Vibration Comfort Improvement through Active Cabin Vibration Control and its Certification on EC130T2

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ABSTRACT

Rotary wings aircrafts are known to be prone to exhibit considerable vibrations, typically because of main rotor induced vibrations. Due to their impact on the ability to safely perform a mission, read the instruments and operate as requested, there have been continuous efforts to alleviate vibration. Significant reduction of the vibration levels has mainly been demonstrated with passive devices. Still, future rotorcrafts have to keep up with increasing customer comfort requirements and to improve due to new stringent demands, like the European parliament Directive 2002/44/EC on vibration. This is applicable to any helicopter. Active control already demonstrated its ability to drastically reduce vibration levels. In the commercial range, active vibration control is mainly applied to medium to large size helicopters. In addition to its intrinsic efficiency, it also offers the ability to adapt to rotor speed variations. This paper presents EUROCOPTERS' application of its already flying EC225 solution to light helicopters. The description of the system and the main results obtained, allowing validating the system which led to the certification on EC130T2, are presented in this paper. The implementation of active vibration control achieved the initial targets in terms of vibration reduction and positive customer feedback.

NOMENCLATURE

AVCA	Active Vibration Control Actuator
AVCCPA	Active Vibration Control Computer & Power Amplifier
AVCS	Active Vibration Control System
FxLMS	Filtered-x-Least Mean Square
GUI	Graphical User Interface
MCP	Maximum Continuous Power
N	Number of blades
NRO	Nominal Rotor Speed
RSS	Rotor Synchronous Signal
SYS-ID	System Identification
T	Transfer function
μ	Convergence rate

INTRODUCTION

Main rotor blades are undergoing periodic aerodynamic loads due to velocity, angle of attack, inflow asymmetry, reverse flow, high Mach numbers on advancing blade and partly stalled span sections. This cyclic loading combined with blade Eigenmodes results in complex, flight condition dependent, dynamic loads at the main rotor center which is the origin of airframe vibrations. These are the so-called rotor induced vibrations which are the main source of vibratory discomfort within a helicopter. The rotor behaves as a filter; blade dynamics loads are harmonics of the frequency of rotation whereas hub loads in the fixed frame are made of a reduced frequency content, kN/rev (k being en integer) for N blades. Hub loads components vary, in terms of relative magnitude and phase, according to flight state; it makes the reduction of their effect a tougher challenge.

Increasing vibration comfort keeps on being a key task to perform, since any global architecture modification impacts the dynamics of the helicopter; every upgrade, such as an improved main rotor, is a new beginning. Alleviation methods are usually divided into three main categories, based upon the location of its implementation:

- At the rotor,
- At rotor/gearbox and fuselage interface ,
- In the fuselage.

In the range of EUROCOPTER light single helicopters, the EC130B4 has been certified in

2000. It shares the AS350 main rotor, but has a completely new airframe and the flight domain is extended in terms of velocity and the helicopter balance in terms of attitude. It inherited the AS350 anti-vibration devices: main rotor head absorber, soft plate suspension and two passive absorbers. This is state-of-the-art technology, with proven efficiency, to reduce vibrations. The EC130 can be considered as a comfortable helicopter. However, dynamic loads and vibration levels increase until MCP level flight and the EC130 is consistent with this commonly known rule. Nevertheless, EC130T2 needed to improve its vibration levels compared to EC130B4 to comply with future standards, with particular emphasis on the European Directive 2002/44/EC on vibration impact on health, and customer requests for constantly improved comfort. In addition, the global target to reduce environmental footprint of rotary air transport, pushes helicopter manufacturers to come up with technical upgrades such as extended variable rotor speed range. This means that commonly used passive tuned systems will have a reduced efficiency, which emphasises the need of active and adaptive vibration reduction [1][2][3]. The implementation of active vibration control allowed reaching the initial targets in terms of vibration reduction and positive customer feedback.

The use of active measures in general is not new in the helicopter community, as few systems are already implemented in medium and large sized helicopters. For example, the 11ton-class EC225 has been equipped with an active vibration system since 2005 [4] which made it a reference in the segment. This achievement emphasized the gain in comfort that can be achieved with the implementation of such an active system. In addition, large successes with near-to-source vibration reduction are achieved in the field of active rotors [5].

