmentation. For this reason, within the MANOEUVRES project, a study was conducted in which measured values of the blade angles are also feeding a Rotor State Feedback control system, to be integrated within the Stability and Control Augmentation System (SCAS), in order to enhance overall rotorcraft handling qualities [12,13].
The white boxes represent rotorcraft system components, i.e. the SCAS and the pilot, both receiving information from the MANOEUVRES noise estimation and indication system, and the avionic bus, which provides the input data contained in the cyan box. Within the orange contour, the preparatory activities carried out to develop the new rotor state measurement system are indicated, while the acoustic studies that led to the production and assessment of the noise emission database appear within the blue contour [14,15].
In the following sections, the main outcomes of the MANOEUVRES project are concisely presented, before drawing concluding remarks and indications for future work.

3 NOISE INDICATIONS TO THE PILOT

The PAI has been designed in order to derive emitted noise information and convey it to the rotorcraft pilot in a convenient fashion. It has been conceived as a practical tool, to monitor acoustic performance and help the steering of the vehicle, for example when tracking a low-noise procedure, such a steep approach, or in the case of flying at low altitude close to noise-sensitive areas.
For this reason, the value of a suitable noise index is displayed on a MFD (Multi-Function Display) according to different operational modes, resulting from the combination of two alternative computations and two alternative visualizations. In fact, the computation of the noise index can be performed in "Emitted mode" or in "Ground mode". The "Emitted mode" computation is based on the processing the SPL values distributed on the noise hemisphere (SPLH) of interest, while the "Ground mode" computation relies on processing the SPL values radiated from the hemisphere to the terrain below the rotorcraft. In the latter case, a simplified radiation model is employed to determine the acoustic footprint on the ideal flat ground, by retrieving additional information from the avionic bus, such as vehicle attitude angles and radar altitude. Figure 3 illustrates the conceptual PAI flowchart.

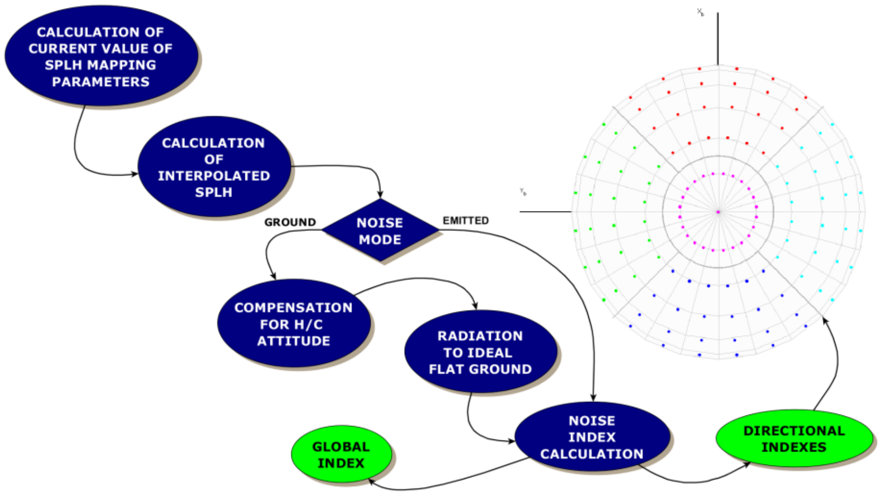


Figure 3: PAI algorithm flowchart

The noise index is then presented through the "Global indicator" or the "Directional indicator". The "Global indicator" shows the value of the current noise index and the predicted value within a near-future time window (a few seconds, adjustable by the pilot), computed by taking into account the whole SPL distribution, either on the hemisphere or on the ground, depending on the active mode. The noise index values are arranged within an articulated, but intuitive visualization in which applicable noise thresholds can be seen, as well as predetermined suggestions to steer the vehicle in order to avoid increasing the noise impact. The "Directional indicator" displays five values at a time, corresponding to the noise index, each one calculated from the SPL distribution within one of the four coordinate sectors (front, left, rear, right), plus the bottom spherical cap (lower sector). Figure 4 shows the appearance of the two presentations, with an explanations of the symbology employed.

