Control law adaptation for helicopter in turbulent air

Qi Lin
lin.qi@tecnico.ulisboa.pt

Instituto Superior Técnico, Lisboa, Portugal

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Abstract

Nowadays, Automatic Flight Control System (AFCS) is used to assist the pilot in performing his tasks in order to reduce his physical as well as cognitive load. However, tuning the AFCS is usually a compromise between performance and comfort. In this study, an example AFCS of helicopter is considered. The goal of this internship in Thales Avionics is to modify this AFCS to improve passengers comfort in turbulent air, while keeping good performance in calm air. The followed methodology is to design a turbulence detection mechanism, which is able to select the original tuning in calm air, and in case of turbulence detection, it switches the controller to the one that increases comfort. In order to increase passengers comfort in turbulent air, the control activity of the AFCS is reduced to eliminate the undesired accelerations. This study was focused on the speed control system, and the modifications performed on this system intend to minimize the longitudinal acceleration encountered in turbulent air. The results obtained are quantified using standard passenger comfort evaluation methodologies (ISO-2631).

Keywords: Automatic Flight Control System (AFCS), performance, comfort, turbulent air, turbulence detection mechanism, speed control system

1. Introduction

The wellbeing and comfort of passengers have always been a concern for the aerospace industry. During flight in calm air, aircraft are quite comfortable. However, in a turbulent air environment, where the movement of air mass changes suddenly in direction and intensity, aircraft are constantly experiencing positive and negative acceleration forces in different directions. Exposure to these accelerations may origin discomfort and interfere with pilots working activities during the flight.

Nowadays, Automatic Flight Control System (AFCS) can take over some parts of the pilots routine task, such as maintaining an altitude, climbing or descending to an assigned altitude, turning to and maintaining an assigned heading. Therefore, pilots use AFCS to reduce their workload, improve mission reliability and enhance safety of flight. However, tuning an AFCS is a compromise between performance and comfort. The AFCS considered in this study has a base tuning biased towards performance. Therefore, the AFCS is not optimised for flying in a turbulent air environment in terms of comfort. Moreover, ineffectual corrective command may be generated by AFCS. The goal of the internship in Thales Avionics is to modify this AFCS to improve passengers comfort in turbulent air, while keeping good performance in calm air.

An AFCS contains several autopilot modes which are used to control the movement of the helicopter in longitudinal, lateral and vertical direction. For instance, if the IAS (Indicated Airspeed) mode is engaged, the longitudinal control is performed to control the airspeed of a helicopter. This study was focused on the speed control system (IAS control system), and the modifications performed on this system intend to minimize the longitudinal acceleration encountered in turbulent air.

2. Context and proposed methodology

When the AFCS is used to maintain a selected airspeed (IAS mode engaged), a comparison between the selected airspeed and the measured airspeed is performed, and the difference between these two quantities is defined as the velocity error. In case the velocity error is not zero, the IAS control system creates a corrective command, to increase or decrease the airspeed of the aircraft, in order to achieve a zero velocity error. The change of air flow caused by turbulence alters the airspeed, which creates a velocity error that the AFCS attempts to eliminate. In the meanwhile, the effect of turbulence alters the inertial velocity (longitudinal ground speed) as well, due to the drag force of the air flow. Nonetheless, the command action applied by AFCS does not erase the inertial accelerations coming from turbulence conditions, but instead deteriorates them. An example of a typical airspeed control system from a US patent [1] describes the fact mentioned.

As have mentioned, in a turbulent air environment, a typical speed control system creates additional longitudinal accelerations apart from those caused by turbulence. In order to increase passengers comfort in turbulent air, the speed control activity should be reduced in order to minimize the longitudinal acceleration encountered in turbulent air. However, tuning the speed control system is a compromise between performance and comfort. On the one hand, it is desired to maintain the airspeed around the selected one, in order to achieve desired performance in calm air. Hence, the control system must be reactive to correct any velocity deviation, but it makes the flight less comfortable in turbulent conditions. On the other hand, the passenger comfort can be increased in turbulent air if the control activity is reduced, but this approach will lead to a loss in performance in calm air.

