PROJECT MANOEUVRES – TOWARDS REAL-TIME NOISE MONITORING AND ENHANCED ROTORCRAFT HANDLING BASED ON ROTOR STATE MEASUREMENTS

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Abstract

The MANOEUVRES project represents an effort aimed at providing innovative solutions for noise abatement in rotorcraft terminal manoeuvres, when the vehicle approaches the ground and the acoustic impact is higher. This is achieved by in-flight monitoring of the emitted noise, enabled by a new cockpit instrumentation, the Pilot Acoustic Indicator (PAI), and by an innovative contactless rotor state measurement system capable of acquiring the blade attitude angles. The PAI displays a condensed acoustic impact information retrieved through a real-time estimation of the actual noise emitted and radiated. Noise strongly depends on the actual helicopter dynamics, and especially on the main rotor loading and orientation. The latter can be estimated by means of the rotor state measurement system and fed to the PAI, which incorporates a pre-calculated acoustic database, to yield a quasi-steady approximation of the full acoustic spatial emission. The paper reports on the project current state, involving studies in unsteady aeroacoustic prediction, rotor state measurement system design and development, PAI design and development, as well as the formulation of innovative flight control laws enabled by the availability of blade angle measurements, which aim at higher coupled vehicle/pilot performance and handling qualities.

1. INTRODUCTION

The MANOEUVRES (Manoeuvring Noise Evaluation Using Validated Rotor State Estimation Systems) project has been launched in response to the SP1-JTI-CS-2013-01 call[1] issued by the Clean Sky Joint Technology Initiative (JTI). The Clean Sky JTI, started in 2008 as a public-private partnership between the European Commission and the aeronautical industry, is the largest aeronautical research programme ever launched in Europe seeking the development of innovative technologies aimed at reducing the environmental impact of air transport. The ambitious goals of the Clean Sky JTI are summarized by a reduction of CO_2 emissions by 50%, of NO_x emissions by 80% and of perceived noise by 50% within the year 2020.

The Clean Sky JTI programme is comprised of six Integrated Technology Demonstrators (ITDs), each of which pertains to a segments of civil air transport. Among these ITDs, the Green RotorCraft (GRC) is dedicated to the enhancement of rotary-wing vehicle environmental performance and sustainability, exploiting various technologies such as innovative rotor blades, airframe drag reduction, high compression engines, advanced electrical systems, and environmentally friendly flight paths. The latter represent the focus of the GRC5 action, expected to provide a reduction in fuel consumption by 6%, and in perceived noise by 5 EPN (Effective Perceived Noise) dB.

The MANOEUVRES project[2] fits into the GRC5 activities by delivering enabling technologies for in-flight noise monitoring, in view of a possible industrial application on current production helicopters. Indeed, noise radiated to the ground is one of the main factors that limit public acceptance of rotorcraft vehicles, especially in connection to terminal operations, *i.e.* approach and departure procedures. This impact is expected to grow as rotorcraft operations to and from airports will increase, with helicopters following terminal routes designed for fixed wing aircraft. However, by exploiting the rotorcraft intrinsic agility, radiated noise may effectively be contained by flying suitable procedures designed to take into account environmental pollution constraints.

2. PROJECT DESCRIPTION

2.1. Consortium

The MANOEUVRES project is been carried out by a consortium involving four partners, in close co-operation with AgustaWestland, a world-class European rotorcraft manufacturer. The consortium participants are two academic institutions, Politecnico di Milano (coordinator) and University Roma Tre, and two SMEs, Logic Spa and Vicoter Snc.

