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WIND TUNNEL HIGH SPEED POWERED TESTS OF THE ERICA TILT ROTOR MODEL IN S1MA - NICETRIP PROJECT

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ABSTRACT

The present paper aims at presenting the wind tunnel high speed tests of the ERICA tilt rotor model in the ONERA S1MA wind tunnel. These tests have been performed in May 2014 on a 1/5th scaled powered model. The whole high speed range has been covered, from M=0.176 to M=0.55, for both aircraft and conversion configurations. In order to complete the high speed tests successfully, several checks have been performed on this very complex model during the preparation phase. The experimental data gathered during the tests allowed the assessment of such a tilt rotor concept in high speed flight conditions.

NOMENCLATURE

AoA	Angle of Attack (°)
AC	Aircraft Configuration
CC	Conversion Configuration
ERICA	Enhanced Rotorcraft Innovative Concept Achievement
M	Mach number
NICETRIP	Novel Innovative Competitive Effective Tilt Rotor Integrated Project
RPM	Rotor rotational speed (Revolutions Per Minute)
TAS	True Air Speed (m.s^{-1})
γ	Glide slope angle (°)

1 INTRODUCTION

Within the framework of European research programs, the NICETRIP project aims at building a flying demonstrator of a European civil tilt rotor aircraft. Previous American projects like FS TRAM studied various aspects of the tilt rotor concept [1]. Previous European projects like DART, TRISYD, TILTAERO, ADYN and ACT-TILT resulted in the definition of the ERICA concept. Aerodynamics studies ([2] to [7]) and wind tunnel testing ([8], [9]) were therefore requested to prove the liability of the ERICA concept with respect to low speed interaction and high speed performance, in order to freeze the general architecture, flight control system and flight control laws and determine the operational performance.

The wind tunnel tests have been performed on a 1/5th scaled powered model and covered a wide range of flight envelope points, from low speed helicopter configuration to high speed aircraft configuration through conversion configuration. The wind tunnel test campaigns have been split into two parts: one low speed test campaign performed in June and July 2013 in DNW-LLF wind tunnel facility in the Netherlands and one high speed test campaign performed in May 2014 in the ONERA-S1MA wind tunnel facility in France.

The main objectives of the high speed tests were the determination of the aerodynamic interactions and the rotor performance between Mach number M=0.176 (minimum speed in aircraft configuration) and M=0.55 (maximum speed in aircraft configuration).

More than 140 data points have been recorded during this test campaign. The model was heavily instrumented and largely remotely controlled, allowing performing several data points without any mechanical change of model configuration. Trimming points have been performed and variations of collective pitch and movable surfaces like flaps, flaperons, rudder and elevator have been tested. Incidence and sideslip sweeps have also been performed for "blade on" and "blade off" configurations.
The current paper focuses on the means and techniques involved for the success of the high speed test campaign of the ERICA model in ONERA S1MA wind tunnel and the preliminary analysis of the acquired database.

2 ONERA S1MA WIND TUNNEL

The S1MA wind tunnel is the largest facility of its kind in the world. It is located in Modane in the French Alps. It is an atmospheric continuous flow wind tunnel, allowing a Mach range from M=0.05 to M=1 in a test section of 8 meters in diameter and 14 meters long (Figure 1).

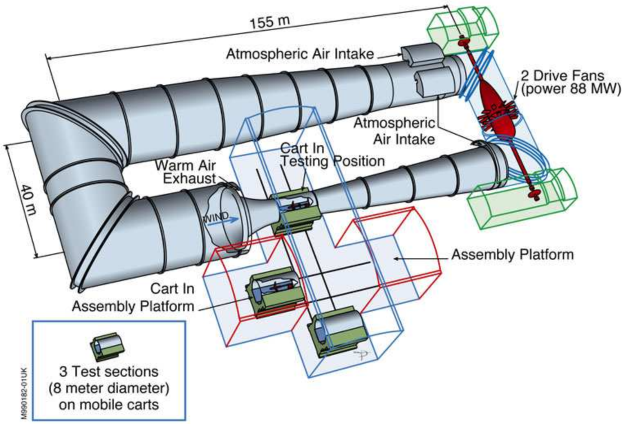

Figure 1. ONERA S1MA aerodynamic circuit

Figure 2. ONERA S1MA contra-rotating fans

The wind is generated by two contra-rotating fans (Figure 2) driven by two Pelton turbines developing a maximum power of 88MW. These turbines are driven directly by water routed through a channeled waterfall of 850m in height.

The size of the facility enables testing large full models with typical wing span of about 4 meters, for better representation of real aircrafts (Figure 3).

