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Flight Tests of Active Tail Surfaces on the Experimental Fly-By-Wire Dauphin Helicopter

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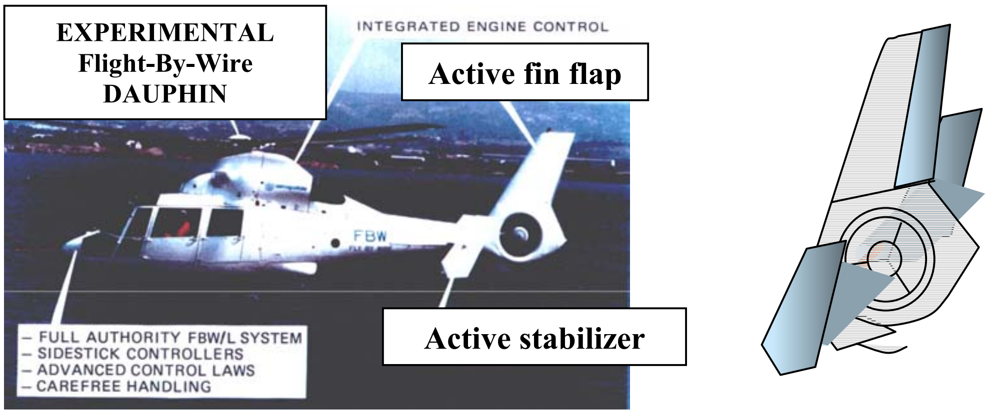

ABSTRACT

In addition to the Fly-By-Wire control system that equips the Dauphin Demonstrator, Eurocopter has investigated the effects of electrically driven flaps installed on the horizontal stabilizer and on the fenestron™ fin.

The aim of this experiment is to assess the advantages, which could be obtained by controlling the tail surfaces of the helicopter. When these two stabilising surfaces are fixed, their setting is determined to trim and stabilise the machine in the whole flight e7nvelope. To design these surfaces a trade off must be found between performance, handling qualities, mechanical stresses and limits of the flight envelope. The controllable horizontal stabilizer and the controllable fin flap can be used to optimise each flight case better.

On helicopters, the rotor safe life is generally limited by the moment on the hub, which results from rotor flapping. With the controllable stabilizer, it is possible to reduce the stress level and increase the lifetime, or increase the operational flight domain. The deflection of the stabilizer changes the pitch attitude and consequently modifies the rotor flapping. The larger the rotor flapping, the more stressed the hub is. That means, thanks to the stabilizer tilt, a trade-off can be achieved between the attitude and the stress on the hub. The centre of gravity, the rotor shaft tilt angle, the rate of turn, the vertical speed, the airspeed and so on, change the aircraft attitude and the rotor flapping. Taking account of these parameters, several control laws have been developed to optimise the static flight case in accordance with the performance and the maximum level of stresses admitted.

The setting of the fin flap is optimised to increase performance. The fenestron™ has the drawback of consuming power and creating drag when the fan is blowing. In order to reduce the resulting total loss of power, the fin flap is used instead of the fenestron™ as soon as the dynamic pressure is sufficient. This transfer allows total power to be saved. This gain is particularly important soon after the take-off phase. This power gained can be used to increase the rate of climb or to increase the weight in the category A take-off procedure.

The global yaw command is shared between the Fenestron™ and the fin flap. Ultimately, the fin flap compensates the torque produced by the main rotor and the tail rotor command converges to the predefined value corresponding to performance criteria.

This experiment has proved it is possible to obtain better performances with these control laws without any drawbacks for piloting. The test pilots have favorably assessed the active tail surfaces mixed control. They feel clearly their effect on the flight attitudes and they control the aircraft flight path without increased workload.

In conclusion, this paper presents the results and the main lessons learned during the flight experiment of the active tail surfaces.

INTRODUCTION

Active tail surfaces have been studied for a long time as a means of optimising the trim and performance of helicopters. They consist of controllable horizontal and vertical stabilisers that supplement the conventional rotor controls and contribute to the overall equilibrium of the helicopter.

Nevertheless, today, for reasons of cost, complexity and reliability, few helicopters are equipped with active tail surfaces.

Today, however, airborne systems are being increasingly used on helicopters and perform critical functions that include piloting aids. Thanks to advanced technology, these airborne systems have become more and more sophisticated, reliable and affordable.

This has spawned a large number of studies aimed at making aircraft easier to use and at enhancing their flying characteristics through the use of control systems. Active tail surfaces are part of this trend.

Thus, an exploratory development of Active Tail Surfaces, partly sponsored by French Government Agencies (SPAé), was launched by EUROCOPTER. The aim of the experiment was to develop and assess in flight new control laws for these active surfaces. First, the tests were conducted on Eurocopter's simulator SPHERE. Control laws were developed and first checked with a pilot in the loop using Eurocopter's generic HOST simulation model. A potential for improvement has been demonstrated on the simulator.

The flight demonstration mainly focused on two aspects:

- To improve the trade-off between the flight attitude and the rotor hub loads and minimise the influence of the CG location by the use of a stabilator.

- To optimise the payload through the minimisation of the Fenestron™ thrust thanks to a controllable flap on the vertical fin.

The goal of the flight tests was to confirm the results in real conditions, with a special focus on the validation of the control laws concept and the analysis of possible interactions with the piloting activity.