The feasibility of airframe active vibration control on light single and twin engine helicopters was first prototype tested and successfully implemented on different aircrafts belonging to EUROCOPTER light helicopters class between 2006 and 2008 [6]. To meet this category of rotorcraft industrial requirements, a family approach has been developed and implemented on three different types of helicopter of the range.

Active vibration control creates a secondary vibration field and can use different actuator design and technology. The superimposition to the primary rotor induced vibration field is performed by adapting magnitude and phase, such that the overall resultant vibrations are minimized. Selecting force and accelerometers locations and their weighting is the way to adapt the vibration field to any design target. The current development of an **A**ctive **V**ibration **C**ontrol **S**ystem for light single and twin engine helicopter (**AVCS**) shows Eurocopter's path forward to fit the low cost, compact and light weight requirements – commonly shared in this particular helicopter spectrum – with the envisaged low cabin vibration level.

First, this paper describes the system followed by the main steps in its development, with ground and flight tests. With as final result the type certification of EC130T2 with this active vibration control system.

SYSTEM DESCRIPTION

The AVCS consists of a three-fold framework containing inertial linear force generators, **A**ctive **V**ibration **C**ontrol **A**ctuators (**AVCA**), feedback piezoelectric sensors and an **A**ctive **V**ibration **C**ontrol **C**omputer & **P**ower **A**mplifier (**AVCCPA**), designed by and developed in cooperation with LORD Corporation. Figure 1 shows a schematic overview of the main components.

The configuration that was selected for flight evaluation has been determined on the basis of the experience gained in the prototype phase [6]. It was used to evaluate the key design parameters such as number of actuators, location of actuators and sensors, optimal control algorithm, a relevant starting point for weightings, attachment stiffness etc. The success of such a development lays not only in a high level of performance at a reduced cost and power consumption, but also to limit the weight impact with respect to present systems (~ 1% TOW). All components are strategically mounted directly under the floor or in tailboom area.

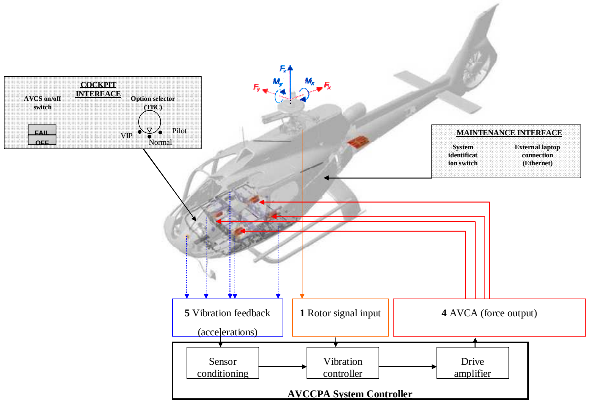

Figure 1: Schematic block diagram of the active vibration control system

Actuator

The AVCA is an electromagnetic actuator which is capable of providing a dynamic load of around 1000N by means of the acceleration of its moving mass. It is using resonant amplification to limit the required power, when powered-off, the force generator works thus as a classical absorber enabling a slight but not negligible vibration reduction. The development of a family concept actuator increased the constraints due the possible location in the involved carriers. The AVCA was specified so that it could even fit in the narrow space in the far front of the cockpit subfloor and avoid clashes with already installed parts. The AVCA bracket design provides adequate stiffness and can enable, if needed, the usage of the attachment base of the current passive and semi-active absorbers as well as coupling two single actuators to a dual force generator in case higher loads are necessary.

Controller and Power Amplifier

The AVCCPA design fulfils a demanding set of requirements. This multipurpose control unit combines a variety of elements, including computer electronics and software, sensor signal conditioning and power amplifiers for the AVCA. Special attention was paid on a strict mass-volume policy. The AVCCPA lay-out is such that it can handle up to four AVCA and up to eight vibration sensors.

Special emphasis has also been put on a high level of connectivity between the system and operators to enhance troubleshooting during the serial life of the product and to permit a high level of diagnosis capabilities, failure indicators and Ethernet serial port for low-level easy communication with the AVCCPA. Multipurpose **G**raphical **U**ser **I**nterface (**GUI**) software was developed by LORD for communication between a standard laptop and the AVCCPA.

