Latest European Achievements
In Tilt-Rotor
Piloted Simulation and Handling Qualities Assessments

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Abstract

This paper describes the tilt-rotor pilot in-the-loop simulations that have been conducted in Eurocopter's SPHERE simulator in RHILP, a Critical Technology Project (CTP) sponsored by the European Union. A generic CTR model, based on the EUROTILT configuration, was created and used to assess the inherent flight characteristics of a Tilt-Rotor in all modes of operation and within the whole altitude/airspeed envelope. Special attention has also been given to the definition of cockpit controls and flight displays for simulation purposes.

A rather simple SCAS structure was found sufficient to achieve safe flight characteristics, i.e. Level 2 HQ, thus allowing the identification of the minimum stability augmentation features that could be included in the high reliability core section of the Flight Control System of a flying demonstrator .

Thanks to the RHILP project simulations, conducted both at the University of Liverpool and at Eurocopter, significant knowledge in Tilt-Rotor flight mechanics and handling qualities has been gained in Europe. The real time simulation environments developed in RHILP will be extensively used for further Tilt-Rotor CTPs, such as ACT-TILT, which is focusing on the definition of a tilt-rotor flight control system to confer Level 1 handling qualities.

Introduction The RHILP (Rotorcraft Handling, Interactions and Load Prediction) project was initiated in the year 2000 within the framework of the 5th EU research programme (Ref.1) and ended in April 2003. The driving objective was to study and assess some critical aspects in the field of tilt-rotor aerodynamics and flight dynamics. Three main areas have been addressed :

- Handling Qualities (HQ) criteria for Civil Tilt-Rotor (CTR)
- Hover and low speed aerodynamic interactional effects
- Structural Load Alleviation (SLA) by active control solutions

The RHILP project has been structured in four technical Work Packages (Fig.1). WP1 to WP3 consisted in developing criteria and models related to each of the selected critical aspects. WP4 consisted to integrate the models and control options produced by previous WPs in a representative simulation environment and then to assess the general flight characteristics of the tilt-rotor in the whole flight envelope.

Two tilt-rotor simulation scenarios have been developed and extensively used during the project. The first one, developed in the FLIGHTLAB-HELIFLIGHT environment at the University of Liverpool, was aimed at supporting the definition of tilt-rotor handling qualities criteria in WP1 (Ref.2,3). The second one, developed in the HOST-SPHERE environment at Eurocopter, has been used to perform the WP4 simulations.

This paper focuses on the piloted simulations performed, as part of WP4, by Eurocopter in the SPHERE simulator.

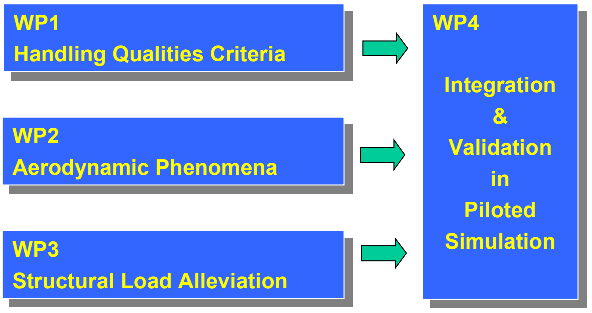

Figure 1 - RHILP Work Packages

The EUROFAR Background

The story of Tilt-Rotor simulation in Europe started more than 10 years ago during EUROFAR, a collaborative study within the Eureka framework at the end of the 80's (Ref.4). At that time, neither tilt-rotor (T/R) flight mechanics models nor simulators were available at Aerospatiale Helicopter Division, (today Eurocopter) and the achievement of the EUROFAR simulations was a real challenge.

At first, it was necessary to develop a T/R simulation code with blade element rotor models that could be run in real time, which was very constraining because computing power available was considerably less than now. This was successfully achieved however by adapting an existing generic helicopter model to the EUROFAR configuration and then by developing a dedicated computing unit to run it in real time.

As no simulator was available at Eurocopter (SPHERE was built in the early 90's), the EUROFAR simulations (Ref.5) have been conducted in EPOPEE, the A320 development simulator located at the Aerospatiale Aircraft Division (today Airbus) premises in Toulouse. This required specific adaptations on the A320 cockpit (Fig.2), such as adding a collective lever and designing T/R-specific flight display symbols.