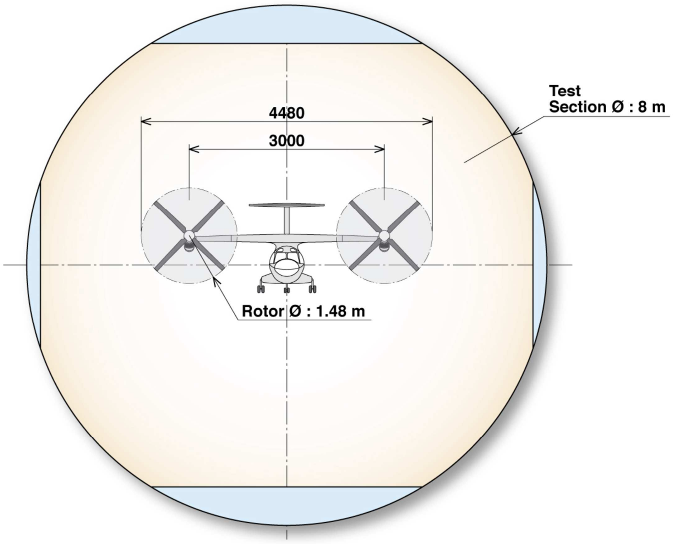

Figure 3. Front view of the ERICA model in S1MA

The models are generally fully equipped with sensors for force, pressure and temperature measurements. Due to the area of the test section, the blockage of the model is low (often less than 0.5%, about 1.5% in case of NICETRIP tests), leading to small wall effect corrections compared to other transonic wind tunnels.

3 TEST PREPARATION

3.1 ERICA model

The ERICA model is a 1/5th scaled powered model of a tilt rotor aircraft. As shown in Figure 4, it consists of:
- one fuselage and one T-tail;
- one inner fixed wing;
- two tiltable outer wings (remotely controlled from 0° to 90°);
- two tiltable nacelles (remotely controlled from 0° to 90°);
- two rotors (one spinner and four blades);
- movable flaps, flaperons, rudder and elevator;
- rotor collective and cyclic pitch angles (by means of a swashplate for each rotor).

The ERICA model is highly equipped with measurement sensors and remote controls to allow acquiring a full set of data during the wind tunnel test campaigns.
The measurements are:
- loads and moments (one 6-component main balance, two 6-component rotor balances, one 6-component tail balance, six 1-component hinge moment balances),
- pressures (672 static taps and 54 dynamic taps);
- vibrations (nacelle 3-axis accelerometers);
- model attitude (goniometers);
- rotor RPM.

In addition to these measurements, several sensors were used for the safety monitoring of the model during the wind-on runs among which:
- blade bending torsion gauges;
- shaft bending and torsion gauges;
- gearbox temperatures;
- lubrication oil and water temperatures;
- engine accelerometers.

Figure 4. ERICA model

3.2 Test set-up

The model was installed on a model support inside the cart #2 of the S1MA wind tunnel (Figure 5). The model support allows covering an incidence range from -10° to +35° and a sideslip range from -10° to +10°. The wall effect and sting effect corrections were determined prior to the tests.

The model was fed with:
- pressurized air for the engines inside the nose;
- oil for the lubrication of the main gearbox;
- water for the cooling system of the three gearboxes;
- power supply for the balance heating system, motors actuating movable surfaces and swashplates, amplifiers.

Figure 5. ERICA model in the S1MA wind tunnel

3.3 Preparation phase in the S1MA assembly stand and the engine test bench

The model was delivered three months before the entry in the ONERA S1MA wind tunnel. The preparation phase in the assembly stand lasted 1.5 months. During that preparation phase, the following activities were fulfilled:
- mounting of the model on S1MA sting;
- cabling between the model and the facility;
- oil / water / air circuit sealing tests;
- load and pressure measurement checks;
- calibration of the pitch angle sensors.

An amount of 36 cables (Ethernet, power supply, measurements) and 14 pipes (oil, water and air) were routed by the rear part of the model.
Figure 6 shows the ERICA model mounted on its support in the assembly stand, while ONERA staff works on the cabling and the pressure measurement checks.

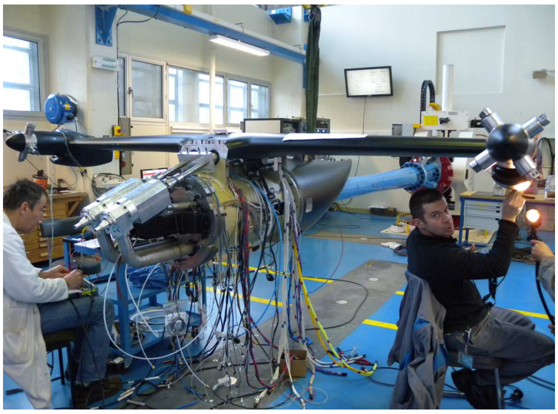

Figure 6. Preparation in the S1MA assembly stand

Figure 7. ERICA model in the S1MA engine test bench

After the preparation phase in the assembly stand, a period of 1.5 months was dedicated to the preparation in the engine test bench. The S1MA engine test bench is a part of the S1MA facility which allows preparing a model outside the aerodynamic circuit, with several possibilities in terms of pressurized air supply (up to 80 bar for the ERICA model) and data acquisition system.

