DEVELOPMENT AND TESTING OF INNOVATIVE SOLUTIONS FOR HELICOPTER IN-FLIGHT NOISE MONITORING AND ENHANCED CONTROL BASED ON ROTOR STATE MEASUREMENTS

Lorenzo Trainelli,[a] Massimo Gennaretti,[b] Emanuele Zappa,[c] Marco Lovera,[a] Alberto Rolando,[a] Potito Cordisco,[d] Riccardo Grassetti,[e] Matteo Redaelli[f]

[a]Department of Aerospace Science and Technology, Politecnico di Milano, Milano, Italy
[b]Department of Engineering, Università Roma Tre, Roma, Italy
[c]Department of Mechanical Engineering, Politecnico di Milano, Milano, Italy
[d]Vicoter, Calolziocorte, Italy
[e]Logic, Cassina de Pecchi, Italy
[f]Leonardo Helicopters, Cascina Costa, Italy

Abstract

The problem of the on-board monitoring of rotorcraft acoustic impact has been studied in an original way, through the development of an integrated system concept in which the pilot is offered an estimation of emitted noise by means of a new cockpit instrument, the Pilot Acoustic Indicator. The noise estimation is obtained in real time by exploiting several parameters retrieved from the aircraft avionics, essentially augmented by offline acoustic predictions and current main rotor blade motion information. As such, this innovative methodology heavily relies on the availability of a new rotor state measurement system capable to acquire the blade dynamics in an accurate and fast way. Such a system may effectively support additional applications, such as Rotor State Feedback control strategies, aimed to enhance fundamental aircraft handling qualities, leading to improved pilot/vehicle capabilities. The complex system concept is illustrated with its main components, updating previous descriptions and reporting on the final phases of this activity. This involved the correlation of acoustic predictions with experimental flight data, the final demonstration of the Pilot Acoustic Indicator through piloted simulation, and the final flight testing of the new rotor state measurement system on board an instrumented helicopter.

1. INTRODUCTION

Although much effort has been spent in the past years, external noise stands among the most limiting factors for the further diffusion of rotorcraft operations. Various approaches carried out towards a mitigation of the acoustic impact of these vehicles, including suitable design of the rotor blades[1] and flapping reduction through harmonic control.[2,3] These methods provide interesting results, but are somewhat limited in that they tackle only one aspect of the problem, which is indeed fairly complex. In fact, the origin of rotorcraft noise is both aerodynamic, through the rotors, and mechanic, through the engine and transmission system, and its radiation intensity on the ground significantly depends on the actual vehicle kinematic state. Therefore, several flight mechanics parameters, such as the aircraft orientation in space, have a significant effect in addition to blade aerodynamic characteristics and flapping motion.

A solution targeted in the Green Rotorcraft (GRC) Integrated Technology Demonstrator of the Clean Sky Joint Technology Initiative involves both the design of inherently lower-noise vehicle and subsystem, and the definition of low noise flight procedures, such as steep approach and departures. In this context, the ability to monitor emitted noise on board assumes a fundamental importance, towards performing such procedures effectively and taking into account the actual operational (possibly, off-design) conditions, such as vehicle characteristics and kinematic state.

The Clean Sky GRC MANOEUVRES (Manoeuvring Noise Evaluation Using Validated Rotor State Estimation Systems) project was carried out in order to develop innovative solutions for rotorcraft in-flight noise monitoring. This 32-month project ended in May, 2016, with the delivery of a set of habilitating technologies aimed to support the execution of low acoustic impact terminal procedures, and also to enable innovative tools for vehicle stability and control augmentation systems. Such technologies have been devised in view of a possible future implementation on board production helicopters and validated through extensive testing in highly representative enviroments, including piloted flight simulation and actual flight testing. Leonardo Helicopters closely co-operated with the partners of the MANOEUVRES consortium (Politecnico di Milano, Università Roma Tre, Logic and Vicoter) throughout the project activities, providing technical support and experimental resources.

The present paper provides an overview on the final project outcomes, updating the the illustration given in previous references which presented a number of mid-term results.[5,6]

2. THE 'MANOEUVRES INTEGRATED CONCEPT'

In the MANOEUVRES project, a complex research activity involving manoeuvring rotorcraft aeroacoustics, rotor state measurements, emitted noise prediction and pilot instrumentation was deployed. This was conceived to back up the development of an integrated concept envisaging an aid to the rotorcraft pilot based on a synthetic representation of the running emitted noise, estimated by an algorithm which uses both pre-calculated data and direct measurements collected on board, exploiting a novel dedicated sensor system.

2.1. General description

The above mentioned representation is implemented within a novel instrument, the Pilot Acoustic Indicator (PAI), which features a complete graphical HMI integrated within in the cockpit panel. The PAI interface presents real-time data related to the values assumed by a suitable noise index in time and space. Such index is computed by evaluating the noise distribution based on a sophisticated aeroacoustic prediction computed offline.