Politecnico di Milano contributes to the project through the commitment of personnel and facilites from the Department of Aerospace Science and Technology, the Department of Mechanical Engineering, and the Department of Electronics, Information and Bioengineering. This involvement provides solid capabilities in modelling, design, simulation and testing of aeromechanical systems, including rotorcraft; measurement system modelling, design and testing; experimental data acquisition and processing; control system design and simulation. University Roma Tre contributes through the commitment of personnel and facilities from the Department of Engineering, with a long-standing expertise in rotorcraft aerodynamic and aeroacoustic prediction and analysis. Logic is a leading avionics company, specialised in the design, development and production of avionics equipment and systems for several production airplanes and helicopters. Its contribution focuses on requirement definition for the innovative rotor sensor system and the pilot graphical interface. Finally, Vicoter is a small engineering company with a strong background in mechanical, structural and acoustic testing and data processing, including design and verification of experimental rigs for testing of aerospace systems.

2.2. Purpose

The MANOEUVRES project aims at the demonstration of the feasibility of an innovative approach to noise abatement in rotorcraft terminal manoeuvres based on in-flight monitoring of the emitted noise. This will habilitate to actually fly improved terminal flight procedures, fostering the public acceptance of rotorcraft operations in densely populated areas.[3] To this end, methods and technologies across several disciplines need to be developed, towards the integration of a real-time onboard noise monitoring system. The main areas involved in this effort are aeroacoustic prediction, rotor state measurement, and onboard instrumentation.

The MANOEUVRES in-flight noise monitoring system delivers a new cockpit instrument, the Pilot Acoustic Indicator (PAI), which conveys noise information to the pilot, allowing him/her to react adequately in case of nearing admissible noise thresholds. The PAI is fed by a noise estimation algorithm which determines in real-time a suitable measure of the acoustic impact, based on a database of acoustic hemispheres, detailing the noise levels associated to spatial directions around and below the helicopter under the assumption of steady rectilinear flight conditions.[4,5] This database is evaluated off-line covering the flight envelope of interest, to be interrogated in-flight by entering the current values of several parameters retrieved from the helicopter avionics, augmented by a direct measurement of the main rotor state. The latter is performed by a novel sensor system capable of acquiring the rotor blade attitude, in order to provide the orientation of the rotor tip-path plane (TPP) with respect to the fuselage. This is a fundamental ingredient for use in the noise estimation algorithm, as radiated noise depends on trajectory parameters, rotor loading, and rotor orientation.

Furthermore, the availability of a rotor state measurement systems makes it all too natural to investigate the possible advantages achievable by appling a rotor state feedback (RSF) approach to the design of innovative flight control laws, in addition to the feedback based on traditional fuselage attitude and rate measurements.[6,7] These are aimed to improve pilot/vehicle capabilities, enhancing noise rejection properties, while retaining adequate levels of robustness and fault tolerance.

2.3. Work overview

The project overview, as sketched above, has led to the following technical implementation. Work Package 1 (WP1) is dedicated to rotorcraft aeroacoustic prediction, including the generation of the steady-state database of acoustic hemispheres, the development of a fully unsteady simulation tool for arbitrary manoeuvring flight conditions, and a wealth of analysis to study the correlation between steady and unsteady predictions, the assessment of the accuracy of fully unsteady predictions compared to flight test data, and the evaluation of the sensitivity of numerical predictions to perturbations in the flown trajectory. The sequence of Work Packages 2 and 3 (WP2, WP3) addresses the development of the novel rotor state measurement system. Relevant activities consist of a thorough technology selection process, followed by a competitive preliminary development of two candidate solutions (WP2), which leads to the choice of the definitive system to be implemented and integrated onboard an actual helicopter for a final demonstration (WP3). WP2 and WP3 also

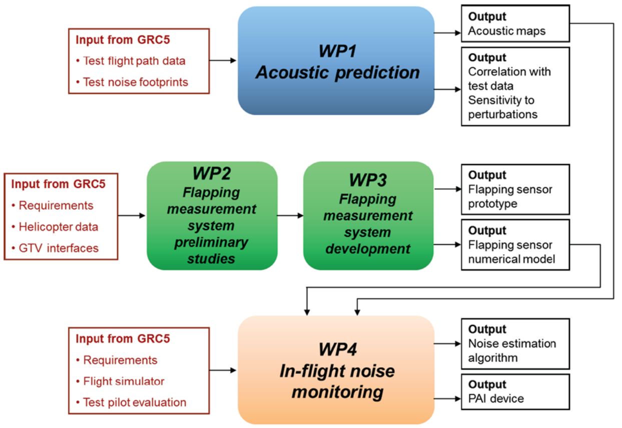

Figure 1: The interaction between the MANOEUVRES project technical Work Packages.