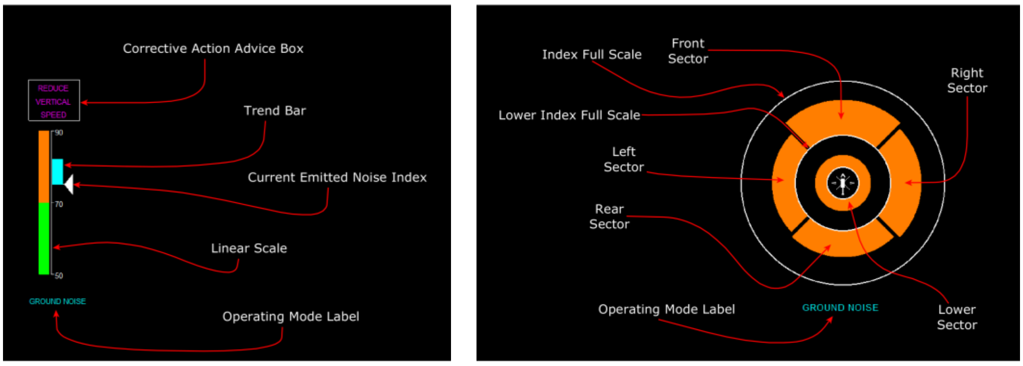


Figure 4: Global (left) and Directional (right) PAI presentations

The noise index is computed as the absolute maximum value of OASLP (Overall SPL) found in the region of interest. This means that first the current noise hemisphere is interpolated based on the current values of advance ratio, thrust coefficient, and TPP-AOA. Then, for "Emitted mode" operations, the maximum value within the full hemisphere (for the "Global Indicator" display) or the maxima within each of the five sub-regions of the hemisphere (for the "Directional Indicator" display) are considered. In the case of "Ground mode" operations, the noise distribution on the hemisphere is radiated to the ideal flat ground, taking into account the vehicle current attitude and altitude, and then the maximum value within the full footprint (for the "Global Indicator" display) or the maxima within each of the five sub-regions of the footprint (for the "Directional Indicator" display) are considered. The reader is referred to [3,4] for a detailed discussion of PAI design and implementation.

The database of OASPL hemispherical distributions is computed offline for a given helicopter with a sophisticated aeroacoustic steady-state prediction tool. As the database is queried through the instantaneous values of advance ratio, thrust coefficient, and TPP-AOA, a quasi-steady estimation is obtained, fit for real-time computations. The accuracy of this method has been assessed by

comparison with the application of a computationally cost-intensive fully-unsteady aeroacoustic prediction tool [14,15]. Results showed the good agreement between the two approaches and the advantage of the method using the measured instantaneous values of the three parameters with respect to a completely steady approximation.
The PAI was implemented as a stand-alone equipment, laboratory tested and then integrated within a LH research flight simulator. Simulated flights carried out by test pilots were performed, assessing the functionality and adequacy of the noise indication, collecting lessons learned and suggestions for further development and optimization. PAI final testing is discussed in [5].

4 OBSERVING THE TPP-AOA

The fundamental ingredient for the PAI noise estimation algorithm is the triad of values assumed by the database parameterizing quantities: advance ratio, thrust coefficient, and TPP-AOA. Once the former is given, from the avionic data bus, the two latter quantities are retrieved through an observation method. This allows to overcome the difficulties related to the unavailability of direct measurements for these two parameters. The method has been proposed in [8] and further refined and extended in [9].
The basic idea is to derive a linear model in which the observed quantities are computed as functions of an array of measurements. These are basic flight condition parameters (weight, air density) and MR blade attitude components (collective and cyclic flappings), complemented in [9] by the tail rotor (TR) control position, or TR collective pitch. The strongly nonlinear, inherent dependence on airspeed, or advance ratio, is taken into account by scheduling the models with respect to this variable. For the observer synthesis, the model coefficients are determined by an identification process, computing a number of maneuvers in such a way that the envelope of interest is well represented, spanning all relevant variables: weight, air density, airspeed, flight path angle, angle of sideslip. Figure 5 shows on the left the observation accuracy for the TPP-AOA obtained when using the method at 35 kn (black) and 45 kn (blue) airspeed, based on the identification performed at 30, 40 and 50 kn, ranging from 68% to 100% in weight and from 3 to 7 deg in descent angle. As seen, the errors are very limited, amounting to an average value of 1.91%. The corresponding performance for the thrust coefficient is even better, with an average error below 0.06%.