In fact, recent research results demonstrated that rotorcraft emitted noise for a given vehicle can be correlated to the values assumed by three fundamental aeromechanical parameters: the advance ratio μ, the thrust coefficient C_T, and the angle of attack of the tip-path plane (TPP-AOA) α_{TPP}.[7,8] The first represents the ratio of vehicle translation airspeed on main rotor blade rotational speed, the second the main rotor disk loading, and the third the relative orientation of the main rotor disk with respect to vehicle airspeed. Figure 1 shows the geometry applicable to a symmetric flight condition, when α_{TPP} is given by the sum of the angle of attack of the fuselage α_s and the longitudinal cyclic flapping a_{1_s}.[9]

Based on these parameters, and under steady-state hypotheses, a noise distribution can be associated to

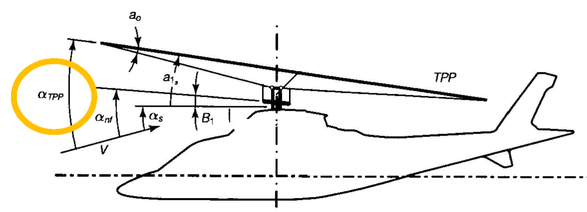

Figure 1: Geometry for TPP-AOA in symmetric flight (modified from Ref. 9).

a sphere (or a part of it, typically the lower hemisphere below the nominal rotor disk plane) of a given radius surrounding the vehicle, and such spheres may be collected in a database for all values of interest of the triplet, which in turn can be correlated to specific flight conditions (*e.g.* in terms of weight, density altitude, airspeed and flight-path angle). When executing an approach maneuver with a given profile, an approximation of the noise emission can thus be retrieved by associating each point in the trajectory with an acoustic hemisphere.[10–12] This clearly allows to avoid costly unsteady acoustic predictions, which would be unsuited to the real-time requirements of an in-flight noise monitoring application, substituting them with relatively inexpensive evaluations of interpolated acoustic hemispheres within the database.

The quality of this quasi-steady approximation has been assessed by correlation with the results of a recently updated and improved fully unsteady aeroacoustic code. Two different quasi-steady approaches, differing for the accuracy in the estimation of the TPP-AOA, have been contrasted and compared to the fully unsteady approach. Different time instants within an array of approach procedures consisting in level decelerations followed by constant-speed descents have been analyzed. Both cases, one featuring a relatively simple steady-state estimation, the other reproducing the availability of a direct measurement of the TPP-AOA, showed generally good results. A higher accuracy has been achieved when using the latter, especially during decelerations, when the TPP-AOA changes significantly. The results of this analysis are reported in detail in Refs. 6 and 13.

In order to implement this strategy, the running value of the three parameters $(\mu, C_T, \alpha_{\mathrm{TPP}})$ must be evaluated. While the advance ratio is relatively easy to de-