Algorithm

EC225 serial application, as well as experience with the prototype system and during various active noise control projects [7], demonstrated that the control algorithm which fits this particular vibration control task best is a Filtered-x-Least Mean Square (FxLMS) algorithm. It is a well-described control approach that is suited for controlling the vibrations appearing at a discrete frequency. This narrowband algorithm adapts a band-pass filter to the frequency, to be controlled using a reference signal from the main rotor through its Rotor Synchronous Signal (RSS). The basic structure of such a control loop is depicted in Figure 2.

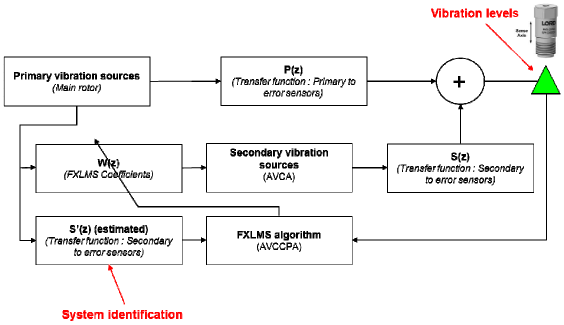

Figure 2: Block diagram of narrowband FxLMS control loop with SYS-ID [7]

An essential step to ensure efficient and stable behaviour of feed-forward control is the setting of an adequate characterization of the system dynamics. This is achieved by producing a set of transfer functions from each AVCA to each sensor in the frequency range of interest, through a so-called SYS-ID procedure. For this purpose, the actuators are driven, one after the other, with a sweep signal which is used as a reference for the transfer function building.

The frequency range, step size and amplitude must be chosen very carefully as the algorithm needs a well-conditioned system. The transfer functions of the force generator may depend on load conditions, which might influence the overall performance; therefore several SYS-ID procedures were performed under various conditions. Based on this data, the robustness and the performance was estimated in theoretical simulations and validated during flight.

MODELLING ACTIVITIES

There are a large amount of possibilities to tune such a system; the path to the final solution can be thorny and time consuming. Therefore, having modeling means a significant amount of time can be saved, which is very beneficial in terms of cost efficiency but also to comply with tighter and tighter planning requirements.

Figure 3 demonstrates that the modeling of the system dynamics can be used to, at least qualitatively, predict the effect of active control.

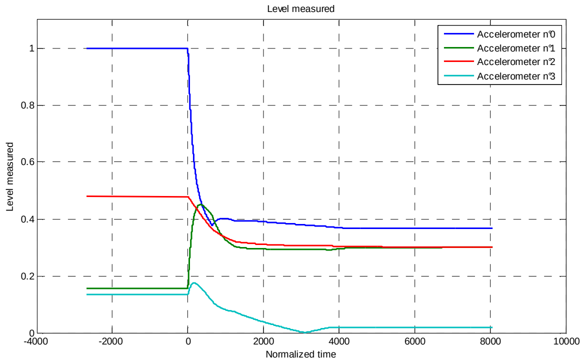

Figure 3: Simulation of the system time response

Figure 4 shows how simulation helped preselecting convergence factors which have been tested in-flight, as it can be seen in the related paragraph.

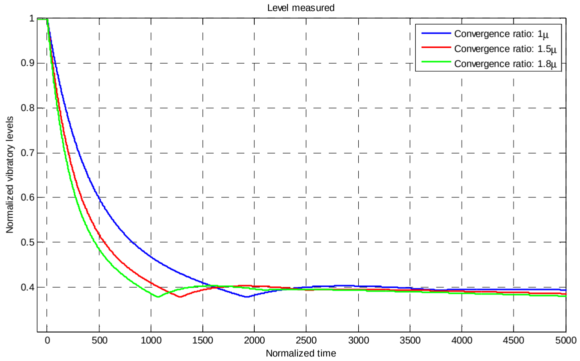

Figure 4: Simulation of the system time response for three different convergence parameters

GROUND TESTS

Bench testing is an essential phase for any active vibration control system development. Firstly, it permits to ensure the good working of a large part of the system before the first flight. Secondly, these tests constitute a very effective way to collect important data of AVC system behaviour and helicopter dynamic structural response. Therefore it allows, early in the project, starting algorithm main parameters optimisation by verifying system performances and algorithm stability, reducing by the way extensive flight hours.