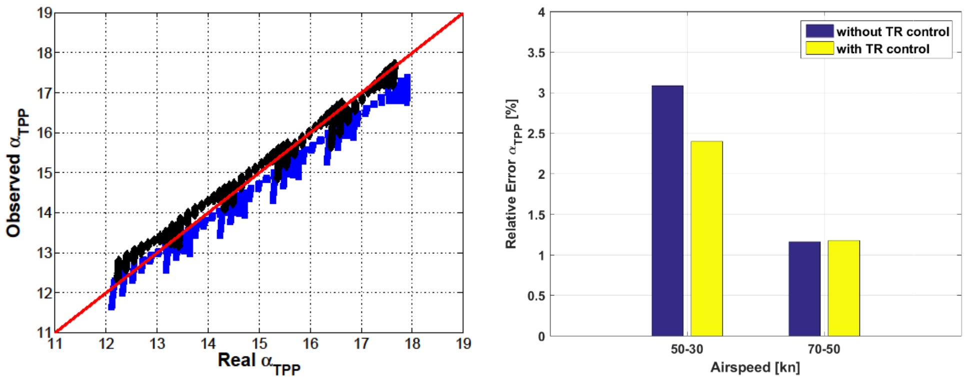
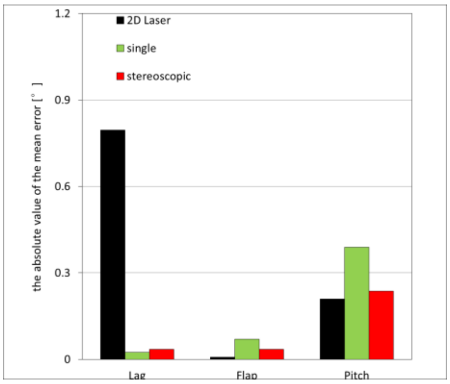


Figure 5: Observation accuracy for TPP-AOA

This approach has proven affective when applied to constant-speed descents in symmetric flight, in both design and off-design conditions, the latter involving non-symmetric flight and decelerations [8]. Further developments, recently published in [9], showed that the inclusion of the TR collective pitch allows to expand significantly the applicability of the approach to decelerated and non-symmetric flight conditions. Figure 5 shows on the right the average errors found when considering two off-design decelerated descents at a given weight, one between 50 and 30 kn, and the other between 70 and 50 kn. Comparing the initial model of [8] and the extended model of [9], the beneficial effect of including the TR pitch control among the measurements is apparent.
The extended model also allows retrieving also the angles of attack and sideslip of the fuselage among the observed set of variables. The knowledge of these quantities may be beneficial to other applications, beyond noise estimation, such as FCS-related functions.

5 CONTACTLESS ROTOR BLADE MEASUREMENTS

From the preceding discussion, it appears that a fundamental ingredient for the in-flight monitoring of emitted noise targeted in the MANOEUVRES project is the availability of real-time measurements of the MR blade angles, in particular the collective and cyclic flappings. Therefore, a highly-structured development path was conceived to design and implement a new vision-based rotor state measurement system capable of supporting the needs of the MANOEUVRES integrated system. This path started with a technology survey, passing through a preliminary selection that provided three candidate sensor systems, all based on the main rotor and pointing to a target placed on the top surface of the blade root: one based on a 2D laser, and two based on camera systems [16]. The latter were different in their measuring principle, as one featured a single camera and used a pose-estimation algorithm, while the other employed two cameras in a stereo arrangement. These candidate sensor systems were actually implemented in full scale, laboratory tested and assessed on the basis of measured performance. Figure 6 shows the mean errors obtained in a specific test case for the three systems, replicating in-flight measured time histories of the blade angles: on the left, the errors on the static components appear and, on the right, those on the cyclic components.