The in-flight experiment was conducted with the R & D Dauphin demonstrator, Figure 1, which was fitted with two active tail surfaces: an all-moving horizontal stabilizer and the Fenestron™ vertical fin equipped with a movable flap. The fly-by-wire control system was utilised to establish the control laws for the tail surface actuators. The duplex architecture provided an acceptable level of safety for these tests.

The first flights took place in 1999 to demonstrate safety and were followed by in-flight assessment of several control laws in 2000. The experiment was completed at the beginning of 2001.

Figure 1: Eurocopter system demonstrator

1 CONTROL PRINCIPLES

Due to the movable tail surfaces, there are now two ways of controlling pitch and yaw axes, either by the rotor control as usual, or by moving the tail surface. Both actions can ultimately produce the same transient response, provided that the forward speed is high enough to generate a sufficient aerodynamic effect. In addition, it is possible to combine the two controls available on one axis and modify the resulting trim of the helicopter.

Two piloting strategies were considered:

- The first one, called "prescribed tail surface control law" makes the tail surface position prescribed according to a given law depending on the flight conditions, whereas the rotor pitch is adjusted to reach the equilibrium.
- In the second, named "prescribed rotor control law" the rotor pitch is prescribed according to a given law depending on the flight conditions and the tail surface is adjusted to reach the equilibrium.

"Prescribed tail surface positioning law"

This method is the simplest and the most broadly used. The additional tail surface is prescribed as a function of flight parameters like the airspeed, the vertical speed or the main rotor collective pitch. The helicopter is then balanced thanks to the conventional rotor control, which can be performed manually by the pilot or automatically by the Autopilot, see figure 2.

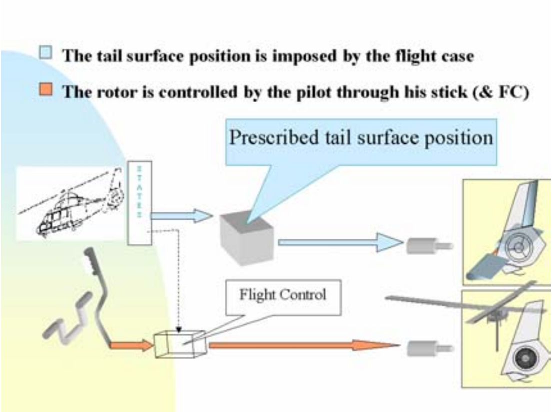

Figure 2: Control principle with "prescribed tail surface positioning " law

"Prescribed rotor positioning law"

The control principle is now to establish the rotor pitch as a function of the flight conditions and to transfer to the tail surface the task of trimming the helicopter. The prescribed rotor pitch is so defined as to reach some optimisation criterion. Two methods based on this principle have been developed:

- In the first method, figure 3, the pilot input is split between the tail surface and the rotor, taking into account the estimated aerodynamic efficiencies of both. Ultimately the rotor goes to the position that corresponds to the rotor reference prescribed by the control law and the tail surface control is adapted accordingly.

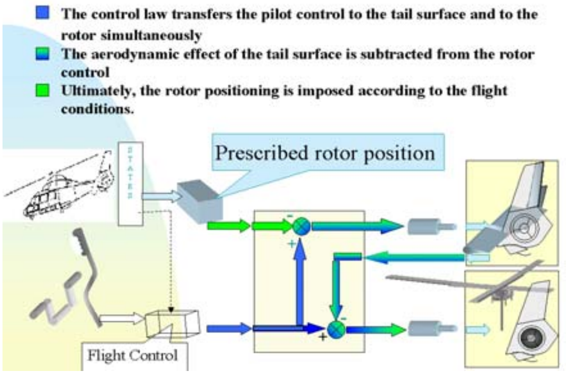

Figure 3: Control principle with Automatic "prescribed rotor positioning" law

The distribution of the controls is completely independent of the pilot. This means that the pilot does not have to worry about how the order is shared between the rotor and the tail surface. That is why this law is called "Automatic".

This control architecture requires an actuator on the rotor controlled by a piloting system (AutoPilot or fly-by-wire controls). It should be kept in mind, however, that this concept uses up part of the control authority, which is limited with an Autopilot system. This means that the overall authority of the Autopilot must be designed accordingly.

- The second method consists in moving the tail surface at a constant rate until the rotor pitch reaches the prescribed pitch value, figure 4. The tail surface deflection induces a movement of the helicopter that will only cease when the pilot or the piloting aid system sets the rotor to its prescribed value. Compared to the first method, this method is called semi-automatic, in that it requires the pilot or the rotor piloting system to intervene.

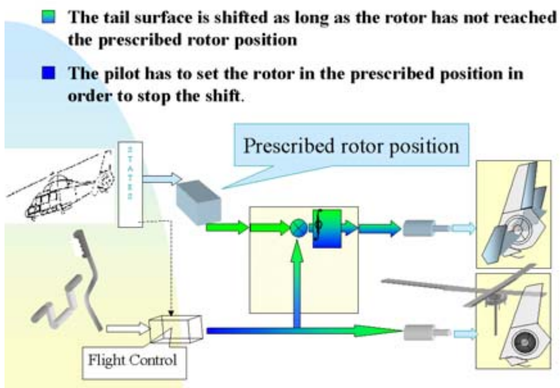

Figure 4: Semi-automatic "prescribed rotor positioning" law

This control architecture does not need a dedicated actuator on the rotor. It can therefore be used on a helicopter without a piloting aid system.