On EC130, the first ground test with AVCS system and the entire helicopter structure took placed a few weeks before first flight. One of the major difficulties of these tests remained to design appropriate bench tools in order to be as representative as possible to flight conditions. As an example, the main objective of AVCS system is to create a secondary vibration field counterbalancing the primary field generated by the main rotor. On ground, since the rotor was non-rotating, no primary field was naturally present. Therefore an electro-dynamic shaker was installed: it supplied the primary source of vibration (in place of the main rotor) and provided the reference rotor signal (RSS). The force generated by the shaker was introduced close to the tail rotor, using the modal deformation of the structure close to the excitation frequency (bending three nodes) This set-up allowed increasing the effects on the front of the helicopter, without interfering with the AVCS actuators placed in cabin.

The first part of these tests was dedicated to the verification of operational system. The following points were successfully validated:

- Correct hardware integration
- Acceleration measurements and sensitivity
- Generated AVCA output force
- First validation of the algorithm convergence

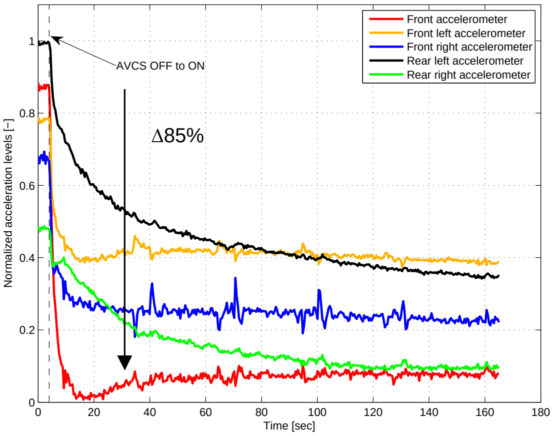

Figure 5: Vibration levels evolution after power on of the system

The second part of the tests was dedicated to system performances. During these tests, the system is powered on and the evolution of vibration levels on each accelerometer is observed. Several weightings for AVCS algorithm are used in order to find an adequate tuning for the first flight. As observed on Figure 5, when the system is powered on, vibration levels are strongly reduced, up to 85% in this test case.

The last part of the ground test was dedicated to the optimisation of convergence parameters and algorithm stability. Indeed, the evaluation of the stability margins is a difficult task since the limit between the stable and unstable area may evolve due to, for example, change into helicopter structural response because of a different mass repartition (number of passengers, location…). Therefore, during the tests, the convergence parameters have been gradually modified until unstable areas were reached as presented in Figure 6. These tests allow finding a safe area for helicopter first flight where algorithm convergence is ensured.

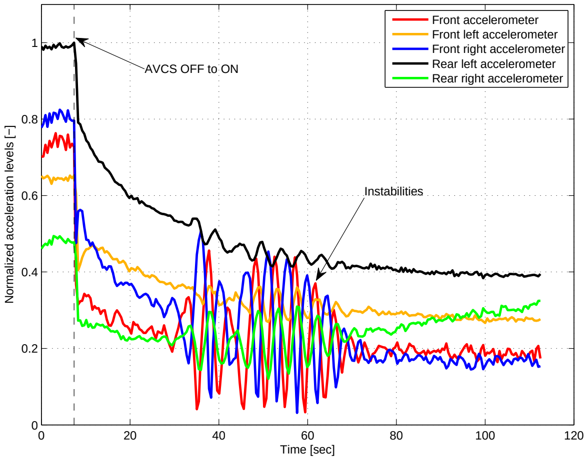

Figure 6: Instabilities observed with strong convergence factor

IN-FLIGHT EVALUATION

This chapter presents the flight evaluation of the system, which is the final step in order to freeze the design. To fit the particular needs of each aircraft in the family concept, three different combinations of the AVCS components have been investigated during flight test campaigns with final target to reach certification of the system. Table 1 shows the various combinations of parameters which were tested. Different levels of complexity and up to two operating directions are validated in serial-type helicopters. In addition to these different hardware configurations, detailed software investigations were performed.