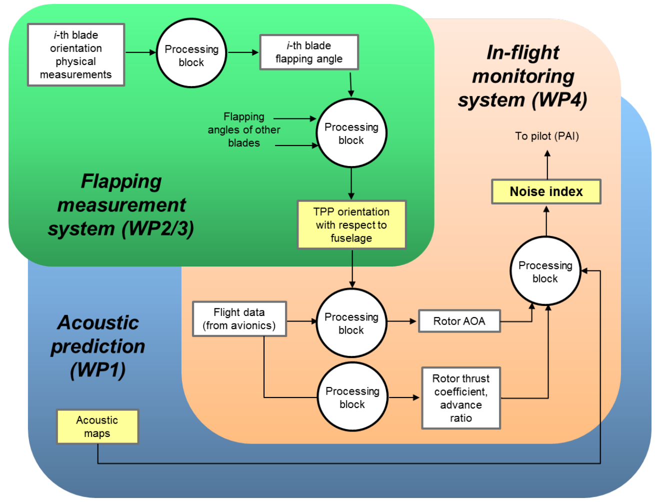

Figure 2: The MANOEUVRES in-flight noise estimation concept.

accomodate the development of innovative RSF control laws enabled by the novel rotor state measurement system. Finally, Work Package 4 (WP4) is devoted to the development of the in-flight noise monitoring system, based on the formulation of the noise estimation algorithm and on the development of the PAI human-machine interface (HMI), including design, implementation and testing.

Figure 1 depicts the main interactions between the disciplinary activities embodied in the four technical Work Packages as described above. Their contribution towards the integrated MANOEUVRES noise estimation process is illustrated in Figure 2, where the rotor state measurement system delivers blade attitude information to the in-flight noise estimation algorithm, which also draws information from the pre-calculated acoustic database, in order to provide the noise index values to be displayed on the PAI HMI.

The following sections provide a discussion of the current state of the MANOEUVRES project with respect to each of the main disciplinary lines of research.

3. ACOUSTIC PREDICTION

Acoustic prediction activities within the MANOEUVRES project address multiple goals, spanning across different computational approaches. First of all, steady-state predictions of the emitted noise are calculated for rectilinear trimmed flight conditions in a sub-envelope of interest for airspeed V, flight path angle γ and weight W, covering all possible values corresponding to a set of chosen terminal procedures. The evaluation consists in the determination of an acoustic emission map over a hemisphere rigidly connected to the helicopter (see Figure 3).[8] These predictions are collected in a database of static acoustic maps, which is provided to the in-flight noise monitoring process. Typically, the database is reparameterized from (V, γ, W) to (μ, C_T, α_{TPP}) triplets, being μ the helicopter advance ratio, C_T the main rotor thrust coefficients, and α_{TPP} the TPP angle of attack (TPP-AOA).

The static acoustic maps are used to estimate manoeuvring noise under a quasi-steady approximation. This computationally cheap approach is contrasted to noise predictions obtained by a more intensive unsteady time-marching acoustic analysis, in order to assess its level of accuracy. To this end, a state-of-the-art fully unsteady acoustic prediction code has been developed and adequately made ready to accept as inputs

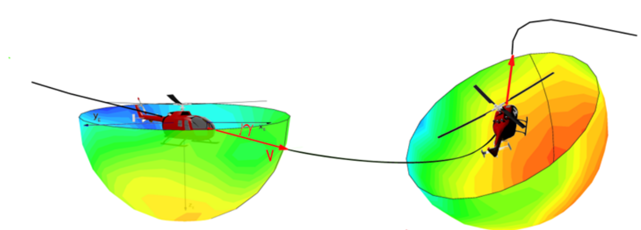

Figure 3: Acoustic emission hemispheric map connected to the manoeuvring helicopter.