2.1. Proposed methodology

The base tuning of the considered AFCS is biased towards performance. The first step of this internship is to seek another tuning for speed control system to increase passengers comfort when flying in a turbulent air. Apparently this tuning leads to a loss in a performance in calm air compared to the original tuning. Therefore, the second objective is to achieve a turbulence detection mechanism. This mechanism should select the original tuning of the speed control system in calm air, and when turbulence is detected, it should select the tuning that increases passengers comfort in turbulent air.

3. Implementation and results

3.1. Speed control activity reduction

A scenery of flight with mode IAS (Indicated Airspeed), ALT (Altitude) and HDG (Heading) engaged is used to evaluate the results obtained. Figure 1 and figure 2 exposes the helicopter response respectively in calm air and turbulent air. In a turbulence condition, constant changes in control inputs and acceleration can be verified in the graphics of figure 2: Accelerations and Pitch Steering.

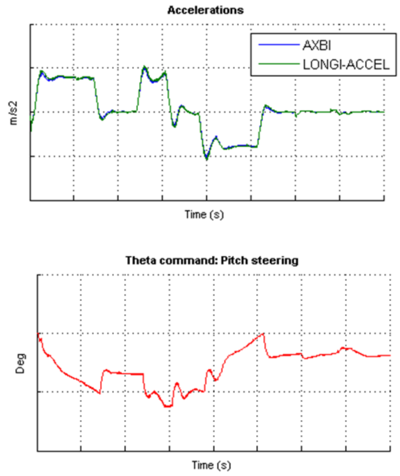


Figure 1: Helicopter response in calm air with the original IAS control system

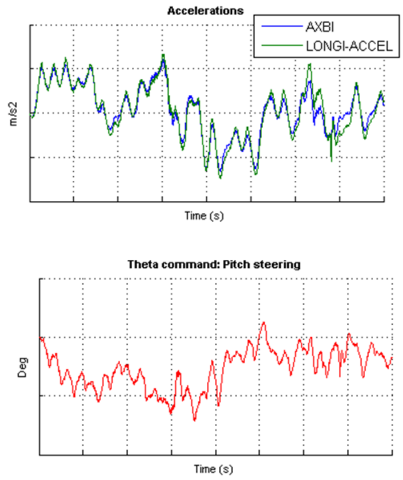


Figure 2: Helicopter response in turbulent air with the original IAS control system

As previously mentioned, the first stage is to reduce the speed control activity in order to minimize the undesirable accelerations experienced by helicopter in turbulent air. The first solution is to reduce control law gains. Smaller gains in control law make the speed control system less reactive to substantial velocity errors, and therefore the objective can be achieved.

As shown in figure 3, the changes in longitudinal accelerations and pitch command are reduced. However, as the control activity is reduced, the speed control system will provide slower response to eliminate velocity errors of any origin. This approach causes a loss in performance, especially when a maneuver is performed. For example, when the airspeed changes are required, the speed control system does not react quickly to bring the helicopter to the velocity target.

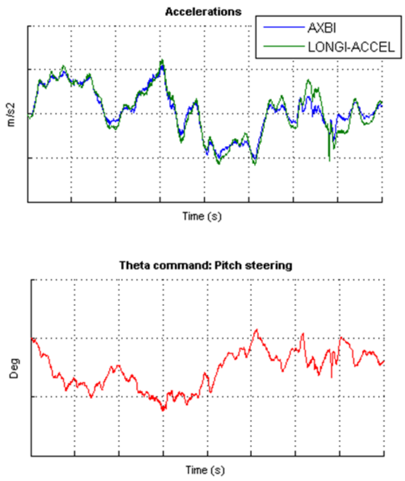


Figure 3: Helicopter response in turbulent air with reduced gains in the IAS control law