2 APPLICATIONS

These control laws have been applied to the stabilator and to the fin flap of the Experimental Fly-By-Wire Dauphin. The criteria chosen for optimising the performance have been determined to match the aircraft features.

Pitch axis application

The purpose optimising criteria for the pitch axis, applied to the Dauphin, is to achieve the best compromise between mast/hub bending moment and pitch attitude, figure 5.

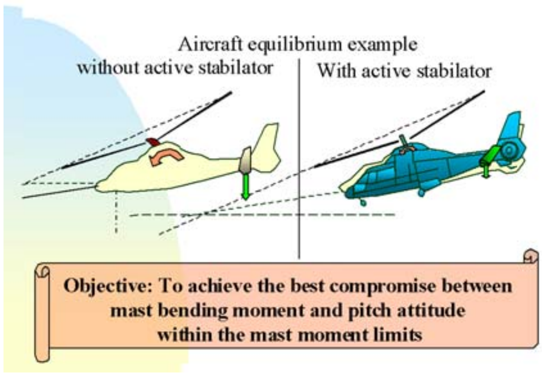

Figure 5: criteria for pitch axis

In level flight, the balance between the rotor thrust and the drag of the helicopter determines the rotor disk attitude. It mainly depends on the weight and the speed in the considered flight condition.

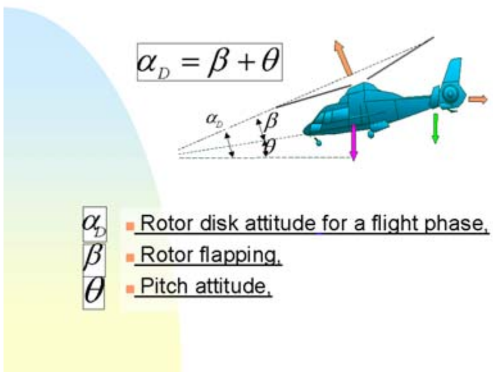

Figure 6: Pitch axis application: Equilibrium

This rotor disk attitude is the sum of the fuselage pitch attitude and of the longitudinal flapping of the rotor (including the mast built-in tilt angle). Once the weight and speed conditions are fixed, the resulting disk attitude is known. Therefore, there is only one degree of freedom to fully define the equilibrium, which is governed by the pitching moment equation. Either the pitch attitude or the rotor longitudinal flapping can be chosen to represent this degree of freedom.

For a given flight condition, with a constant setting stabilizer, moving the centre of gravity forwards induces a nose-down pitching moment that has to be counterbalanced by a nose-up rotor moment. This implies a backward rotor longitudinal flapping. The amplitude of the centre of gravity range directly controls the amplitude of the pitch attitude or longitudinal flapping at trim.

In hover, the only forces to be considered are the weight and the rotor thrust: there is little to do to modify the trim and the designer has to deal with the pitch attitude and longitudinal flapping variations resulting from the centre of gravity range.

In high-speed flight, the aerodynamic pitching moment of the airframe is an additional contribution that has to be taken in account. The designer now has an available parameter to make this moment vary and adjust the equilibrium: the stabilizer setting.

When this angle is kept constant, the trim variations due to the centre of gravity range still exist. The choice of the stabilizer setting usually results from a compromise to be achieved in high speed flight between the longitudinal flapping of the rotor (mast/hub moments) in aft centre of gravity conditions and the nose-down attitude (performance / comfort) with forward centre of gravity.

A moving stabilizer gives the designer an additional way to improve this compromise.

The stabilizer setting can be varied with speed, which can be achieved with a "prescribed stabilator positioning" law. However, in the critical high-speed flight conditions, the pitch attitude or longitudinal flapping amplitude in the centre of gravity range is exactly the same as it would be if the stabilizer setting was fixed at the value selected in the law for the high-speed conditions. This does not make it easier to find the compromise between mast moments and pitch attitude. The degree of freedom brought by the stabilator can however be used to improve the trim in the intermediate speed range or reduce the stick motion when varying the power setting for example.

Further improvements can be achieved if the stabilizer can be moved as a function of the centre of gravity location for a given flight condition. It is then possible to compensate for the change in the pitching moment by means of the stabilator. In these conditions, the pitch attitude and the longitudinal flapping are independent of the centre of gravity position. Such a result can be obtained with a "prescribed rotor positioning" law, as shown hereafter.

A movable stabilizer is sometime used to reduce the pitch attitude change due to the stabilizer entering the main rotor wake. This optimisation was not considered for the testing and the selected laws were mainly oriented towards a reduction of the mast/hub stresses in forward flight.

"***Prescribed stabilator positioning" law***

This law, presented in Figure 7, was designed to be as simple as possible, the aim being to reduce the bending moment of the mast in flight level, climb and descent. The flight case is identified by the measured airspeed, whilst the vertical speed is estimated from the collective pitch signal. All other parameters will be discussed there after.

The critical cases from the mast/hub stress point of view, are hover with a forward centre of gravity where the rotor is tilted backwards, and maximum cruise speed with an aft centre of gravity where the rotor is tilted forwards.