the results of the flight mechanics and aerodynamic codes in use by AgustaWestland.[9] This tool also provides a noise pressure distribution over a hemisphere rigidly connected to the helicopter, allowing a direct comparison of the quasi-steady and fully unsteady predictions in terms of sound pressure level (SPL) according to various specific definitions, such as A-weighted SPL, OASPL (OverAll SPL), BVISPL (Blade-Vortex Interaction SPL). The sensitivity of noise predicted during a given flight path to deviations from the reference flight conditions will also be considered. This will provide information useful in evaluating the robustness and reliability of acoustic estimations for the design of low-noise procedures and the definition of appropriate corrective actions when nearing maximum admissible noise thresholds.

Furthermore, the unsteady acoustic prediction code is coupled with a procedure that allows radiation on ground, taking into account typical atmospheric and terrain effects.[10] This combination is used, within the MANOEUVRES project, to assess the correlation with experimental data retrieved from a GRC flight testing campaign performed in October 2014 with an instrumented AgustaWestland AW139 flying over an area equipped with 31 ground microphones for acoustic measurements. This ongoing work will provide an appraisal of the actual capabilities of predicting noise footprints of rotorcraft manoeuvring in the vicinity of the ground.

In turn, this will be important in the assessment of the actual capability of quasi-steady approaches based on the above mentioned static acoustic maps to capture unsteady noise effects when fed with estimations of (μ, C_T, α_{TPP}). These can be provided by resorting to a simple dynamic model of the helicopter and retrieving some data available on the helicopter avionic bus.

In particular, two possible arrangements are considered, one (termed *technique C*) in which the TPP-AOA is evaluated from the enforcement of the force balance, with suitable approximations, while the other (termed *technique B*) employs an estimation of the TPP-AOA that descends from a direct measurement of the main rotor blade attitude angles, made available by the installation of the MANOEUVRES rotor state measurement system. Indeed, the TPP-AOA may be computed through geometrical reasoning based on the knowledge of the longitudinal and lateral cyclic flappings, and of the fuselage angles of attack and sideslip. While the former are immediately retrieved from the rotor state measurements, the latter are typically not available on today's civil production helicopters and would need a suitable dedicated sensor, such a swivel-head air data boom.

Within the MANOEUVRES project, a promising methodology to tackle this difficulty has been developed. This identification procedure allows to observe the TPP-AOA, as well as other flight mechanics performance parameters, such as the thrust coefficient, starting from a basic set of available parameters augmented by those acquired by the rotor state measurement system. In this case, he need of a direct measurement of the fuselage angles of attack and sideslip will be by-passed. A detailed account of this methodology is scheduled for presentation at the 41st European Rotorcraft Forum 2015.[11]

Eventually, the MANOEUVRES project aims to provide a thorough comparison of the performance of techniques A (*i.e.* that based on the fully unsteady approach), B and C, in connection to low-noise terminal manoeuvres. Preliminary results on this topic are scheduled for presentation at the 41st European Rotorcraft Forum 2015.[12]

4. ROTOR STATE MEASUREMENT SYSTEM

In the MANOEUVRES project, a great effort is committed to the development of an innovative rotor state measurement system able to capture the rotor TPP attitude by sensing the rotor blade angles with respect to the hub. This system is designed for integration on board current production helicopters, departing from the configurations applied in experimental devices currently employed in prototypal applications, such as AgustaWestland's MOVPAL.[13] Therefore, a complete set of requirements concerning not only the system's functionality and safety, but also environmental resistance, reliability, testability and maintainability have been considered.

This measurement system is meant to support acoustic estimation, as well as innovative vehicle monitoring and control applications. Accordingly, suitable requirements for measuring range, accuracy and frequency bandwidth have been set.