The alternative solution is to change the inputs of the control law. The speed control law generates its corrective command according to the velocity error, which is defined as the difference between filtered Calibrated Airspeed (CAS) and velocity reference. By lowering the cut-off frequency of the velocity filter, the filtered velocity will track CAS slower and smoother. Therefore, the velocity error that is taking into account in the speed control law will be less and the control activity of the speed control system will be reduced. figure 4 confirms the improvement achieved by the modified filter with respect to the original filter presented in figure 2. Both changes in longitudinal inertial acceleration and control input are reduced. In addition, unlike the first solution, this alternative one does not present drawbacks on the performance when a maneuver is performed.

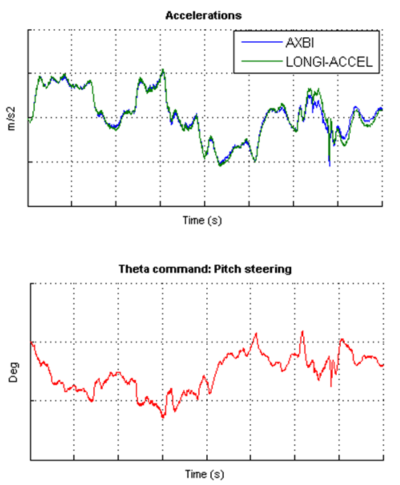


Figure 4: Helicopter response in turbulent air with modified filter in the IAS control system

3.2. Turbulence detection mechanism

If one can detect perfectly turbulence occurrences, one can always have a controller more leaned to comfort issue in turbulent air.

The turbulence detection mechanism proposed is based on the statistic parameter, Root Mean Square (RMS). The RMS value of a set of values is the square root of the arithmetic mean of the squares of the values. In the case of a set of n samples $x_1, x_2, .., x_n$, the RMS value of the set is defined by equation 1.

$$x_{rms} = \sqrt{\frac{1}{n}(x_1^2 + x_2^2 + ... + x_n^2)} \qquad (1)$$

The corresponding formula for a continuous function defined over the interval $T_1 \leq t \leq T_2$ is given by equation 2.

$$f_{rms} = \sqrt{\frac{1}{T_2 - T_1}\int_{T_1}^{T_2} [f(t)]^2 dt} \qquad (2)$$

The RMS of the pairwise differences of the two data sets, one from the theoretical prediction of a physical variable and other from actual measurement of this variable, can serve to measure how far the average error is from zero. Therefore, assuming the velocity reference as the theoretical prediction of CAS output, the RMS of the difference between the velocity reference and actual measurement of CAS could be a criterion to measure how far the average velocity error is from 0.

First, the simulation was performed in airspeed hold condition without any maneuvers. Graphic 5 a) and 6 a) present respectively airspeed response of the helicopter in calm air and turbulent air. By observing helicopter behavior in turbulence, an evident characteristic is constant airspeed changes, so it should origin bigger RMS velocity error than in calm air. Graphic 5 b) and 6 b) show respectively the value of RMS calculated during T seconds in calm air and turbulent air. One can confirm that the RMS in turbulent air is bigger than the RMS calculated in calm air. However, this fact is only correct when the airspeed is hold without any maneuvers. Operations like speeding up or speeding down the helicopter creates a response delay of helicopter airspeed with respect to the selected velocity reference; turning right or left causes the CAS to deviate from the selected velocity and it takes some seconds to converge. Therefore, maneuvers can create significant RMS velocity error in calm air, which can not be distinguished from those caused by turbulence.