Table 1: Test configurations

Direction	Y	Z	Y + Z
Envisaged Platform	EC135	EC130T2	EC135/145
N/rev - Hz	26.4	19.5Hz	26.4/25.6
RSS	Sine wave	Pulse	Sine wave
Blades	4	3	4
AVCA	2	4	2 / 2
AVCCPA	1	1	1
Sensor	4	5	8

The development and certification flights on all target helicopters included standard flight conditions, like level flights at different forward speed, climb and descent rates as well as during rotor speed sweeps. The evaluation of the performance achieved during these steady maneuvers was completed by transient evaluation in bank turns, pull-ups and flares for example. In addition, performance in differently tuned helicopters with a variety of (artificial) reference levels was checked. Main emphasis was to adjust the system, from both hardware configuration and software tuning, to efficient vibration reduction, stable and quick adaptation to changing operational conditions and rotor speed variations.

Further details about the development of the active vibration control system on the other platforms are given in [8].

As shown in Table 1, the EC130T2 uses a vertical axis system composed with four actuators on stiff beams under the cabin floor for loads introduction and five accelerometers placed at relevant position according to the dynamic behavior of the cabin.

As a first step, it has been chosen to focus only on one relevant flight phase for performance evaluation. In this case, MCP level flight has been considered since the vibration pattern exhibits a strong influence of the forward speed on the vibration levels over the last knots.

The AVCS tuning was performed in two main steps:

1. Identification of the best accelerometers weighting with a define convergence ratio in steady conditions,
2. Optimisation of the convergence ratio to improve the transient behaviour.

Initial settings used the same weight in the control loop for all accelerometers.

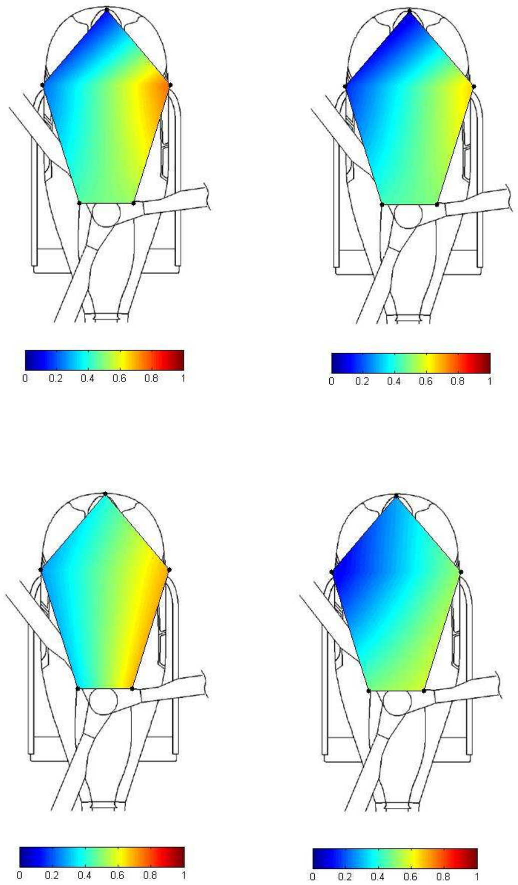

Figure 7: Vibratory field for level flight @ MCP for different tuning parameters (Normalized to maximum vibration level in active mode)

Even if this configuration already gave acceptable results closed to passive absorber performances, previous tests performed with prototype AVCS system have shown that better performances could be reached with an active system. Therefore, parameters have been adapted considering the dynamic behaviour of the cabin based upon flight results. Figure 7 presents the results obtained with four sets of parameters which led to the final selection of accelerometers weighting; each corner of the pentagon represents a measurement point performed on the cabin floor in the vertical axis. From left to right on the figure, it clearly can be seen that the variation of the front to aft accelerometers ratio is reducing the relative importance of feet measurement compared to seat. This allows making the vibration field more homogenous and thus reducing the intrinsic differences that can exist.

Additional results are presented in the pentagon of Figure 8. On the left hand side, the initial set of weighting is presented, whereas the optimized set of values certified on EC130T2 is presented on the right hand side. This change of weighting leads to a significant modification of the pattern of the resulting vibration fields in the cabin: the vibration levels are clearly reduced with respect to front seat vibrations levels. After having selected the weighting coefficients for steady flights, the second main target was to tune the system to stable and quick adaptation of changing operational conditions and rotor speed variations.