Simple and robust command-model control laws were developed and introduced in the EUROFAR simulation model. As these control laws were tuned just to rapidly allow a first survey of tilt-rotor flight characteristics, no detailed assessment of EUROFAR handling qualities was performed in the EPOPEE simulator.

Finally, once the integration of EUROFAR simulation in EPOPEE was achieved, several pilots from Aviation Authorities and Industries connected to EUROFAR were invited to Toulouse to familiarise with tilt-rotor flight characteristics. This event constituted the very first T/R piloted simulation in Europe and provided Eurocopter with a useful background experience for developing later RHILP-WP4 simulations in SPHERE.

Figure 2 - View of EPOPEE Cockpit

Tilt-Rotor Simulation Models

Essentially, two T/R simulation models have been used in RHILP : FXV-15 and EUROTILT.

The FXV-15 represents the Bell/NASA XV-15 experimental tilt-rotor which started to fly at the end of 70's and is today still used by Bell for in-flight demonstrations and research. The FXV-15 model was developed from published XV-15 data by the University of Liverpool in the FLIGHTLAB simulation environment. As this model has, to some extent, been validated with respect to real flight data, it was used in RHILP for simulations in support to the development of HQ criteria in WP1 and also for the initial development of SLA control options in WP3 (Ref.6).

EUROTILT is a 10 tons, 19 pax. civil transport tilt-rotor configuration derived from EUROFAR, which has been selected as a baseline for the RHILP studies (Fig.3). A powered wind tunnel model of EUROTILT has been manufactured and tested in WP2 (Ref.8). Finally, SLA control options have also been applied to the EUROTILT configuration.

As this paper focuses on WP4 simulations, all aspects described herein are related to the EUROTILT CTR configuration.

Figure 3 - Artist view of EUROTILT

The SPHERE Simulator

SPHERE is the Eurocopter R&D simulator. Since its opening in 92, it has been extensively used for the development of the NH90 systems, in particular the Fly-by-Wire flight control system, as well as for many research activities dealing with advanced flight control laws and man machine interfaces (MMI) studies. It should be highlighted that, among the very first simulations conducted in SPHERE, a preliminary assessment of T/R steep approach capabilities was conducted with the EUROFAR model.

The main characteristics of SPHERE are summarised below :

- Fixed-base cockpit in 8 m diameter dome
- 6 channels image projection system
- 180° H x 80° V Field-of-View
- Wide terrain data base (90 x 65 Km) representing the actual Marignane area
- 2 cockpits : NH90 and Research Cockpit
- Configurable flight displays
- Conventional and sidearm controls with adjustable force-deflexion characteristics

Regarding Tilt-Rotor simulation, and more generally the rotorcraft handling qualities assessments, the strong points of SPHERE are the wide field of view and the adjustable control force feel system :

- The wide field of view provides the pilot with good visual cues in hover and low speed flight, as required for reliable HQ assessments. In particular the 80° in vertical allows the pilot to keep a good perception of the speed vector even for large angle of attack manoeuvres (e.g. final deceleration to hover).
- The force feel system is fully adjustable and can be set to model any kind of force-deflexion law, this for each control (central stick, sidestick, pedals and collective).

  Moreover, these characteristics can be adjusted in real time, thus making the force feel law depend on flight conditions (e.g. stiffening control forces when airspeed increases).

Cockpit controls and displays

Travels and forces of the SPHERE research cockpit controls (Fig.4) have been adjusted to provide adequate tactile cues in all modes of operation. Hover and low speed flight requires preferably low control forces, as on current helicopters, with a trim release option for quick re-centring. Conversely, cruise in airplane mode requires relatively high control forces to prevent for oversensitive responses and inadvertent exceedance of structural limits. Therefore, it was necessary to find an acceptable compromise to meet both helicopter (H/C) and airplane (A/C) mode requirements. This was achieved rather easily for roll and yaw control forces but not for pitch. Indeed, as explained later, it appeared necessary to make the spring gradient dependent on airspeed.

The conversion logic and its controls have been directly derived from EUROFAR simulation. Typically, two conversion control buttons are available on the collective grip. The first one is a four-way coolie-hat switch whose fore and aft positions command continuous nacelle tilting at 4°/s. The second one is a fore and aft pulse switch commanding nacelles motion between pre-set angles.