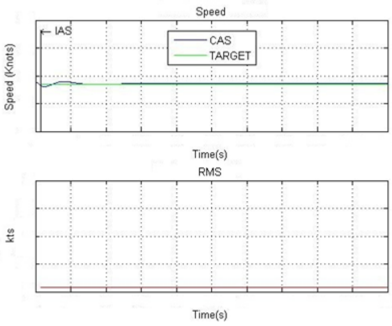


Figure 5: Speed response and RMS velocity error in calm air

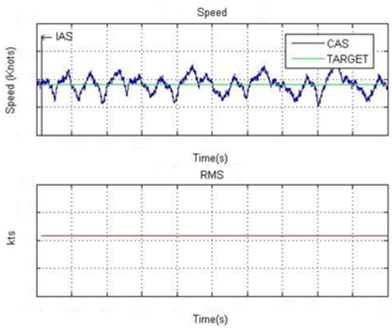
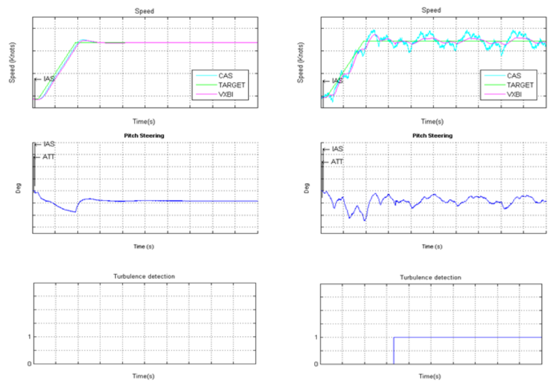


Figure 6: Speed response and RMS velocity error in turbulent air

The RMS method mentioned above requires the velocity reference, which is only available when a speed hold mode like IAS is engaged. Therefore, the mechanism can only be applied during speed hold condition. Moreover, as mentioned earlier, maneuvers cause airspeed deviation with respect to the target in calm air, which can mislead to turbulence detection. Therefore, the RMS error method cannot be used to detect turbulence when a maneuver occurs. Logic operators can be included to deactivate the detection mechanism in maneuver conditions.

The turbulence bloc, which includes RMS velocity error calculation and activation mechanism, was added to switch the speed controller. Figure 7 shows the behavior of the turbulence detection mechanism in calm air and turbulent air. At the beginning, where the velocity change is performed, the RMS calculation is not activated; therefore the detection is false in both calm and turbulent air. When the airspeed is hold, the RMS velocity error is computed and compared to the RMS limits at each instant. As shown in the graphics, turbulence is detected in turbulent air, while the detection of turbulence is always false in calm air. When the detection is true, the mechanism changes the controller to the more damped one for comfort issue. In the case presented, the alternative filter is included in the AFCS for operating in turbulent air. It can be seen in the figure, when turbulence is detected, the behavior of the VXBI (filtered CAS) changes due to the selection of the alternative filter by the turbulence detection mechanism.



(a) Calm air (b) Turbulent air

Figure 7: Response of the turbulence detection mechanism in calm air and turbulent air

3.3. Performance evaluation of the modified filter

Since developing a turbulence detection mechanism is very difficult task due to the random behavior of turbulence, one has thought to evaluate the possibility of using the improved filter all the time. Unlike a control law gains reduction, it seems possible to keep a reactive control law by using the improved filter. Therefore, if the loss in performance is admissible, one can use this modified filter continually in either turbulent or calm environment. The airspeed performance given by the modified filter is analysed in two maneuvers condition:

- Speed hold with airspeed reference change
- Speed hold while performing a climb

First, the airspeed performance in calm air is studied. The results show that in both maneuvers, the airspeed performance given by the modified filter is good as the one given by the original filter.

In the presence of turbulence, velocity deviation from the reference is inevitable. In spite of the improvement achieved by modified filter in term of acceleration changes, the consequence on the performance should be analysed. Concerning the speed performance in a turbulent environment, the RMS velocity error is used to evaluate the performance of improved filter with respect to the original filter. In both maneuver conditions, there is no significant difference in airspeed deviation between using the original filter and the modified filter. The RMS errors are practically the same, even when maneuvers are performed.