In low speed flight, due to low dynamic pressure the horizontal stabilizer has only little efficiency. Therefore, setting the stabilizer with a negative angle however induces a nose-up pitching moment that reduce the longitudinal flapping in forward centre of gravity conditions. This is also applicable to turns where the longitudinal trim is very similar to hover with an increased rotor thrust.

As the speed increases, the horizontal stabilizer becomes much more effective. Therefore, setting the stabilizer at a positive incidence will generate a nose-down moment and tend to reduce the rotor mast moment at high speed with aft centre of gravity. Beyond a certain limit, this can degrade passenger comfort and increase the drag. As a greater nose-down attitude on the Dauphin has a negligible effect on the drag, this setting was adopted.

In climb and descent, the tilt variations are relatively large. Therefore the law calls for a setting that aligns the horizontal stabilizer in the airflow: either negative in descents, or positive in climbs.

Flight Test Results

In level flight, the results, presented on Figure 8, indicate that the mast bending moment curve has been shifted downwards in the intermediate speed range. This means that this moment will be reduced in the low speed critical loading condition (forward CG). The trim in high speed condition is little changed, which is due to the fact that the stabilizer setting compromise has not been modified in the tested law.

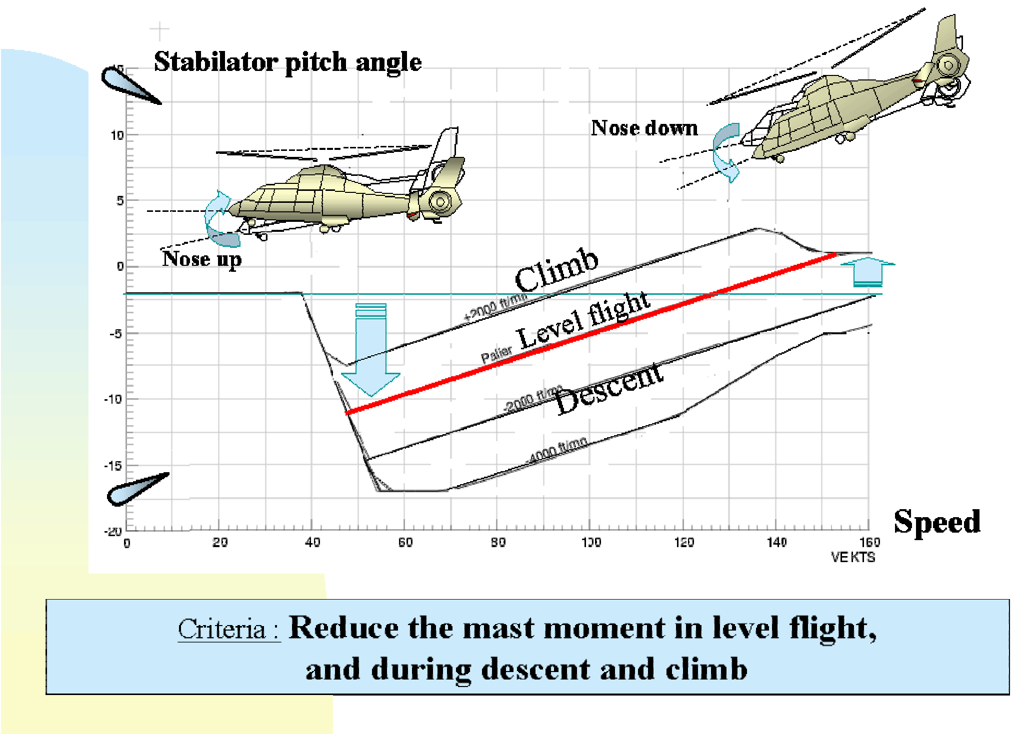

Figure 7: Prescribed stabilator positioning law

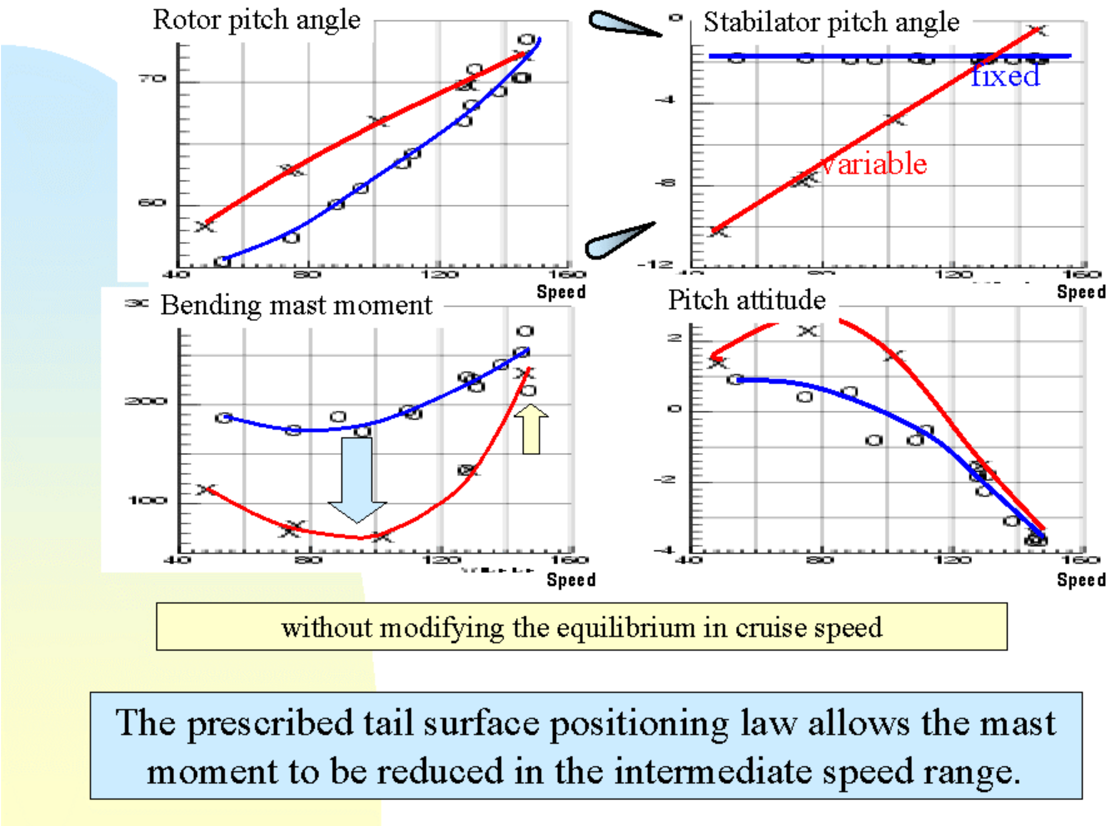

Figure 8: Example of Flight results with prescribed stabilator control law in level flight.

As far as handling qualities are concerned, the pilots have not experienced any difficulty with this law. The stabilizer motion is slow enough and can be anticipated by the pilot.

This tail surface positioning system has the advantage of being simple thanks to the limited number of inputs required by the law. As the architecture of the stabilator positioning system is independent of the piloting system, the stabilator positioning system can be installed on any helicopter, irrespective of whether it has a piloting aid system or not.