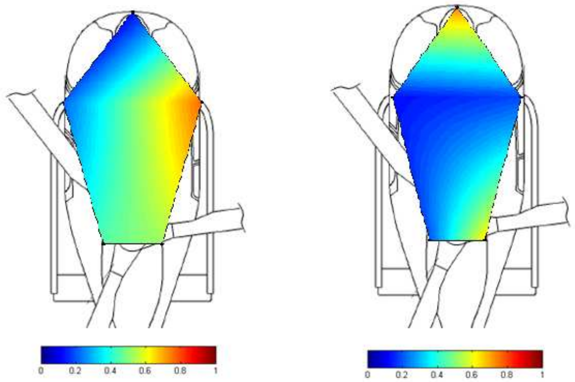

Figure 8: Vibratory field for level flight @ MCP

The AVCS uses its capability of frequency adaptation during flight to yield in extremely low vibration levels over the complete flight domain. Parametric investigations have been made on the convergence rate factor μ as presented in Figure 9: when increased, the convergence rate factor ensures a quicker convergence of the vibratory levels. From the different values tested, the best compromise between convergence speed and algorithm stability has been made for serial EC130T2.

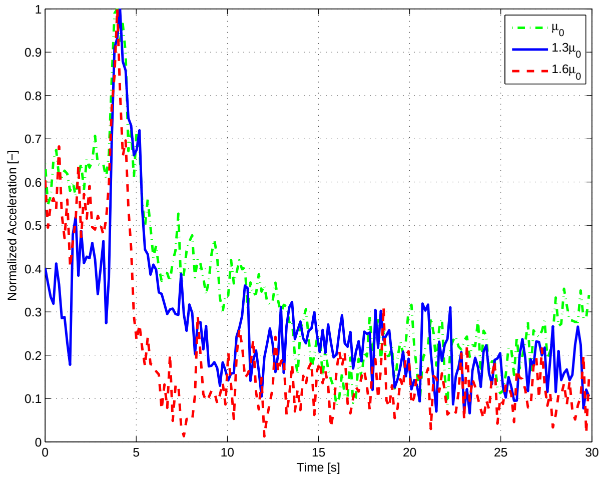

Figure 9: Convergence investigation

After the optimization of the AVCS parameters during level flight at MCP, development and certification flight were extended to an enlarged flight envelope in order to validate the settings and challenge the robustness of the system. Figure 10 presents the vibration levels versus indicated airspeed for the most relevant sensor location in the cabin:

- Green line shows EC130T2 vibratory levels without AVCS
- Blue line shows EC130T2 vibratory levels with AVCS in the certified configuration
- Orange line shows the vibratory levels of EC130B4 equipped with two passive absorbers.

Figure 10 demonstrates the great improvement made on EC130T2, in particular the strong attenuation of the influence of the forward speed over the last knots on the vibratory levels, allowing a significant increase in the EC130T2 comfort. All flight tests showed excellent performance of the active system with significantly reduced vibration levels in the cabin compared to passive absorbers and confirmed exceptional potential for vibration reduction that exhibits active control in the light helicopter class.

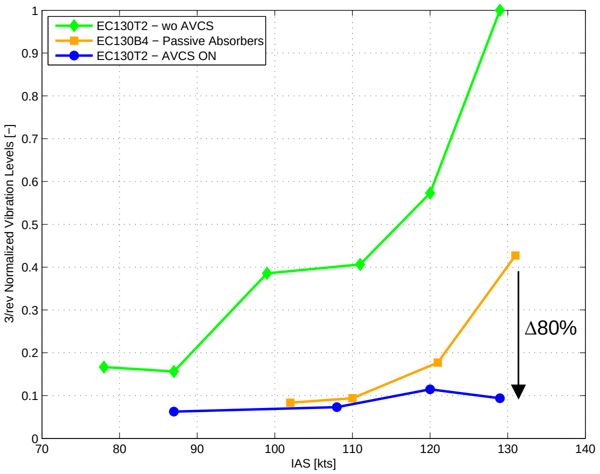

Figure 10: Vibration in level flight – At

An important advantage of an active system is, as said before, that the vibratory map can be tuned by adjusting sensors weighting thus increasing the importance of specific locations in the global vibration reduction.