3.4. Comfort evaluation of the modified filter

The comfort criterion based on ISO 2631-1 standard described in [2] is applied to evaluate passengers comfort in turbulent air.

According to ISO 2631-1, in order to evaluate "low frequency" comfort (vibrating comfort) and "very low frequency" comfort (motion sickness), the accelerations have to be measured at the pilot position. Then, the measured accelerations have to be filtered with frequency weighting curves specified by the standard, in order to represent the physiologic sensitivity of human body to vibration and motion sickness. The documentation [3] presents the low order filter approximations of the frequency weighting curves, which are used to obtain frequency weighted acceleration.

For "low frequency" comfort, the RMS of the frequency weighted acceleration for each component of the acceleration is computed by using equation 3, where a_w (m/s^2) is the instantaneous frequency weighted acceleration and T, the length of time over which the RMS value is being computed.

$$\bar{a_w} = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{\frac{1}{2}} \tag{3}$$

Then the total vibration value a_v at a measurement point can be computed from the RMS values of weighted accelerations on each axis, as shown in equation 4.

$$a_v = ({k_x}^2 {a_{wx}}^2 + {k_y}^2 {a_{wy}}^2 + {k_z}^2 {a_{wz}}^2)^{\frac{1}{2}} \tag{4}$$

Where:
a_{wx}, a_{wy}, a_{wz} are RMS values of the weighted acceleration on x, y and z axes;
k_x, k_y, k_z are weighting factors; for a seated person the standard proposes the following factors:
-at the supporting seat surface: $k_x = 1$, $k_y = 1$, $k_z = 1$;
-at the feet: $k_x = 0.25$, $k_y = 0.25$, $k_z = 0.4$.

When comfort is affected by vibrations at several points, the overall vibration can be computed from RMS value of global vibrations at each point, equation 5. For a seated person, this involves the vibration measured at the supporting seat surface, at the feet and at the seat back.

$$a = ({a_{p1}}^2 + {a_{p2}}^2 + {a_{p3}}^2)^{\frac{1}{2}} \tag{5}$$

The standard gives approximate indications of the likely reactions to various magnitudes of overall vibration value (a in m/s^2) in public transport (see figure 8).

weighted acceleration a [m/s^2]	(Dis-) comfort categories
< 0.315	not uncomfortable
0.315 to 0.63	a little uncomfortable
0.5 to 1	fairly uncomfortable
0.8 to 1.6	uncomfortable
1.25 to 2.5	very uncomfortable
> 2	extremely uncomfortable

Figure 8: Scale of vibration (dis-) comfort adapted from ISO 2631-1 (1997) from [4]

Concerning the motion sickness phenomenon, "very low frequency" comfort, the standard is based on vertical acceleration felt by a human passenger. As for "low frequency" comfort, there is also a frequency weighting function for representing human sensitivity to motion sickness.

The motion sickness index defined in [2] can be represented by equation 6, where PIP is the Percentage of Ill Passengers and a_w is the instantaneous acceleration (m/s^2) weighted by the motion sickness filter. The relation between the integral of the weighted acceleration and PIP was obtained by linear approximation of experimental data. It is important to acknowledge the nature of the data from which the procedure has been developed since this defines the scope of application. See [2] for more information concerning the application of PIP to evaluate passenger comfort in a civil aircraft.

$$PIP = \frac{1}{3}\left[\int_0^T a_w^2(t)dt\right]^{\frac{1}{2}} \tag{6}$$

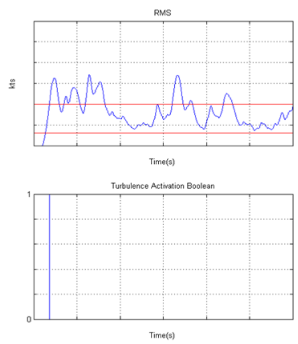
The RMS value of the weighted acceleration (a_v) is calculated to evaluate vibrating comfort, while PIP criterion is used to evaluate motion sickness phenomenon. The objective is to compare the comfort given by the original filter and the modified filter.