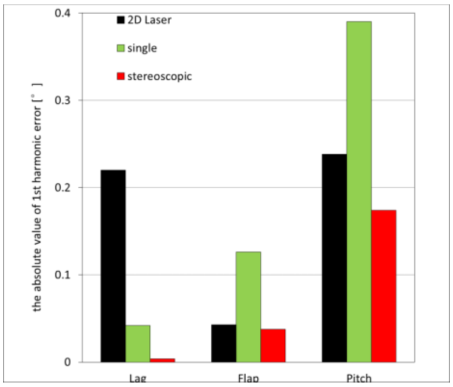


Figure 6: Measurement errors for the three candidate systems

Although all three fulfilled the design requirements, eventually, the stereo system achieved the best accuracy. The sensor part of this system is composed of a pair of smart cameras and a lighting device using LEDs, with an optical target glued to the blade root (Figure 7, left). Its performance is listed in Table 1 and is to be compared with the required accuracy considered in the MANOEUVRES project for the flapping measurement, 0.5 deg (mandatory) and 0.1 deg (desired). Furthermore, these figures show a significant improvement on a recent device based on an array of Anisotropic Magnetoresistive (AMR) presented in [17], which showed an accuracy of 1.0 deg in lag, 0.3 deg in flap, and over 1.0 deg in pitch during laboratory tests in much simplified conditions.

Table 1: Accuracy of the three candidate systems

Measurement system	Mean value error [deg]	Cyclic value error [deg]
2D laser	0.72	0.89
Single camera	0.15	0.35
Stereoscopic	0.15	0.09

The stereo system was chosen for the final phase of development [10,11]. This involved two main tasks. The first was the optimization of the system and the integration on the main rotor head of a AW139 helicopter. The system was installed on the MR experimental beanie provided by LH and thoroughly tested in order to fulfill the following requirements:

1. Optimize the system parameters and support subsystems (such as signal processing and transmission devices, synchronization, lighting, etc.).
2. Assess the installed system functionality and metrological performance.
3. Assess the structural performance and the overall safety of the installation.

The latter is clearly a fundamental prerequisite for the achievement of the permit to fly.

Figure 7: Measurement system installed on board a AW139

Indeed, the second task called for testing the rotor state measurement system on board a AW139 helicopter (Figure 7, right), involving overall more severe conditions with respect to rig testing. Initially, the project was intended to end with a ground demonstration only (TRL5), but given that the system performance exceeded expectations under many respects, an additional effort was made to perform a comprehensive flight test campaign, with 4 flights and over 3 hours of continuous system operations without any failure (TRL6). This was the first ever stereo camera system for blade attitude measurement to be flight tested to date.

The acquired data were processed and compared with those gathered through an independent, contact-based sensor system used for experimental activities at LH, the Movpal [7]. The analysis showed a very good agreement, except for an offset that may be attributed to the combination of a number of factors, including the on-board calibration procedure of both systems and modelling assumptions employed in the data processing of the contact-based system. The mean discrepancy between the two measuring systems was found to be 0.15 deg, 0.97 deg and 0.59 deg for lag, flap and pitch angles, respectively. The values of the 1/rev amplitudes (cyclic components) showed a maximum discrepancy of 0.55 deg.