As previously stated, this kind of law does not reduce the influence of the centre of gravity position. To overcome this drawback, it would be necessary to include a CG estimate which would considerably complicate the piloting law. Therefore, another law, called "Prescribed rotor positioning" law, was tried out and It has been proved to cancel out the effect of the centre of gravity more easily.

"Prescribed rotor positioning" law

As explained previously, the rotor disk attitude in level flight results from the weight and speed conditions. Within this rotor attitude constraint the stabilizer setting allows the pitch attitude and consequently the longitudinal flapping to be changed, as explained in Figure 9.

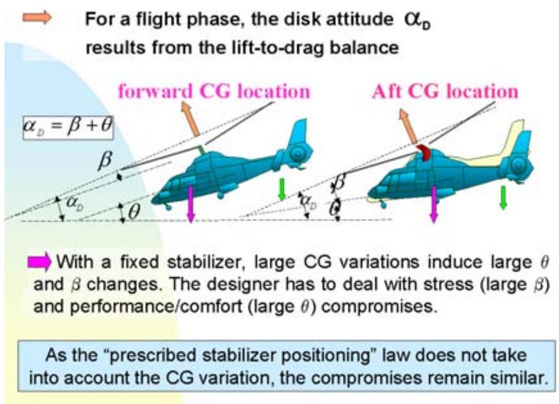

Figure 9: Centre of Gravity effects

If the rotor flapping can be rendered independent of the CG location, the resulting trim will no longer be governed by the CG position.

The longitudinal flapping cannot be easily measured but the stick position can give a good indication. The longitudinal flapping is the sum of the response of the rotor to the longitudinal cyclic pitch and of the flapping due to the forward speed. The latter mainly depends on rotor loading and on speed and is not influenced by the CG position. In a given flight condition, getting the same longitudinal stick position throughout the whole CG range will therefore guarantee the same longitudinal flapping to be reached, figure 10

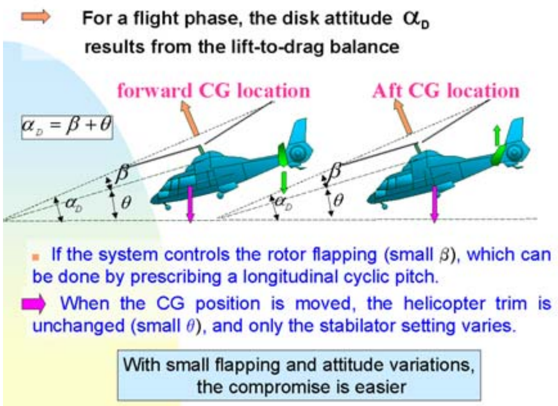

Figure 10: Prescribed rotor positioning law

- <u>Prescribed main rotor longitudinal cyclic law</u>

The prescribed rotor longitudinal position has been computed not only to keep the rotor tilt within a non-damaging range, but also to impose the smallest flight attitude possible in this range. After

an analysis over the whole weight-CG envelope, it has been possible to define a longitudinal cyclic set curve as a function of the forward speed, figure11.

The other parameters considered in the law are the vertical speed and the vertical acceleration. The vertical speed is used to reduce the trim variations with the rate of climb/descent. The vertical acceleration is used to reduce the mast/hub stresses in turns and pull-up manoeuvres.