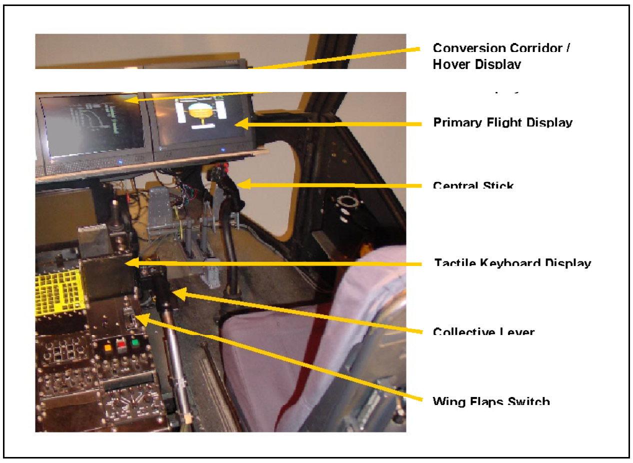

Figure 4 - Cockpit Controls

Symmetric deflection of flaperons for lift augmentation is commanded manually by a paddle switch on the central console. Furthermore, to decrease the wing download (rotor-to-wing interaction), flaperons are automatically set at 60° when flying at low speed in H/C mode.

Flight information is presented on two 12.5”x10” LCD flat displays (Fig.5). The Primary Flight Display (PFD) includes ADI, scrolling bands for IAS, altitude and heading, and a nacelle angle indicator. The Navigation Display (ND) is used to present the T/R status in conversion corridor, as well as other parameters such as load factor, true airspeed, rotor RPM, flap setting, blade flapping angles, engines power and collective pitch.

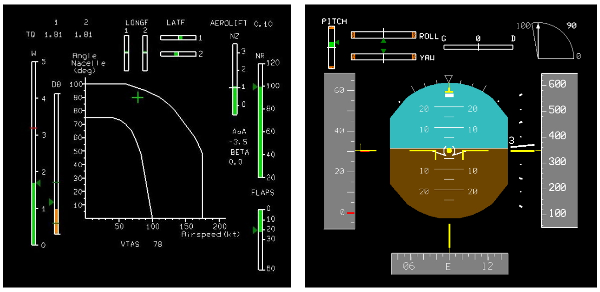

Figure 5 - Flight Displays

Flight Mechanics Model

The flight mechanics model HOST (Ref.7), developed by Eurocopter, ONERA and DLR, is the standard code for all simulations in SPHERE. It has therefore been used in RHILP to model the EUROTILT configuration and then perform the WP4 simulations.

As HOST is a generic helicopter model with a modular structure, some adaptations were necessary to model the EUROTILT CTR configuration. Typically the following additional models were incorporated in HOST :

- Aerodynamic control surfaces (elevator, rudder and flaperons)
- Nacelles model (inertial and aerodynamic)
- Wing-to-horizontal stabiliser deflection
- Basic controls mixing for initialisation purposes (taken in charge by the control laws when simulation running)

In addition to these adaptations that were made at the very beginning, aerodynamic interaction models developed in RHILP WP2 (Ref.8, 9) have been incorporated as soon they were available, in particular :

- Rotor-to-wing interaction model depending on flaperon deflection angle and height over ground
- Ground effect model

For both rotors, the HOST blade element model option was used. To obtain a reasonable compromise between model accuracy and computation time, a 10 ms sampling period with 7 sections per blade was selected.

Basic Control Laws and SCAS

In terms of controllability and handling qualities, the objectives of RHILP were to assess the characteristics of the bare (unaugmented) EUROTILT model, then to define the minimum stability and control augmentation structure (SCAS) required for achieving safe flight in the whole flight envelope. Consequently, the control structure defined in RHILP WP4 is, to some extent, representative of the high reliability core section of a Fly-by-Wire (FBW) Flight Control System (FCS).

EUROTILT basic control laws include the usual (XV-15 like) tilt-rotor control mixings and the power/thrust management. The SCAS was designed and tuned to meet Level 2 HQ, according to the criteria proposed by WP1. Off-line analysis of EUROTILT model dynamics showed that Level 2 could be achieved with relatively few augmentation features, typically :

- Angular rates feedback (SAS) in pitch, roll and yaw, with gain scheduling versus airspeed
- Control quickener in yaw for hover and low speed flight in H/C mode

In the simulator, a tactile keyboard allows the pilot to engage / disengage the SCAS on each axis and at any time. This independent selection of SCAS lanes greatly facilitates the assessment of on-axis responses by providing stabilisation on other axis.