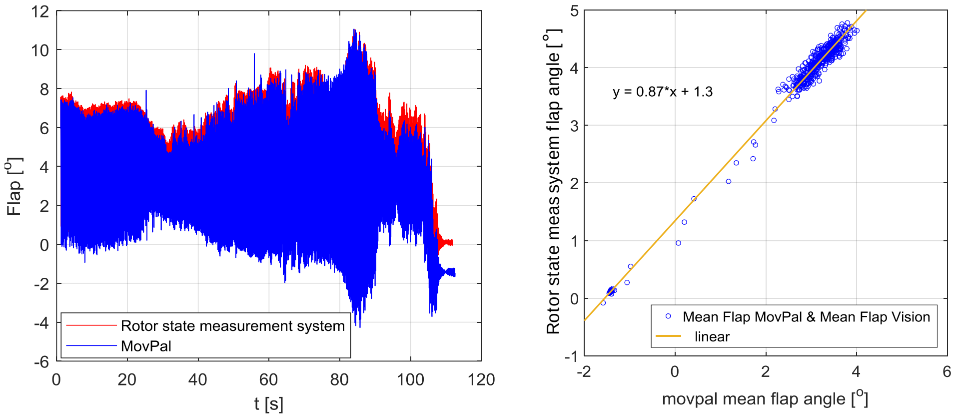


Figure 8: Flap angle in-flight measurements

Figure 8, on the left, depicts the time histories for the flap angle during one of the test flights: the contact-based system data are shown in blue, while the MANOEUVRES system data in red. The same figure, on the right, shows the correlation between the running averages of both data series. The test flight preparation and outcomes are discussed in detail in [18].

6 CONCLUSIONS AND FUTURE WORK

A significant effort has been made in developing and validating habilitating technologies and tools necessary to an integrated system aimed at providing a rotorcraft pilot with an accurate, reliable, real-time information of the external acoustic impact. The system conceived aims at a possible integration on board current and future production rotorcraft, going beyond a mere concept demonstration. The paper introduced the complex framework established within the MANOEUVRES project, which involves: noise index definition, computation and cockpit presentation; accurate offline acoustic predictions; in-flight estimation of non-measurable quantities; and rotor blade motion measurements. The Pilot Acoustic Indicator, a new flight instrument providing noise information on a dedicated HMI in the cockpit, has been implemented and tested in a simulated environment. The new vision-based rotor state measurement system was implemented and tested, first in a laboratory setting, and then in flight on board a helicopter. The general results of this activities are considered very successful and worth further developments.

Indeed, many lessons have been learnt in the process and further ideas emerged, in an attempt to achieve the maximum effectiveness of the proposed framework. A first possible activity exploiting the PAI may focus on pilot training on acoustic impact. This aims to make the pilot aware of the noise emission, in relation to the specific flight conditions and maneuver strategies. The PAI may be used in its current state of development, or enhanced by integrating a presentation of the ground acoustic footprint on a map of the overflown terrain, completed with noise-sensitive area markings. This would allow the pilot familiarization on the acoustic effects of its actions in a simulated flight environment, and may lead to the drafting of a training protocol to drill pilots in low-noise steering.

The same outfit may be used for the assessment of low-noise procedures through simulated flight test campaigns. This would contribute to the design and optimization of these highly-desired procedures, shrinking the costs of validation to a minimal fraction of what is currently needed, which involves flying the aircraft on an ground area instrumented with a number of microphones.

Concerning the rotor state measurement system, the equipment developed within the MANOEUVRES project is characterized by a high degree of reliability and portability on different rotor systems. An industrialized version for experimental activities (relying on an experimental MR slipring) may be easily obtained through limited interventions on the target, the lighting device, and/or the signal electronics. Furthermore, a stand-alone solution (not relying on an experimental MR slipring or other FTI items) fit for standard production helicopters may be derived by powering the system with suitable batteries placed on the rotor head and storing acquired data on a local mass memory, so that the whole measurement system would stay on the rotating subsystem and would not interact with the fuselage in any way. This solution would allow, in addition to noise-related applications, the gathering of a very significant amount of data for health and usage monitoring activities, with possible impacts on flight safety, as well as on operating costs.

An enhanced version of the rotor state measurement system may also make use of strain gauges placed along the monitored blade, in an arrangement that may provide shape sensing [19] along with blade rigid motion, for a full characterization of the blade dynamic response.

Finally, further optimization and validation of the TPP-AOA observation methodology may constitute a promising first step towards the design and implementation of a specific equipment, conceived to be integrated within the on-board avionics. The observation system may then be assessed through simulated flight tests and, upon reach of an adequate maturity, installed on board and thoroughly flight tested. This would allow to reach the complete goals of the MANOEUVRES project by completing the integration with the rotor state measurement system and the PAI, allowing the final flight testing of the integrated noise monitoring equipment. Also, the observer may be used in new FCS-related applications, exploiting its ability to estimate the TPP-AOA and also the fuselage angles of attack and sideslip with remarkable accuracy.

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