Flight Test Results

In the same helicopter configuration as for the "prescribed stabilator positioning" law, the mast moment is brought to a very low level in the entire forward speed range while limiting the pitch attitude change. The rotor position complies with the set value, and the stabilizer position adapts to match this objective, as presented figure 12.

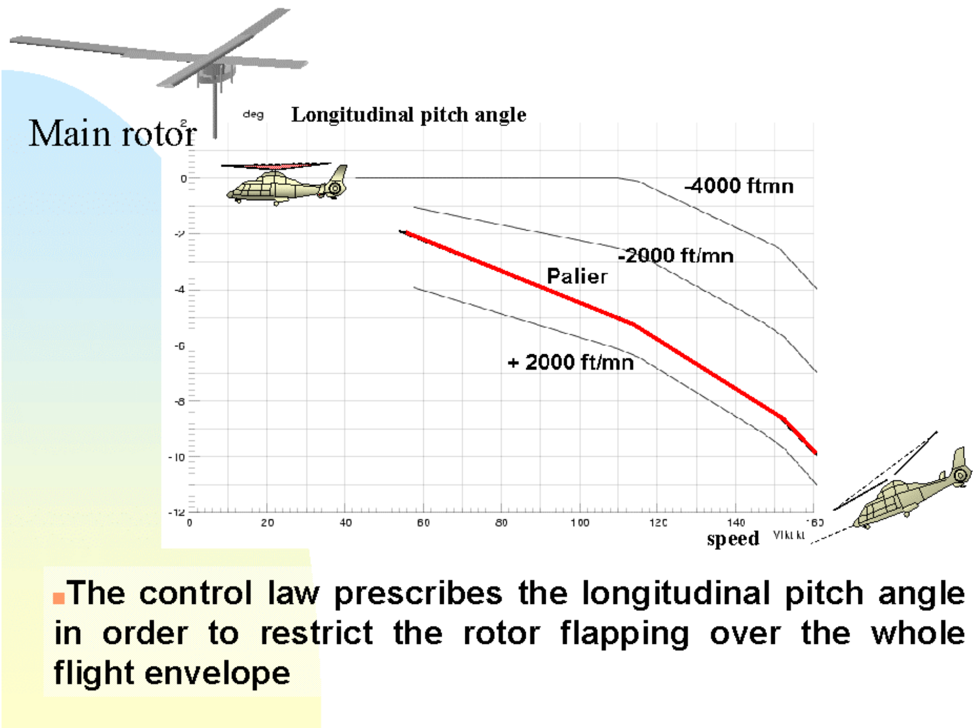

Figure 11: main rotor longitudinal pitch angle prescribed

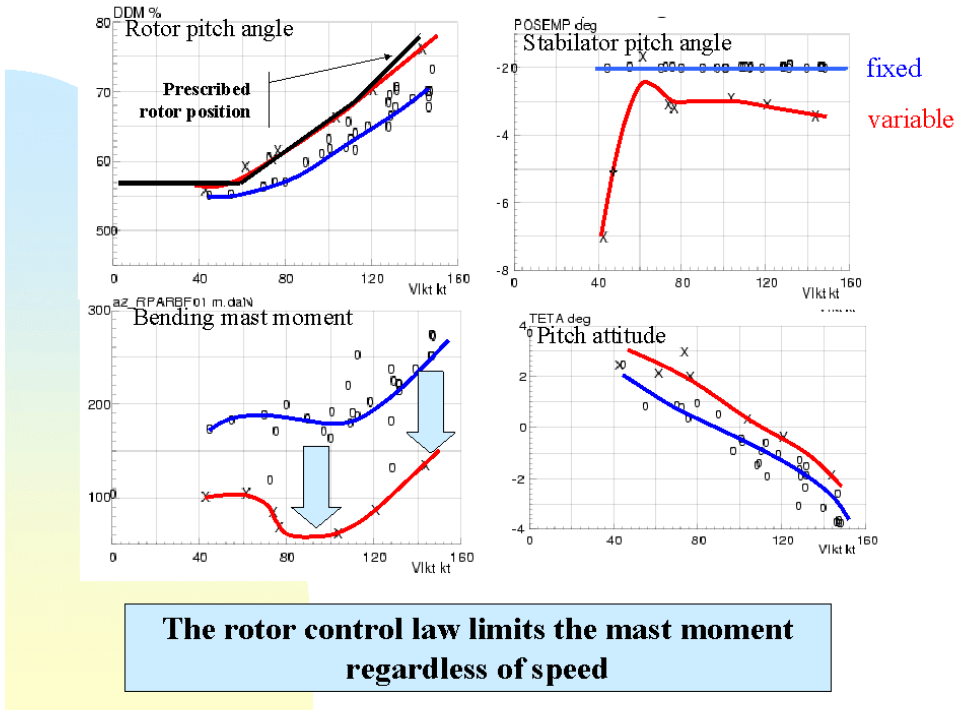

Figure 12: Example of flight results with prescribed rotor positioning law in level flight.

The decrease of the mast and hub stresses is valid throughout a large flight envelope and similar results can be shown for descent and turn phases.

Yaw axis application

The "prescribed rotor positioning" law has been studied on the yaw axis, figure 13.

The purpose of the optimising criteria for the yaw axis, applied to the Dauphin, is to minimise the power consumption.