A first stage analysis considered a wide range of possible technologies, envisaging their possible application with transducers located either on the fuselage, or on the main rotor head. All contemplated concepts implement *contactless* measurement techniques, in an effort to maximise the system reliability, endurance, and applicability to multiple rotorcraft vehicles. Subsequently, on the basis of expected metrological performance, as well as installation and environmental requirements,

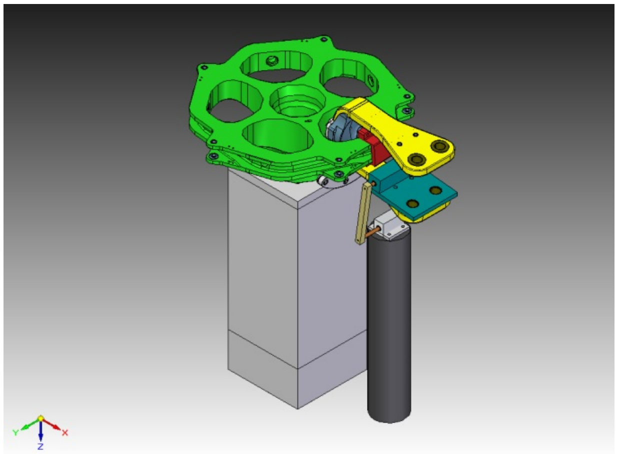

Figure 4: Pure flapping testbed rigged in the laboratories of the Department of Aerospace Science and Technology, Politecnico di Milano.

general regulations, flight standards and design guidelines, three candidate solutions, all mounted on the main rotor head, have been selected.

These concepts have been integrated in full-scale prototypes and thoroughly tested on 4 different laboratory rigs. These include three equipments specifically built or adapted for the MANOEUVRES project at the Politecnico di Milano laboratories: a vibration bench, a pure flapping testbed, and an Agusta A109MKII ironbird. The vibration bench has been used to verify the system measuring reliability under realistic vibratory spectra. The pure flapping testbed (Figure 4) has been rigged using real parts of the AW139 rotor head to ensure the highest possible representativeness in the system geometry and relative motion while assessing the measurement system performance on the blade motion component that is most important for the MANOEUVRES application, *i.e.* flapping. The A109MKII ironbird consists in a complete helicopter fuselage frame with the original transmission gearbox and a simplified rotor head (Figure 5). This complex rig is electrically actuated and provides authentic centrifugal and vibratory loading for any equipment located on the rotor head. Test campaigns performed on these three rigs allowed to assess the measurement system capabilities in simplified conditions, tackling flapping measurement accuracy, and functionality under representative vibration and rotation conditions separately. A further test campaign involved the AW139 hub endurance rig made available by AgustaWestland at its Cascina Costa premises. This is a highly complex (non-rotating) equipment capable of reproducing arbitrary blade motions relative to the hub, and in particular actual motions as found in operational flight conditions, with full coupling of flap, pitch and lead/lag rotations.

Figure 5: Agusta A109MKII ironbird in the laboratories of the Department of Aerospace Science and Technology, Politecnico di Milano.

The above sketched test campaign led to promising results for all three solutions, which have been ranked in a final list, from which the best option has been picked for final implementation (given that a patent procedure is currently ongoing, it is not possible to detail the system specifications and performance here). This final phase involves the bringing to maturity of the selected solution. This system, complete with proper signal processing procedures and suitable mechanical, power and communication interfaces, is currently further developed and tested, towards the integration onboard a ground-tied AgustaWestland production helicopter (Ground Test Vehicle, GTV). This will allow a final demonstration of the MANOEUVRES rotor state measurement system prototype by means of a test campaign on the GTV. A flight test campaign is also currently being considered, to achieve an even more representative demonstration. The system functional characteristics and performance in a real installation will be assessed through a comparison with an existing experimental measurement system based on mechanical probing,[13] and a comprehensive analysis of results, conclusions and recommendations will be drawn.