Flying the EUROTILT model

The first step consisted in assessing the flight characteristics of the bare EUROTILT model. As none of the invited pilots had a previous tilt-rotor flight experience, excepted for those having flown the FXV-15 simulation before in Liverpool, trials started cautiously with the 3-axis SAS engaged to allow an easier familiarisation with the specific flight characteristics of the tilt-rotor. After a short period of training, all pilots were capable of handling the model satisfactorily in H/C, conversion and A/C modes. However, jerky manoeuvres were sometimes noticed, mainly because of control strategy mistakes or(and) overcontrolling. Typically, a common mistake was to accelerate in H/C mode using a helicopter strategy, i.e. pitching down the fuselage, thus generating large negative wing lift, whereas forward nacelle tilt shall be used to accelerate while keeping a level attitude.

Once familiarisation was completed, pilots were asked to assess the Handling Qualities of the EUROTILT model. Because of lack of time, only two test manoeuvres, hover repositioning and slalom in H/C mode, were defined and used for quantitative HQ assessment (HQR). Other Mission Task Elements (MTEs) have been assessed qualitatively.

Hover repositioning is directly derived from the Precision Hover of ADS-33 (Ref.10). Position cues are provided by a set of poles enabling the pilot to see whether he meets the desired or adequate performance. Flying this manoeuvre in the SPHERE simulator is known to be very demanding and exposes any PIO tendencies.

The slalom is based on the Lateral Jinking test course (Fig.6) which was developed in the 80's within the ACT collaborative project (Ref.11). The reference speed, initially set to 60 Kt for the aggression level of an attack helicopter, has been reduced to 50 Kt for EUROTILT simulation assessment purposes.

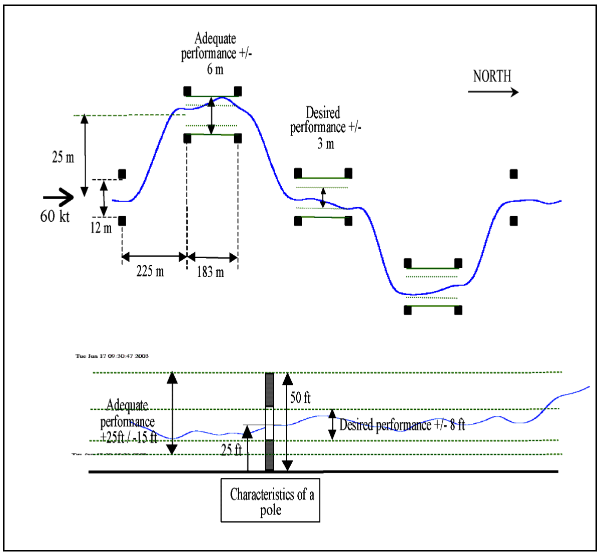

Figure 6 - Slalom Course

Hover & Low Speed in H/C mode

Hovering close to obstacles was rather easy to achieve, even if a PIO tendency in pitch was always noticed when SAS OFF. However, for higher precision tasks such as the hover repositioning manoeuvre, the PIO tendency became significant in pitch, roll and heave with SAS OFF, and the bare EUROTILT model was rated HQR 5 - 6.

Once the SAS were engaged on all axes, pilots were able the achieve the desired precision with a moderate workload (HQR 4).

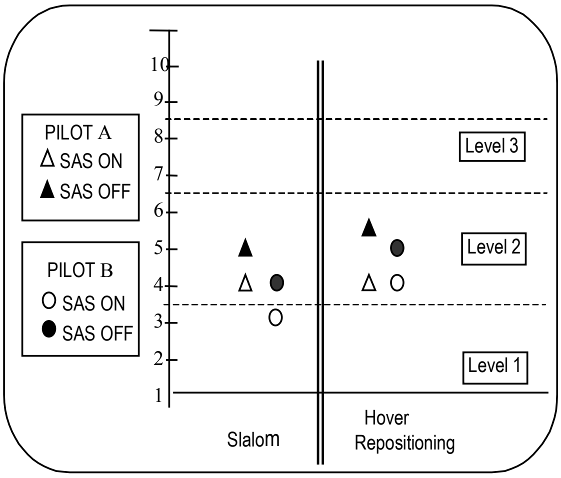

Figure 7 - HQ Ratings in H/C Mode

The yaw and heave responses have been assessed qualitatively through the respective achievements of hovering turns and vertical steps near obstacles. For both manoeuvres, pitch and roll SAS were engaged to minimise the workload on the axes not submitted to the pilot assessment.