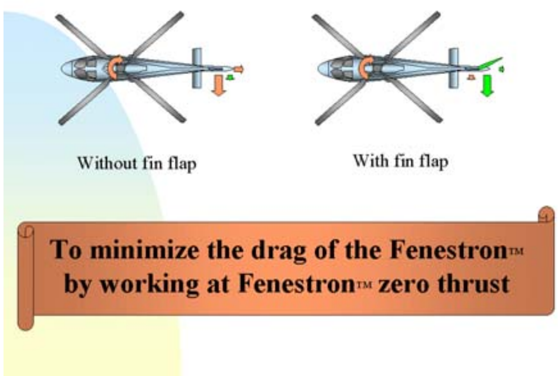

Figure 13: Yaw axis application

On the R&D Dauphin demonstrator the yaw axis trim is reached by using both the fin flap and the Fenestron™ controls.

The interest of the fin flap is linked to a specific Fenestron™ feature: in forward flight the lift-to-drag ratio of the Fenestron™ rotor is poor. A better ratio can be reached with the fin. So, it is much more efficient, from the performance point of view, to counterbalance the main rotor torque in loading the fin rather than the Fenestron™.

This is taken into account when designing a helicopter with a Fenestron™ tail rotor. The fin setting is optimised to minimise the Fenestron™ thrust in high-speed cruise. However this optimisation is only valid for a limited speed range: when reducing the speed the fin lift decreases with the square of this parameter, whereas the main rotor torque is less reduced. It would be necessary to increase the fin setting in order to optimise the performance for intermediate speeds, including Vy, which is of special interest when Cat A performance is considered.

The fin flap allows the fin thrust to be adjusted at any time to cancel the Fenestron™ thrust, and thus minimise its drag. This means a tail rotor pitch close to zero: the optimum operating point was established to be around 5° Fenestron™ collective pitch, as show figure 14. This optimum is roughly constant throughout the flight envelope, regardless of the helicopter's aerodynamic configuration.

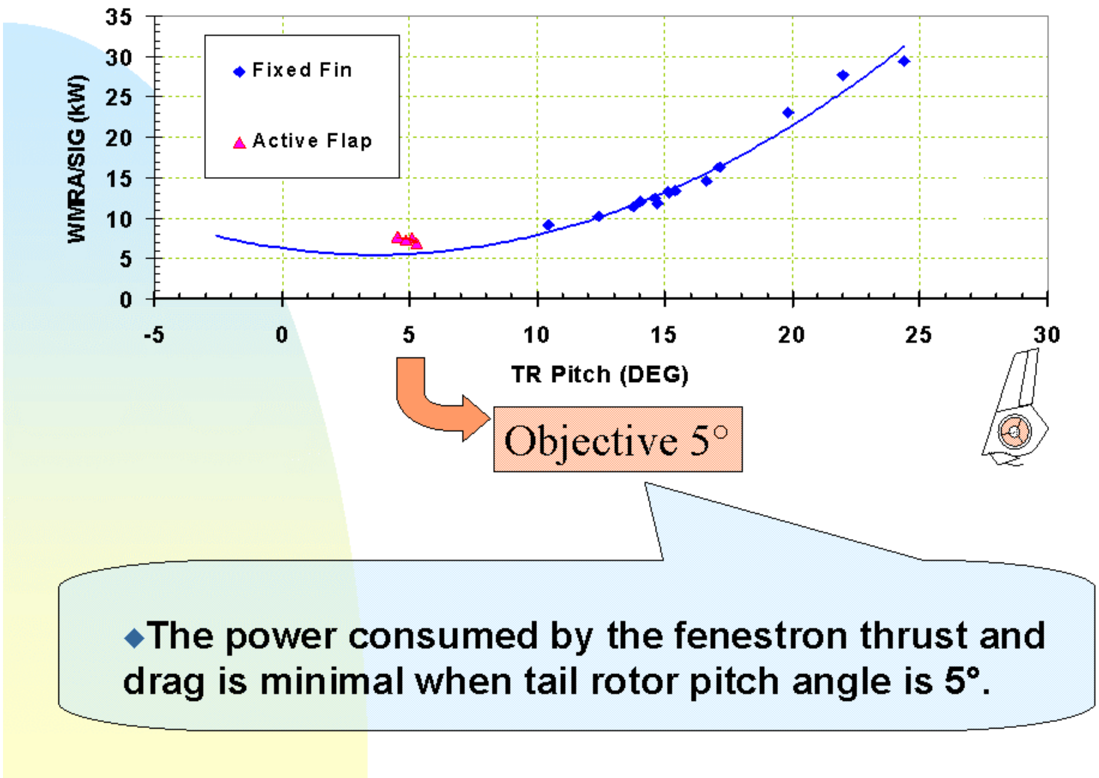

Figure 14: Fenestron™ rotor pitch setting

The "prescribed rotor control" law is therefore well suited to the objective of optimising the performance of a helicopter equipped with a Fenestron™ and a constant prescribed value for the tail rotor pitch can be used.