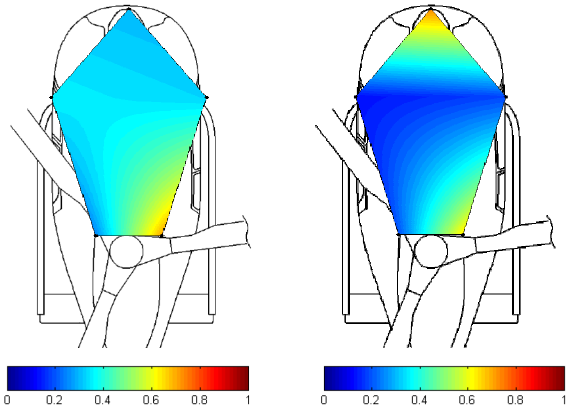

Figure 11: Vertical vibration in level flight

Figure 11 demonstrates the impact on the vibration cartography of different controller settings. A refined distribution of the relative weighting between seats and feet allows a better balance of the resultant vibration levels.

The crew feedback has been essential to establish the most appropriated feedback law since, for example, the comparative effect of vibrations measured at the feet or on the seat cannot be established that easily.

CERTIFICATION

The final challenge of the system implementation has been its certification. This long term activity started indeed at the beginning of the development.

Beyond classical equipment functions substantiation, which ensures that the system functions properly when installed, the substantiation of the vibration requirement, in the frame of JAR 27.251 was carefully considered. The impact of the implementation of such a system on the substantiation has been investigated.

The Functional Hazard Analysis determined the working hypothesis to make the design consistent to safety requirements. The conclusions of this analysis raised the working hypothesis and allowed to classify the system as a “comfort” system, which means that it is not safety critical. This may seem obvious at first sight however this classification is not only driven by failure but also by malfunction. The consequences of malfunction of every component of the system has been cautiously analysed with associated impacts on Flight Manual and Minimum Master Equipment List of the EC130T2.

Dedicated flight tests with the system inhibited, system switched off as well as analysis of malfunctions impact resulted in the demonstration that no malfunction or failure can affect the airworthiness of the helicopter, which is consistent with a “comfort” system.

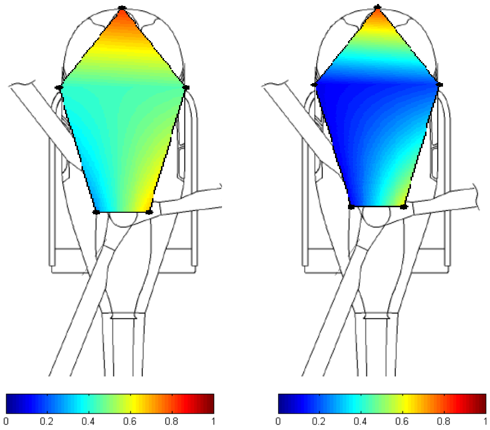

Figure 12: AVCS System ON vs. OFF

To fully perform the certification process until its end, the evaluation of the system switched-off is mandatory to allow the crew to fly in such a configuration. This required the demonstration that the aircraft is, despite the system being switched off, still airworthy. Figure 12 shows this in-flight demonstration where vibration levels are obviously higher when the system is switched off. The crew assessment in that particular flight condition allowed concluding that the helicopter can be safely operated.

CONCLUSIONS

The future of vibration reduction in rotorcraft industry will require even higher efficiency and demonstration of its abilities over a wider range of rotor rotational speed.

This paper presents the latest design of an active vibration control system for application of light rotorcrafts. Three different configurations have been successfully implemented and flight evaluated on different types of aircrafts; this extensive work allowed the validation of the global approach chosen for this system, i.e. to be capable of operating on different helicopters. For the EC130T2 specific variant, a summary of the most important results achieved during ground and flight tests is given, including evaluation of different settings.

Proper and refined tuning of the controller algorithm parameters is a key item and challenging property to account for the particular behavior of each application. It has also been shown that simulations and optimizations can help in this process and are an aid to reduce the amount of testing.

A very high level of performance has been shown, exceeding significantly the efficiency of passive absorbers even for fixed rotor RPM. The perspective of variable rotaional speed allows to determine all the additional benefits of such a solution. The robustness of the system has been proven in both stationary as transient maneuvers. These experiments confirmed the exceptional potential for vibration reduction that exhibits active control in the light helicopter class resulting in the EC130T2 certification with active vibration control and very positive customers’ feedback during evaluation of the prototype. This achievement is a path forward for implementation on future light helicopters.

ACKNOWLEDGMENTS

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