The yaw response was judged very sluggish and, once the yaw rate was established, a large amount of control anticipation was required to stop the rotation. This is a well known inherent characteristic of tilt-rotors due to their large inertia and poor aerodynamic damping in yaw. However, this objectionable behaviour mainly occurred during large amplitude rotations whereas small and precise heading were easily achieved. With both the yaw SAS and Control Quickener engaged, the yaw response characteristics was found to be adequate, even for large amplitude hovering turns.

The heave response was also judged sluggish but, in a similar way to the yaw axis, small and precise height changes were nevertheless easy to achieve. The ground effect model was judged realistic when performing vertical landings. The effect of flaperon setting angle on rotor-to-wing download was seen to be consistent with off-line simulation predictions.

Forward flight in H/C mode

The slalom manoeuvre was used. Although this test course is designed to capture roll axis HQ, it also exercises height, speed and turn co-ordination control.

Even with SAS OFF, the handling qualities have been rated in the Level 2 area (HQR 4 - 5). With SAS ON, the EUROTILT model was rated on the Level 1 / Level 2 boundary (HQR 3 - 4).

Some specific behaviours were also noticed during free flight assessments, in particular :

- Adverse apparent dihedral effect on rudder inputs. This is also a well known characteristic of tilt-rotors which is due to the use of differential longitudinal cyclic for yaw control. Although such behaviour is definitely not allowed by current airworthiness regulations for helicopters (FAR/JAR 29), it was never judged hazardous by the pilots and consequently should be allowed for tilt-rotors when flying in FCS back-up mode.
- A significant decrease of pitch damping in steep climb conditions, thus requiring to switch on the pitch SAS to restore acceptable HQ, whereas the bare model was flyable with moderate workload in level flight.
- Trouble with the rotor RPM governor when lowering sharply the collective pitch. Similar behaviour was also noticed at the University of Liverpool with the EUROTILT FlightLab simulation model. After many investigations, it appeared to be a rotor modelling issue rather than a real physical phenomenon. The problem has been temporarily fixed, both on SPHERE and HELIFLIGHT, by constraining the outboard blade sections to keep a constant drag coefficient (Cd) for negative incidences. An induced flow model better adapted to highly twisted rotors in descent would very likely be necessary to allow the use of true Cds in the whole incidence range.

Conversions

Many conversion and re-conversion manoeuvres have been achieved in the SPHERE simulator, both SCAS OFF and SCAS ON, without major difficulties. Conversions were usually initiated from a 80° nacelle angle / 80 Kt trim point. The objective assigned to the pilot was to keep a level altitude throughout the manoeuvre. Once 0° nacelle angle was reached, flaperons were manually retracted to the clean configuration (0° setting angle) and then the rotor RPM lowered to 80%.

Conversions / re-conversions were judged rather easy to achieve, the most noticeable effect being large trim changes in pitch which the pilot has to compensate to keep a level altitude. Typically, a progressive stick pull back was required at the end of the conversion to avoid altitude loss (Fig.8). Conversely, stick forward was required during re-conversion to compensate a ballooning tendency.

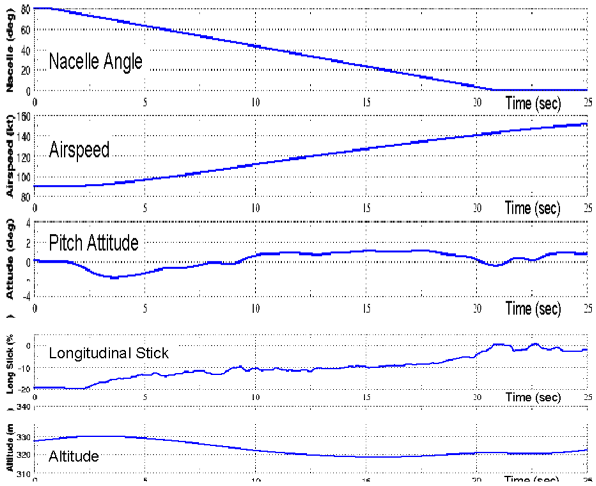

Figure 8 - Conversion Time History

Airplane mode

The full airspeed / altitude envelope has been explored, from stall conditions to design cruise speed (300 Kt TAS, 25,000 ft). As soon as the first assessments were made at low altitude, the bare EUROTILT model appeared to be definitely oversensitive in pitch and poorly damped in yaw. When increasing altitude, this behaviour worsened and beyond 10,000 ft the Dutch-Roll became divergent, thus making the model unflyable. Therefore, off-line analysis using HQ criteria produced by WP1 have been conducted to identify solutions for restoring an acceptable behaviour (Level 2 HQ).