Several simulations were performed by introducing different turbulence conditions.

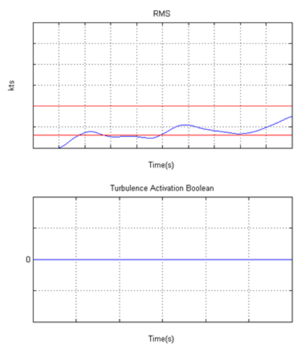
Concerning the vibrating comfort, the (dis)comfort category is "not uncomfortable" according to figure 8 for both filters. Indeed, the response of longitudinal acceleration in frequency domain of the considered simulations evidences that the frequencies of longitudinal accelerations affected by turbulence is far way from the critical frequencies of vibrating comfort. Regarding the motion sickness phenomenon, the effect of turbulence on the accelerations at frequencies of motion sickness is small and the comfort criterion indicates less than 2% of ill passengers. One should take into account that the values a_v and PIP depend on the intensity and frequency of the turbulence. In addition, the standard was derived from seaboard studies. Therefore, one can not affirm that the passengers are far from discomfort for the considered cases. Even though the comfort criterion is not derived for helicopter flight studies and the critical comfort frequencies are unknown, the amplitude of longitudinal acceleration is always reduced with modified filter in the considered cases. It is also important to take into account that all the results are obtained with turbulence model defined in the documentation [5].

4. Evaluation with flight test data

In order to evaluate the turbulence detection mechanism in a realistic random turbulence and calm conditions, flight test data was used. Figure 9 shows the results for calm air and turbulent air. The curves of color blue are the RMS values and curves of color red are RMS limits for activation and deactivation. Turbulence detection mechanism achieved what intended in both cases; turbulence is detected all the time in the turbulent flight, while the detection of turbulence is always false in the calm flight case.



(a) Turbulent air flight test case



(b) Calm air flight test case

Figure 9: RMS of velocity error and turbulence detection in calm and turbulent air

5. Conclusions

The reduction of the speed control activity is achieved by using small gains in the control law or by reducing the cut-off frequency in the filter. In both cases, the undesirable acceleration changes, encountered in turbulent air, are less than the ones given by the original speed controller. However, it seems that the approach of the modified filter is more advantageous. The study revealed similar airspeed performance of the modified filter with respect to the original filter, in both calm air and turbulent air. In the future, other factors should be analysed to evaluate the possible consequences of using the modified filter in all conditions.

Detecting turbulence is a difficult task due to its random behavior. The RMS method alongside with the low pass filter and the confirmation logic performed as desired in two flight test cases. Though, this first approach for the turbulence detection mechanism has to be analysed under more flight test cases, in order to adjust the activation/deactivation mechanism. In the future, the detection mechanism should be improved to overcome some limitations.

References

[1] Kynn J Schulte and G Eldredge. AUTOMATIC VELOCITY CONTROL SYSTEM FOR AIRCRAFT, 2011.

[2] Francois Kubica and Beatrice Madelaine. Passenger Comfort Improvement by Integrated Control Law Design. Technical report, Aerospatiale Matra Airbus, Toulouse, 2000.

[3] L. Zuo and S. Nayfeh. L. Zuo, S. Nayfeh. *JOURNAL OF SOUND AND VIBRATION*, 2002.

[4] Michael A. Bellmann. *Perception of Whole-Body Vibrations: From basic experiments to effects of seat and steering-wheel vibrations on the passenger's comfort inside vehicles.* PhD thesis, Oldenburg, 2002.

[5] D. J. Moorhouse and R. J. Woodcock. Background Information and User Guide for MIL-F-8785C, Military Specification - Flying Qualities of Piloted Airplanes. Technical report, AF Wright Aeronautical Laboratories, AFSC, Ohio, 1982.