5. PILOT ACOUSTIC INDICATOR

The PAI design and development has been fully carried out to date, completing the integration of a demonstrator complete with all necessary hardware and software in a research flight simulator made available by AgustaWestland.

The process involved the formulation of the in-flight

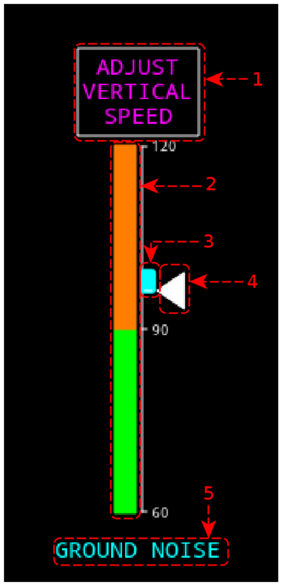

Figure 6: PAI global indicator: 1 – corrective action advice box, 2 – linear scale of the noise index with threshold, 3 – trend bar for the noise index, 4 – current emitted noise index, 5 – operational mode label.

Figure 7: PAI directional indicator: 1 – front sector, 2 – right sector, 3 – back sector, 4 – left sector, 5 – lower sector, 6 – helicopter symbol, 7 – full scale value circle for radial sectors, 8 – full scale value circle for lower sector, 9 – operational mode label.

noise evaluation algorithm, and in parallel the design and implementation of the hardware and software solution for the noise monitoring device prototypal implementation. Concerning the first element, a procedure fed by the current values of (μ, C_T, α_{TPP}) consults the pre-calculated static acoustic map database, interpolating within the nearest elements to retrieve the acoustic hemisphere representative of the current noise emission conditions.

Two different PAI operating modes, termed *Emitted Noise* and *Ground Noise*, are available. The former simply draws pilot noise information from the current acoustic hemisphere, while the latter involves the propagation of the SPL values from the surface of the acoustic hemisphere to the ground below the helicopter. The *Emitted Noise* mode allows to appraise noise emission on a local, helicopter-centred scale and can be useful to enhance crew and passenger comfort, in principle in any flight phase. The *Ground Noise* mode comprises, albeit in a simplified manner, the effects or radiation to the affected population on the ground and is clearly the most interesting in terminal manoeuvring applications. In both cases, the spatially distributed SPL information (either on the hemisphere or on a ground surface parcel) is condensed in a single *noise index* for cockpit display. Along with this, a prediction on a short-term window is also provided, to allow an enhanced pilot's situational awareness, in order to devise possible correcting actions if required.

A graphical interface, fully compliant with relevant general helicopter HMI requirements, helicopter cockpit display characteristics, and helicopter terminal procedures, has been designed and implemented, to convey noise index values, together with relevant supplementary information such as distance to thresholds, trend based on the short-term prediction, and possibly a suggestion for a correcting action. In the implementation, a number of elements such as symbology, information content, advisory thresholds, guidance suggestions, enabling and disabling controls, data updating rate have been considered, leading to the selection of a candidate PAI architecture and its hardware implementation on commercially available equipment.

Two different graphical representations are available, the *global indicator* and the *directional indicator*. The global indicator, shown in Figure 6, displays a global noise index, obtained as the maximum SPL computed on the reference surface according to the selected operational mode. The directional indicator, shown in Figure 7, depicts the values of the noise index along five spatial directions around the helicopter: front, right, back, left and below. These representations, to be hosted on the central MFD (Multi-Function Display), are designed to promote prompt and intuitive interpretation by the pilot, seeking an effective means to reduce his/her workload when flying low-noise trajectories.

The PAI prototype, appropriately interfaced with AgustaWestland's flight simulator, is currently undergoing a test campaign to assess its potential, effectiveness, advantages and drawbacks. A full account of the PAI design and development is scheduled for presentation at the 41st European Rotorcraft Forum 2015.[14]

6. ROTOR-STATE-FEEDBACK CONTROL LAWS

Although the primary aim of the MANOEUVRES projects lies in the mitigation of the acoustic impact of rotorcraft operations, the development of the novel rotor state measurement system makes it natural to investigate possible advantages in the field of flight control augmentation systems.