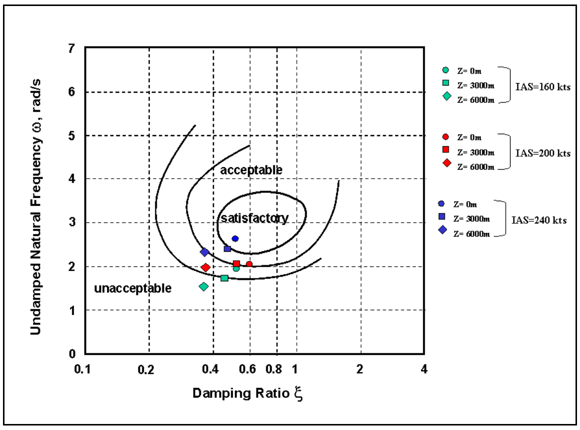

Figure 9 - Thumbprint Criteria

According to the thumbprint criteria (Fig.9), the model short term dynamics in pitch should produce acceptable HQ at sea level. It was then suspected the oversensitivity was related to control forces rather than stability. After several iterations, it was found that stiffening the spring force by a factor of 4 was necessary to restore an acceptable sensitivity in pitch at sea level. Control forces in pitch were therefore made dependent on airspeed.

However, the thumbprint criteria also shows that both stiffness (undamped natural frequency) and damping in pitch are insufficient in high altitude cruise. During the piloted simulations, switching on the pitch SAS was judged sufficient to provide Level 2 HQ in cruise but enlarging the stabiliser area could be another option.

Regarding lateral-directional characteristics, the Evans-plane confirmed the divergence of the Dutch-Roll mode beyond 3000 m (10,000 ft) altitude (Fig.10). The use of a yaw SAS was a straightforward solution to fix the problem and to restore Level 2 HQ in high altitude cruise (Fig.11). Pilots confirmed that the activation of the yaw SAS was sufficient to provide adequate lateral-directional characteristics in the whole airplane mode flight envelope. Consequently, the yaw SAS is considered a mandatory stabilisation feature for the EUROTILT model, i.e. to be incorporated in the high reliability FCS core section.

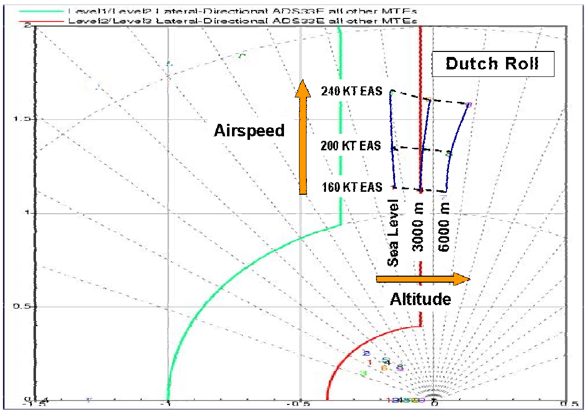

Figure 10 - Evans Plane

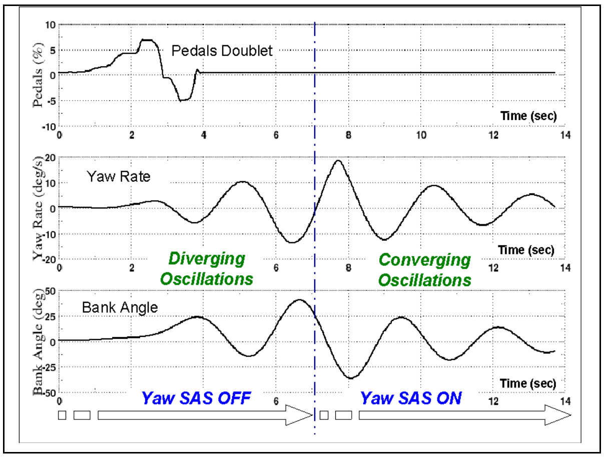

Figure 11 - Dutch-Roll Stabilisation

Finally, following the stiffening of pitch control forces and the activation of pitch and yaw SAS, the pilots judged the EUROTILT HQ in airplane mode sufficient for flight in FCS back-up mode.