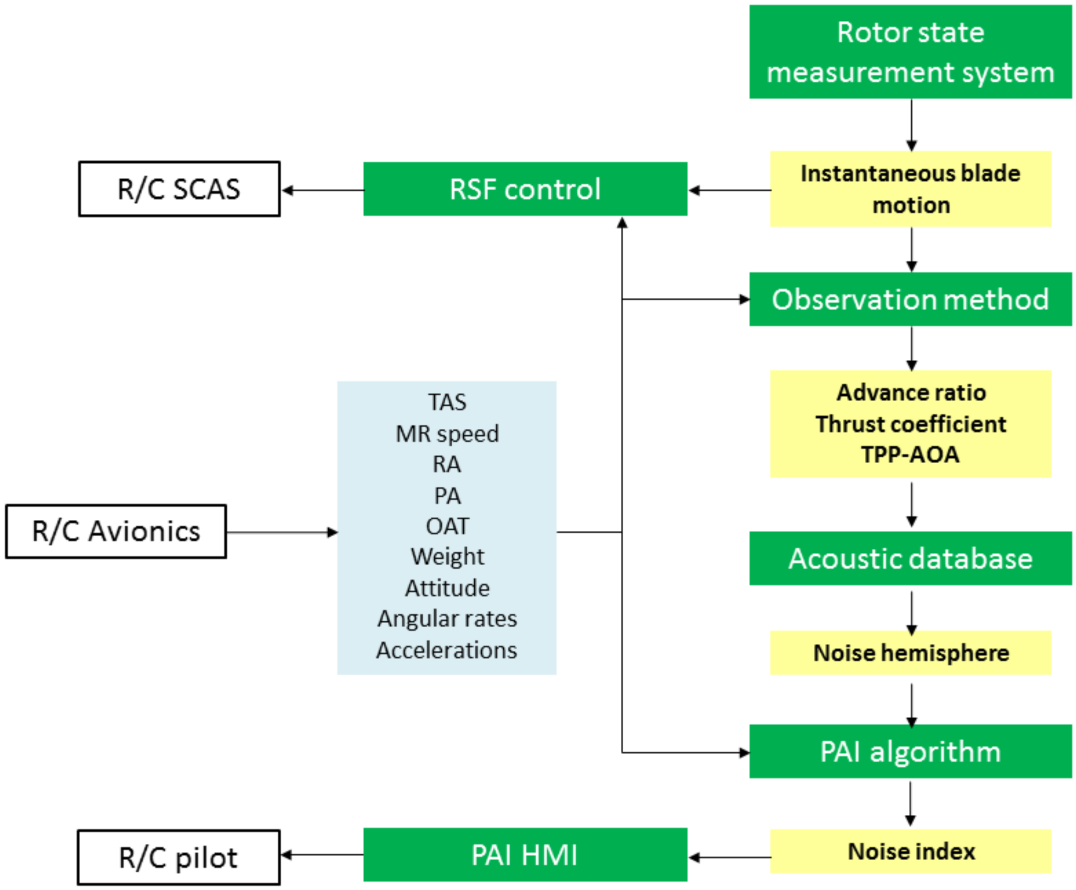

Figure 2: The MANOEUVRES integrated concept.

rive from measured data available on board, the other two parameters involve some difficulties, as typically there are no direct measurements that can be related to the rotor thrust and the TPP-AOA. As an estimation of the pair $(C_T, \alpha_{\text{TPP}})$ based on a simplified, real-time capable performance rotorcraft model may involve excessive inaccuracies, and thus lead to significant errors in noise prediction, the approach followed in the MANOEUVRES project is to exploit as much as possible a direct measurement of the rotor kinematic state. Indeed, by measuring the motion of a rotor blade in real time, it is possible to retrieve the orientation of the tip-path plane (TPP) with respect to the rotorcraft airframe. This, coupled with the knowledge of the orientation of the airframe with respect to the airspeed vector (*i.e* the combination of the airframe angles of attack and sideslip) permits the evaluation of the TPP-AOA.

The real-time acquisition of blade motion is accomplished by a new, dedicated rotor state measurement system, designed for general rotorcraft applications. This, in addition to the TPP-AOA determination and therefore noise estimation, may support a range of different future applications related to vehicle model identification, health and usage monitoring, and rotor-state-feedback (RSF) control laws.

In order to overcome a further difficulty, that of the general unavailability of direct measurements of airframe angles of attack and sideslip, a novel methodology has been proposed to retrieve accurate estimations of the pair $(C_T, \alpha_{\text{TPP}})$. This is accomplished by means of an observation technique fed by generally available aircraft parameters, augmented by the running values of

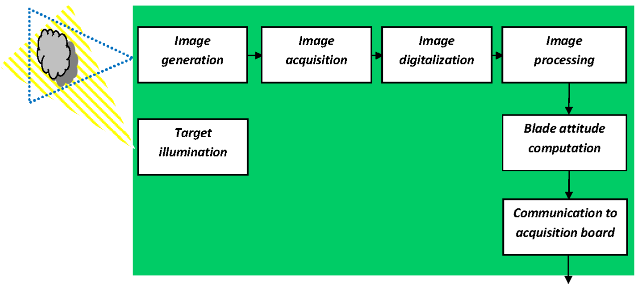

Figure 3: Vision-based rotor state measurement system architecture.

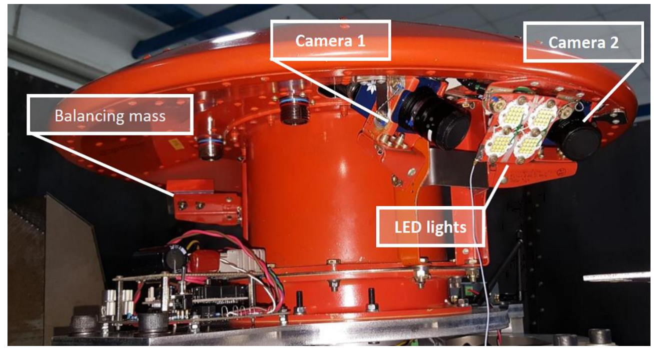

Figure 4: Rotor state measurement system prototype integrated on the AW139 main rotor 'beanie'.

the collective and cyclic components of blade flapping, which are immediately retrieved from the rotor state measurements.