Indeed, a RSF approach to attitude control based on modern robust analysis and synthesis methods using non-smooth optimisation of structured controllers has been developed and numerically tested. Preliminary work showed the benefits of this RSF robust approach applied to a reduced, linearised rotor/fuselage model and ideal rotor state measurements.[15,16] The results illustrate the ability of a a structured H_∞ control system to overcome the bandwidth/damping ratio trade-off limitations of traditional controllers, improving disturbance rejection bandwidth and damping of oscillations.

Furthermore, a systematic approach to the design of structured RSF attitude control laws, aimed at achieving nominal stability and prescribed performance of the closed-loop system, robustness to model uncertainty, and fault tolerance with respect to openings of the RSF feedback channel, has been pursued. The results, which include a realistic model of the rotor state measurement system, are very promising, as seen in Figure 8, which depicts the closed-loop response of the lateral cyclic flap to a step change in the roll angle set point. A comprehensive discussion of this activity is scheduled for presentation at the 41st European Rotorcraft Forum 2015.[17]

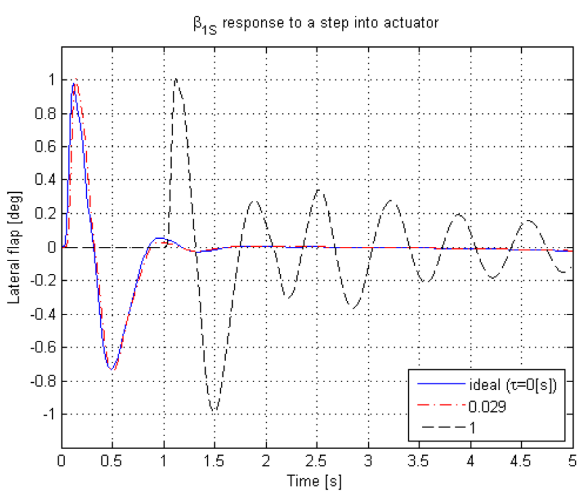

Figure 8: Closed-loop lateral flap response to a step change in the roll angle set point: ideal sensor (blue), realistic sensor (red), low sampling frequency (1 Hz) reference case (green).

7. CONCLUDING REMARKS

The MANOEUVRES project started in October, 2013, for a duration of 24 months, with an extension of further 6 months currently being implemented. WP1, WP2 and WP4 all started at the project inception. WP1 and WP4 are currently active, together with WP3, which started at the end of WP2. In fact, WP2 ended with the selection of the final rotor state measurement system, and WP3 is currently developing this solution, heading towards its demonstration onboard the AgustaWestland GTV, and possibly on a flying helicopter. WP1 delivered the acoustic database, the full unsteady acoustic prediction code, and the first results for the comparison between quasi-steady and fully unsteady approaches. The correlation of numerical predictions with experimental data is currently undergoing, while the sensitivity analysis will be taken on soon. WP4 delivered the noise estimation algorithm, the PAI prototypal hardware and software, and its integration to the AgustaWestland flight simulator. The final step, the simulator test campaign, is currently under development. As per the situation to date, all goals of the project will be achieved within the scheduled duration.

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ACRONYMS

BVISPL	Blade-Vortex Interaction SPL
EPN	Effective Perceived Noise
GRC	Green RotorCraft

GTV	Ground Test Vehicle
HMI	Human-Machine Interface
ITD	Integrated Technology Demonstrator
JTI	Joint Technology Initiative
MFD	Multi-Function Display
OASPL	OverAll SPL
PAI	Pilot Acoustic Indicator
RSF	Rotor State Feedback
SPL	Sound Pressure Level
TPP	Tip-Path Plane
TPP-AOA	TPP Angle Of Attack
WP	Work Package

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