Concluding Remarks

Within the frame of the RHILP project, Europe took a major step forward in tilt-rotor knowledge, and in particular in tilt-rotor flight mechanics modelling and simulation.

Thanks to the previous experience gained in EUROFAR end of the 80s, and the contributions of other RHILP work packages, a valuable tilt-rotor real-time simulation environment has been developed at the University of Liverpool and at Eurocopter.
As expected from the beginning of the RHILP project, pilot in-the-loop simulation was realised as the most efficient way for exploring rapidly and exhaustively the flight envelopes of new air vehicles having multiple flight configurations, such as the tilt-rotor. Typically, it was seen that piloted simulation allows the engineers to detect most of the model deficiencies almost immediately, when they arise, and provides useful clues for corrective actions. In comparison, extensive off-line simulations are usually required to achieve a similar level of knowledge.

The bare EUROTILT simulation model was judged flyable by the pilots in all modes of operation, i.e. helicopter, conversion and airplane mode, except in high altitude cruise condition.

The minimum stability and control augmentation features necessary to provide safe flight characteristics in case of degraded FCS operation have been identified. A rather simple SCAS structure, but with gains scheduled versus airspeed, was found sufficient to provide Level 2 Handling Qualities in the whole flight envelope.

Further piloted simulation assessments are currently being conducted within the frame of ACT-TILT, a sister project of RHILP focusing on CTR FCS design and the achievement of Level 1 Handling Qualities in normal FCS operation.

Acknowledgement

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REFERENCES

1. Ph. Rollet: *“RHILP - A major step for European Knowledge in Tilt-Rotor aeromechanics and flight dynamics”*, Aeronautics Days 2001, Hamburg, Germany, Jan 29 - 31, 2001

2. Meyer, M., Padfield, G.D., *“First Steps in the Development of Handling Qualities Criteria for a Civil Tilt Rotor”*, 58th American Helicopter Society Annual Forum, Montreal, June 2002
3. Meyer, M., Padfield, G.D., Haverdings, H., Taghizad, A., Naddei, M., *“Civil Tilt Rotor Handling Qualities”*, 29th European Rotorcraft Forum, Friedrischshafen, Germany, Sept. 2003
4. Renaud, J., Huber, H., Venn, G., The EUROFAR program; *“A European Overview on advanced VTOL civil transportation system”*, 17th European Rotorcraft Forum, Berlin, Germany, 1991
5. Rollet, Ph., Thibaudat, C., *“EUROFAR simulation trials on EPOPEE simulator”*, 18th European Rotorcraft Forum, Avignon, France, Sept. 1992
6. Manimala, B., Padfied, G.D., Walker, D., Naddei, M., Verde, L., Ciniglio, U., Rollet, Ph., Sandri, F., *“Load Alleviation in Tilt-Rotor Aircraft through Active Control Modelling and Control Concepts”*, 59th American Helicopter Society Annual Forum, Phoenix, May 2003
7. B. Benoit, A.-M. Dequin, P.-M. Basset, B. Gimonet, W. von Grunhagen, K. Kampa *"HOST, a general helicopter simulationtool for Germany and France"*, 56th A.H.S. Annual Forum, Virginia Beach (US), May 2000
8. Desopper, A., et al*., “Study of the Low Speed Characteristics Of a Tilt Rotor”*, 28th European Rotorcraft Forum, Bristol, UK, Sept. 2002
9. Heuzé, O., Diaz, S., Desopper, A., *“Simplified models for tiltrotor aerodynamic phenomena in hover & low speed flight”*, CEAS Aerospace Aerodynamics Research Conference, Cambridge, UK, June 2002
10. Anon. “Aeronautical Design Standard, Performance Specification, Handling Qualities Requirements for Military Rotorcraft”, ADS-33E-PRF”, United States Army Aviation and Missile Command, Aviation Engineering Directorate, Redstone Arsenal, Alabama, USA, March 2000
11. Charlton, M., Guyomard, C., Lane, R., Mödden, H., Schimke, D., Taghizad, A., *“The European ACT Programme: A Collaborative Approach to Handling Qualities Evaluation and Control Law Design”*, 49th AHS Annual Forum, St Louis, May 1993