The MANOEUVRES integrated concept summarized above is graphically shown in Figure 2. In this figure, the green boxes represent original elements developed within the MANOEUVRES project. These are either methods or equipment providing as output the parameters contained in the yellow boxes. The white boxes represent rotorcraft system components, *i.e.* the Stability and Control Augmentation System (SCAS) and the pilot, both receiving information by the MANOEUVRES system, and the avionic bus, which provides the data contained in the cyan box.

In the following, a brief description of each element in the green boxes is offered, with references to the relevant literature for further details.

2.2. Rotor state measurement system

A new rotor state measurement system has been designed, developed and tested within the MANOEUVRES project. This brand-new device has been conceived for general rotorcraft applications and is intended as a technology demonstrator in view of possible application on current and future production rotary-wing aircraft. From the beginning of the project, contactless sensor technologies were targeted, in order to allow high reliability and portability on board diverse rotorcraft vehicles. As the result of a thorough evaluation, including the manufacturing and laboratory testing of three full-scale competing candidate solutions, a stereoscopic vision system was selected and brought to considerable maturity.

Figure 3 illustrates the general architecture of this solution which, in the current implementation, includes a pair of small cameras operating in the visible spectrum, a lighting LED device, a suitable optical target, and a stand-alone set of equipments for power supply, synchronization, signal processing and communication.

This system has been fully integrated within the main rotor 'beanie', a hat-shaped component placed on the top of the main rotor mast, of a AW139 helicopter. Figure 4 shows the integrated system. Eventually, a ready-to-fly, fully operational demonstrator was set up, tested in the Politecnico di Milano laboratories, installed and experimented on board an actual helicopter.

The system is capable of acquiring an accurate, high-frequency representation of the typical main rotor blade angles of lead-lag, flap and pitch. From these measurements, it is possible to derive, among other results, the tip-path-plane orientation with respect to the fuselage which, according to the integrated concept describe above, is passed to the observation algorithm in order to produce an estimation of the main rotor thrust coefficient and TPP-AOA.

The technology selection, design, development and testing of this system required the majority of the effort exerted in the MANOEUVRES project. A detailed illustration of this process is offered in Refs. 14–16.

2.3. Observation method

The blade motion sensed by the rotor state measurement system allows to retrieve the running values of the collective and cyclic components of the three blade angles of lead-lag, pitch, and flap. The cyclic flappings (a_{1_s}, b_{1_s}) basically describe the orientation of the TPP with respect to the airframe (*e.g.* the helicopter fuselage). In order to determine the TPP-AOA, this orientation must be combined with the orientation of the airframe with respect to the airspeed vector, which may be measured by means of a swivelling air data boom. However, as this is not typically mounted on current helicopters, especially for civil usage, a direct measurement to complement that obtained by the rotor state measurement system is not available. In order to overcome this difficulty, a novel observation method was presented in Refs. 6 and 17.

The method relies on an assumed model of the relation between $(C_T, \alpha_{\text{TPP}})$ and (a_0, a_{1_s}, b_{1_s}), where a_0 represents the collective flapping, or coning angle. This relation is inspired by a simplified blade flapping model and involves a linear dependence of the unknown states (thrust coefficient and TPP-AOA) on the measurements (flapping components). Basically, the observer is synthesized by identifying the coefficients of the model matrices through a substantial set of simulations for which both states and measurements are known. The relation is parameterized by μ (for which a linear dependence is clearly unfeasible) and can be further improved taking into account vehicle weight and air density in the measurement array.

The resulting methodology was tested through a vast array of simulations, including many related to terminal maneuvers, in both design and off-design conditions, showing promising performance, especially in view of enabling the in-flight noise estimation targeted in the MANOEUVRES project. Further improvements to the methodology are currently ongoing.

2.4. Acoustic database

With the knowledge of the three mapping parameters $(\mu, C_T, \alpha_{\text{TPP}})$, provided by the previous step, the corresponding noise hemisphere can be retrieved from the pre-computed database by interpolation. This database is obtained by collecting the noise hemispheres resulting from the aeroacoustic emission calculated for a number of steady-state flight conditions covering the flight envelope of interest.

The computational process typically starts with the computation of the trim conditions for the vehicle for given values of weight, density altitude, airspeed and flight-path angle, by means of a comprehensive numerical model. Blade kinematics is fed into a specialized aerodynamic code for the computation of blade loading conditions. Eventually, the pressure distribution on the rotor blades serve as input to a steady-state aeroacustic solver, producing the noise propagation from the rotor to a surrounding sphere of radius equal to 150 m. This process is detailed in Refs. 10–12.

2.5. PAI algorithm

The noise index presented to the pilot is determined by the noise estimation algorithm which, upon receiving the interpolated noise hemisphere representative of the acoustic emission for a given time instant, proceeds to a different calculation depending on the selected mode.