Flight Test Results

In the flight cases tested, this tail rotor pitch setting resulted in substantial gains in power at the intermediate speeds, as presented figure 15. The gain for 'category A' takeoff is particularly significant because this procedure stipulates a rate of climb of 150 ft/min. at 75 kts. Any gain in power means that the maximum takeoff weight can be increased. The results were corrected for the differences in weight, vertical speed (vz) and sideslip of the various flight test points, and then analysed. Compared to the standard Dauphin, the gain in weight was about 90 kg - equivalent to one passenger, which can be a decisive advantage.

In addition to this gain at the intermediate speeds, the fin flap can be used to optimise the helicopter performance throughout the flight envelope. The flap adapts automatically to changes in the helicopter's configuration as resulting for example from addition of optional equipment.

Synthesis of flight assessments about active surfaces

These flight tests have made it possible to assess different concepts of active tail surfaces on two axes, pitch and yaw.

This experiment has proved that it is possible to meet the objective of mast moment reduction and power reduction without drawback for the handling qualities. The test pilots have not been disturbed by the active tail surfaces. They clearly feel their effects on the flight attitudes but they still control the aircraft flight path without increased workload.

The active tail surfaces have been tested with an active Automatic Pilot. No interference has been noticed between the objective of the Automatic Pilot and the objective of the active tail surface.

Among the tested laws, the "prescribed rotor positioning" law is, by design, more robust, as regards the aircraft configuration variations, as the CG location for the stabilator, as the optional equipment for the fin flap, for example.

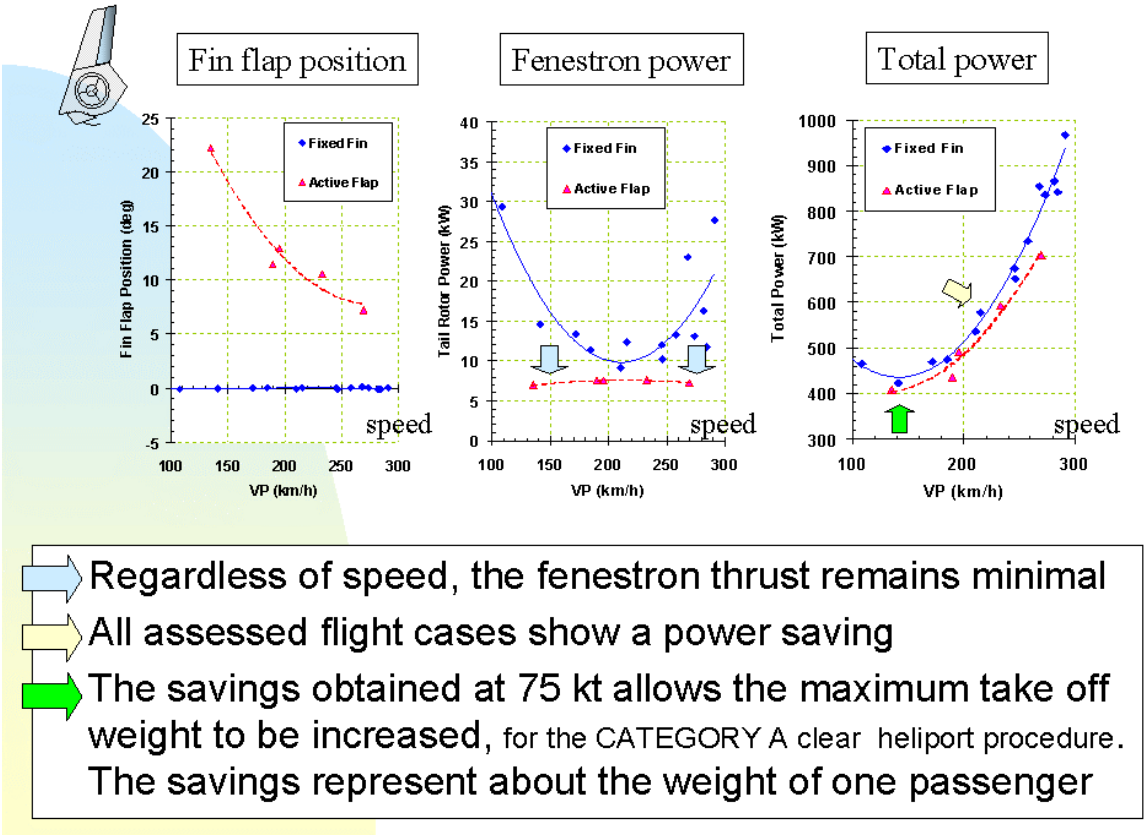

Figure 15: Example of Flight results with the Fenestron™ rotor control law in level flight.

3 CONCLUSION

Eurocopter has experimented, in flight, two controllable tail surfaces: a horizontal stabilizer and a Fenestron™ fin flap with a view to optimising the trade-off between mast moment and aircraft attitudes on pitch axis and performance on the yaw axis.

The demonstration has taken place on the Eurocopter flight system demonstrator, Dauphin 6001, which is equipped with a Fly-By-Wire system. The Fly-By-Wire system controls the two electrical actuators of the active tail surfaces.

Several control laws have been successfully tested as:

- "prescribed tail surface positioning" law,
- "prescribed rotor positioning " law

The latter has been proved more robust as regards aircraft configuration changes.

This experiment confirms the possibility of simultaneously managing two controls on a single axis without disturbing the pilot. It can be applied to a helicopter equipped either with a Fly-By-Wire system or with an Autopilot system.

4 ACKNOWLEDGEMENTS

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