The hemisphere is subdivided into four regions along the azimuth (front, right, left and back), plus the lower spherical cap. In *Emitted mode*, the noise index is assumed as the maximum OASPL value for each region of the hemisphere. In *Ground mode*, the noise on the hemisphere is radiated to the ground based on the vehicle current attitude and height above ground level. The ideal flat ground below the aircraft is subdivided in five areas, corresponding to the projections of the hemisphere regions, and the noise index is given by the maximum OASPL value for each area on the ground. The interested reader is referred to Refs. 6 and 18 for a detailed presentation on this matter.

2.6. PAI HMI

The PAI graphical interface has been designed according to airworthiness standards and applicable guidelines for cockpit instrumentation. It is intended to be diplayed on a Multi-Function Display (MFD) present in the cockpit, without interfering with flight-critical information, typically displayed on the Primary Flight Display (PFD). The presentation can be set to show either the *Global indicator* or the *Directional indicator*, where the former displays the 'global' noise index, *i.e.* the maximum value attained by the noise index among all regions considered, irrespective of the direction, while the latter displays the five noise index values corresponding to each region, in an intuitive format. Both the presentation types are shown in Figures 5 and 6.

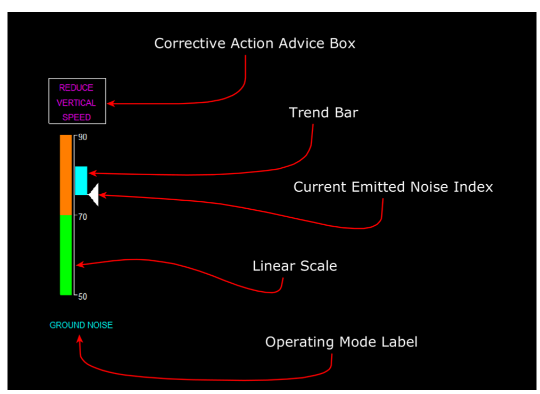

Figure 5: PAI *Global Indicator* presentation.

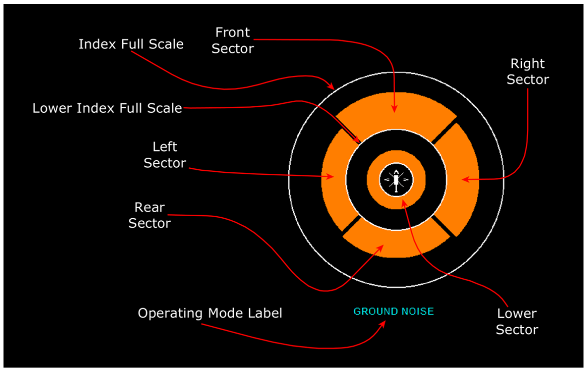

Figure 6: PAI *Directional Indicator* presentation.

In addition to the current value of the 'global' noise index, the *Global indicator* presents also its predicted value over a short time-window (such as 5 s), in order to enhance the pilot's situational awareness and possibly allow corrective actions in case of nearing, or passing, admissible noise thresholds. Also on this matter, the interested reader is referred to Refs. 6 and 18 for a detailed illustration.

2.7. RSF augmented control

The availability of real-time measurements of the blade attitude can be useful to several innovative applications. Within the MANOEUVRES project, a focus on RSF-augmentation for the vehicle flight control system led to the synthesis of novel control laws capable to enhance helicopter handling qualities and reduce pilot workload.

In particular, single-axis roll-attitude control in both hover and forward flight was targeted. A novel RSF control law was obtained by introducing flap measurements in the attitude feedback loop, formulated through an optimization-based methodology applied to a reduced-order linear model of the rotorcraft. As a result, the coupling between fuselage lateral attitude dynamics and lateral flap dynamics is taken into account, with beneficial effects with respect to bandwidth and noise rejection properties.

This methodology showed significant robustness with respect to model uncertainty, as stability and performance are not significantly affected by variations of vehicle physical parameters. Also, tolerance with respect to failures of the rotor state measurement system was demonstrated and the effects of a realistic rotor state measurement system model on closed-loop performance were shown to be negligible.

These promising results, detailed in in Refs. 19–21, motivate further investigations, currently ongoing, including multi-axis and tilt-rotor applications.[22]

3. FINAL TESTING AND DEMONSTRATIONS

The final phase of the MANOEUVRES project activities involved several tasks related to experimental assessment and demonstration, in three research areas: acoustic prediction, PAI development, and rotor state measurement system development. This allowed to obtain a preliminary validation of several MANOEUVRES integrated concept components, although – given the complexity of the system – much space is left for further analysis.

3.1. Experimental /numerical acoustic correlation

Within the MANOEUVRES project, a fully unsteady aeroacoustic formulation evoted to industrial rotorcraft applications has been developed and applied. This formulation includes a compact-source unsteady aeroacoustic solver[6,13] which provides a hemispherical noise distribution to an atmospheric noise propagation algorithm,[23] which radiates the acoustic disturbance to the ground, taking into account propagation losses, in order to obtain the Sound Exposure Level (SEL) of the full trajectory. The input to the nsteady aeroacoustic solver was provided by aeromechanic and aeroacoustic simulations performed by Leonardo Helicopters using proprietary numerical models of the AW139 helicopter.

A dedicated Clean Sky GRC experimental campaign was accomplished in 2014 on the airport at Cameri, Italy, with an instrumented AgustaWestland AW139 helicopter flying over an area equipped with 31 ground microphones located around the runway. Among the flight test data, two trajectories have been considered, both characterized by significant unsteady effects.

The correlation of the noise experimental measurements with numerical results showed that predictions capture fairly well the noise-increase effect of the helicopter passage over the microphones and the rate of perceived noise attenuation due to the increase of helicopter distance. However, instantaneous values of the noise perceived at the microphone often present relevant differences with respect to those measured experimentally. Therefore, further correlations of numerical predictions with measured data will be performed and an in-depth investigation of some steps in the complex computation process will be carried out, with the aim to identify areas of improvement and achieve a higher accuracy of the simulated results. A detailed report of this activity is provided in a dedicated companion paper.[24]

3.2. PAI final demonstration

The PAI system has been implemented in a stand-alone equipment for preliminary laboratory testing and eventually for its integration within a research flight simulator at Leonardo Helicopters. This setup has been tested through a number of piloted simulations, culminating in a final demonstration campaign which involved a professional test pilot. A set of pre-defined approach procedures at various degrees of glide slope, from standard to steep, was flown with the aim of assessing the general PAI functional characteristics and the impact on pilot workload and situational awareness (SA). Furthermore, pilot suggestions for future developments and possible usage were collected.

During the final demonstration, the PAI performed flawlessly in both *Emitted mode* and *Ground mode*, presenting both the *Global indicator* and the *Directional indicator* to the pilot during the execution opf the manoeuvres. The impact on workload was judged negligible and the overall level of information and pilot awareness provided by the simulator displays was judged good, with a clear statement tha the PAI increases SA level and that it could effectively assist a pilot in flying a low-noise trajectory. A detailed report of this activity is provided in a dedicated companion paper.[25]

3.3. Rotor state measurement system final demonstration

The final development of the novel vision-based rotor state measurement system involved an extensive flight test campaign on board an instrumented AW139 helicopter. Figure 7 shows the arrangement of the helicopter main rotor head, with the experimental 'beanie' hosting the sensor system on top of the hub.

Four test flights were performed, for a total of 64 tested flight conditions including steady-state trim shots in hover and forward flight, standard transient manoeuvres such as take-off and landing, and aggressive dynamic manoeuvring, including steep approaches and landings.

The rotor state measurement system proved highly successful, performing flawlessly without the occurrence of any malfunction, either hardware or software, and providing continuous blade motion acquisition for a total duration of over 3 hours. In particular, this activity demonstrated the system ability to operate correctly and safely when integrated on board, providing valid blade angle measurements on ground and in flight. This raised the maturity of this application to a considerable TRL6 level.

Figure 7: Main rotor head of the instrumented AW139 used for the rotor state measurement system flight demonstration.

The blade angle measurements were correlated with those simultaneously acquired by an independent sensor system based on mechanical probing provided by Leonardo Helicopters.[26] This device, used by the company in experimental activities, is not fully characterized with respect to measurement accuracy, due to its dependence on some kinematic hypotheses assumed in the calibration algorithm, and therefore is not considered as a fully qualified reference. On the other hand, the developed stereoscopic system does not rely on any kinematic hypotheses, but captures the target orientation irrespective of the characteristics of its motion.

Indeed, some differences among the two sets of measurements have been observed. The analysis of the discrepancies resulted in an generally acceptable correlation for the mean values observed for the three lag, flap and pitch blade angles, and an even better correlation for their $1\mathrm{st}$ and $2\mathrm{nd}$ harmonic components. Although further analysis are currently being carried out, the developed rotor state measurement system appears as a very promising candidate for future experimental and, eventually, production applications in which the real-time acquisition of the blade motion is required, such as emitted noise monitoring and RSF-augmented control. A full account of this activity is provided in a dedicated companion paper.[27]

4. CONCLUDING REMARKS

The Clean Sky GRC MANOEUVRES project recently concluded its duration, leading to a number of innovative results concerning both novel research and product-oriented applications in rotorcraft technology. In particular, on-board monitoring of rotorcraft acoustic impact and enhanced handling qualities, leading to improved pilot/vehicle capabilities, have been targeted.

The ‘MANOEUVRES integrated concept’ involved substantial progress in unsteady aeroacustic simulation, real-time rotor blade attitude measurement, real-time accurate estimation of aeromechanical parameters for which a direct measurement is not available, cockpit instrumentation for noise-related SA and guidance, and innovative control laws development. All these elements have been subjected to a research effort leading to various degrees of validation.

In particular, in the final phases of the project, experimental assessment was achieved for

- the aeroacoustic prediction methodology for manoeuvring rotorcraft, by means of a correlation with flight test data;
- the novel cockpit instrumentation developed to convey run-time acoustic information to the pilot, by means of a demonstration and testing campaign comprising piloted simulations carried out by a professional test pilot;
- the novel vision-based rotor state measurement system developed to capture the run-time blade attitude angles, by means of a demonstration and testing campaign for a fully-fledged prototypal device integrated on board an instrumented helicopter during several flight trials.

In summary, the project outcomes have been judged very satisfying under all respects. The technologies habilitating an effective on-board noise monitoring and a practical RSF control augmentation have been developed to a highly promising level of maturity, culminating in the in-flight demostration of the rotor state measurement system.

The project opened a range of research lines which are currently being pursued beyond its formal completion, especially concerning aeroacoustic prediction, real-time observation of vehicle states, and RSF control laws. Further developments of the two equipments produced, the PAI and the rotor state measurement system are also being carried out in close collaboration with Leonardo Helicopters, in view of possible operational uses, starting with experimental and training activities.

ACKNOWLEDGMENTS

Project MANOEUVRES is funded by European Community’s Clean Sky Joint Undertaking Programme under Grant Agreement N. 620068.

ACRONYMS

GRC	Green RotorCraft
HMI	Human-Machine Interface
MFD	Multi-Function Display
OASPL	OverAll Sound Pressure Level
PAI	Pilot Acoustic Indicator
PFD	Primary Flight Display
RSF	Rotor State Feedback
SA	Situational Awareness
SCAS	Stability and Control Augmentation System
SEL	Sound Exposure Level
TPP	Tip-Path Plane
TPP-AOA	TPP Angle Of Attack
TRL	Technology Readiness Level

REFERENCES

[1] Brès G. A., Brentner K. S., Perez G., Jones H. E., Maneuvering rotorcraft noise prediction, *Journal of Sound and Vibration*, **275** (3–5): 719–738, 2003.

[2] Brooks T. F., Booth E. R., Jolly J. R., Yeager W. T., Wilbur M. L., Reduction of blade-vortex interaction noise using higher harmonic pitch control, NASA Technical Memorandum 101624, NASA Langley Research Center, Hampton, VA, USA 1989.

[3] Beaumier P., Prieur J., Rahier G., Spiegel P., Demargne A., Tung C., Gallman J. M., Yu Y. H., Kube R., Van der Wall B. G., Schultz K. J., Splettstoesser W. R., Brooks T. F., Burley C. L., Boyd D. D., Effect of higher harmonic control on helicopter rotor blade-vortex interaction noise: prediction and initial validation, 75th Fluid Dynamics Symposium, Berlin, Germany, 1994.

[4] Trainelli L., Rolando A., Zappa E., Manzoni S., Lovera M., Gennaretti M., Bernardini G., Cordisco P., Terraneo M., Vigoni E., Grassetti R., MANOEUVRES An effort towards quieter, reliable rotorcraft terminal procedures, Greener Aviation Conference 2014: Clean Sky breakthroughs and worldwide status, Brussels, Belgium, 2014.

[5] Trainelli L., Lovera M., Rolando A., Zappa E., Gennaretti M., Cordisco P., Grassetti R., Redaelli M., Project MANOEUVRES Towards real-time noise monitoring and en-hanced rotorcraft handling based on rotor state measurements, 41st European Rotorcraft Forum ERF2015, Munich, Germany, 2015.

[6] Trainelli L., Gennaretti M., Bernardini G., Rolando A., Riboldi C. E. D., Redaelli M., Riviello L.,

Scandroglio A., Innovative Helicopter In-Flight Noise Monitoring Enabled by Rotor State Measurements, *Noise Mapping*, **3** (1): 190–215, 2016.

[7] Chen H. N., Brenter K. S., Anantham S., Leishman J. G., A computational study of helicopter rotor wakes and noise generated during transient maneuvers, 61st Annual Forum of the American Helicopter Society, Grapevine, TX, USA, 2005.

[8] Le Duc A., Spiegel P., Guntzer F., Kummer M., Götz J., Modelling of Helicopter Noise in Arbitrary Maneuver Flight Using Aeroacoustic Database, 9th Onera-DLR Aerospace Symposium (ODAS 2008), Châtillon, France, 2008.

[9] Arra M., *L'Elicottero*, Hoepli, Milano, 2012; ISBN: 9788820325510 (in Italian).

[10] Gennaretti M., Serafini J., Molica Colella M., Bernardini G., Simulation of helicopter noise in maneuvering flight, 40th European Rotorcraft Forum ERF 2014, Southampton, UK, 2014.

[11] Bernardini G., Anobile A., Serafini J., Hartjes S., Gennaretti M., Methodologies for helicopter noise footprint prediction in manoeuvring flights, 22nd International Conference on Sound and Vibration, Firenze, Italy, 2015.

[12] Gennaretti M., Serafini J., Bernardini G., Castorrini A., De Matteis G., Avanzini G., Numerical Characterization of Helicopter Noise Hemispheres, *Aerospace Science and Technology*, **52**: 18–28, 2016.

[13] Gennaretti M., Bernardini G., Anobile A., Serafini J., Trainelli L., Rolando A., Scandroglio A., Riviello L., Acoustic prediction of helicopter unsteady manoeuvres, 41st European Rotorcraft Forum ERF 2015, Munich, Germany, 2015.

[14] Cordisco P., Liu R., Redaelli M., Riviello L., Rolando A., Rossi F., Trainelli L., Vigoni E., Zappa E., Developing a Novel Contactless Sensor for Helicopter Rotor State Measurement, 36th European Telemetry and Test Conference ETC2016, Nuremberg, Germany, 2016.

[15] Cigada A., Colombo A., Cordisco P., Ferrario A., Grassetti R., Manzoni S., Redaelli M., Rolando A., Terraneo M., Trainelli L., Vigoni E., Zappa E., Contactless Rotor Flapping Sensor Design, Implementation and Testing, American Helicopter Society International 72nd Annual Forum, West Palm Beach, FL, USA, 2016.

[16] Zappa E., Trainelli L., Liu R., Rolando A., Rossi F., Cordisco P., Vigoni E., Redaelli M., Real Time Contactless Sensor for Helicopter Blade Angle Measurement, 3rd IEEE International Workshop on Metrology for Aerospace, Firenze, Italy, 2016.

[17] Trainelli L., Riboldi C.E.D., Bucari M., Observing the angle of attack of the tip-path plane from rotor blade measurements, 41st European Rotorcraft Forum ERF 2015, Munich, Germany, 2015.

[18] Rolando A., Rossi F., Riboldi C.E.D., Trainelli L., Grassetti R., Leonello D., Redaelli M., The Pilot Acoustic Indicator: a novel cockpit instrument for the greener helicopter pilot, 41st European Rotorcraft Forum ERF 2015, Munich, Germany, 2015.

[19] Panza S., Lovera M., Rotor state feedback in helicopter flight control: robustness and fault tolerance, IEEE Multi-Conference on Systems and Control, Antibes/Nice, France, 2014.

[20] Panza S., Lovera M., Rotor state feedback in the design of rotorcraft attitude control laws, in Bordeneuve-Guib J., Drouin A., Roos C. (eds.), *Advances in Aerospace Guidance, Navigation and Control*, Springer, 2015.

[21] Panza S., Bergamasco M., Viganò L., Lovera M., Rotor State Feedback in Rotorcraft Attitude Control, 41st European Rotorcraft Forum ERF 2015, Munich, Germany, 2015.

[22] Panza S., Guastalla L., Roda B., Lovera M., Tilt-rotor multivariable attitude control with rotor state feedback, 20th IFAC Symposium on Automatic Control in Aerospace, Sherbrooke, Quebec, Canada, 2016 (accepted).

[23] Hartjes, S., An optimal control approach to helicopter noise and emissions abatement terminal procedures, Ph.D. Thesis, Faculty of Aerospace Engineering, Delft University of Technology, 2015.

[24] Gennaretti M., Bernardini G., Hartjes S., Scandroglio A., Riviello L., Paolone E., Experimental/Numerical Acoustic Correlation of Helicopter Unsteady Manoeuvres, 42nd European Rotorcraft Forum ERF 2016, Lille, France, 2016.

[25] Rolando A., Rossi F., Trainelli L., Leonello D., Maisano G., Redaelli M., Demonstration and Testing of the Pilot Acoustic Indicator on a Helicopter Flight Simulator, 42nd European Rotorcraft Forum ERF 2016, Lille, France, 2016.

[26] Colombo A., Locatelli A., Measuring blade angular motions: A kinematical approach, 30th European Rotorcraft Forum ERF 2004, Marseilles, France, 2004.

[27] Zappa E., Trainelli L., Rolando A., Cordisco P., Vigoni E., Liu R., Rossi F., Redaelli M., A Novel Contactless Sensor for Helicopter Blade Motion In-flight Measurements, 42nd European Rotorcraft Forum ERF 2016, Lille, France, 2016.