The main goals of that part of the preparation were:
- calibration of the load measurement corrections due to the pressurized air interactions;
- wind-off runs up to 2500 RPM (with blade cuffs) to check the behavior of the lubrication system.

Figure 7 shows the model in the engine test bench mounted on its support with the pressurized air supply connection.

4 TEST MATRIX AND TEST PERFORMANCE

The S1MA NICETRIP test matrix was defined to cover the whole AC range, from M=0.176 (AC1) to M=0.55 (AC3) and the end of the conversion corridor at M=0.176 with the nacelles tilted at 30°. Figure 8 shows the test matrix with the nacelle angle vs. TAS. The rotational speed of the rotors was defined at 2130 RPM for the AC mode and 2765 RPM for the CC mode.

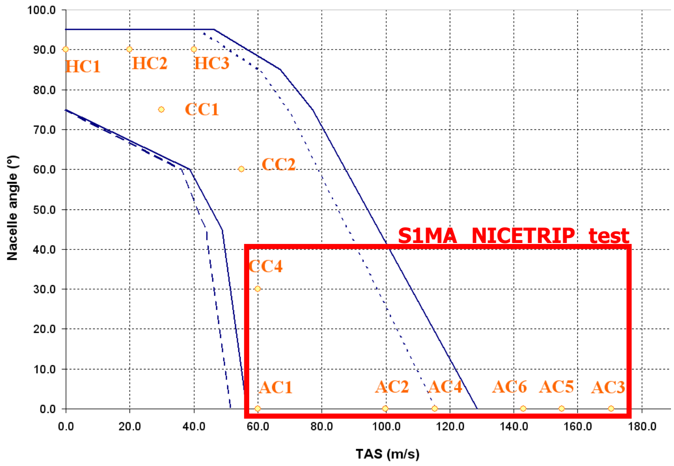

Figure 8. S1MA NICETRIP test matrix

For each flight condition, the objective was to perform:
- one trimmed data point with blades,
- one collective pitch sweep,
- one model incidence sweep,
- one model sideslip sweep,
- some other actuator sweeps,
- one trimmed data point with cuffs (blade off).

The trimming is obtained at given lift and rotor rotational speed by adjusting the global loads and moments to zero. Then the sweeps are performed only by adjusting one parameter. So as to reach the first trimmed point, the following sequence was implemented in a "human closed loop":
- starting of the rotors up to around 1000 RPM;
- starting of the wind tunnel;
- adjustment of the swashplate by step of 2°;
- adjustment of the rotational speed of the rotors, the Mach number and the collective pitch angle step by step;
- final adjustment of the rotational speed of the rotors, the collective pitch angle and the model incidence.

Then the acquisition is synchronized with the rotor rotational speed and is performed over 100 revolutions at a rate of 128 data points per revolution (12800 micro data points).

The initial test matrix consisted in 141 data points. Due to some limitations of the model mechanics, 7 data points were not performed. However, 13 data points were added by the customer during the wind-on tests. Thus, 147 data points were acquired in 13 runs in a period of 4 days (32 hours).

5 RESULTS

The data processing can be divided into two parts:

- the real-time data processing, done by ONERA staff during the wind tunnel test, which allows the test team monitoring and piloting the model and the wind tunnel, and the customer checking the parameters on its model (loads, pressure,…) and adjusting the test matrix accordingly,
- the data post-processing, done by ONERA staff and/or by the customer after the wind tunnel tests, which allows a deeper analysis of the measurements (vibrations, high speed assessment).

5.1 Loads and pressure distributions

Loads were measured on the model by means of several balances (main balance, rotor balances, tail balance, hinge moment balance on each movable surface). Figures 9 and 10 show examples of results processed during the tests, concerning the effect of the variation of AoA on the model lift and the variation of sideslip angle on the model side force at M=0.5 and M=0.55.

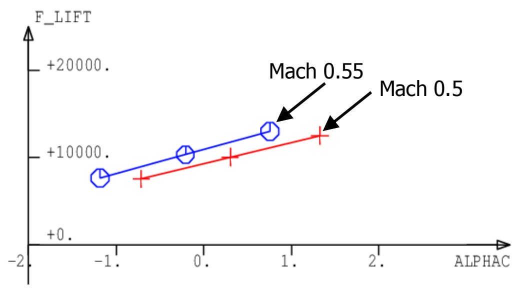

Figure 9. Global lift vs. angle of attack

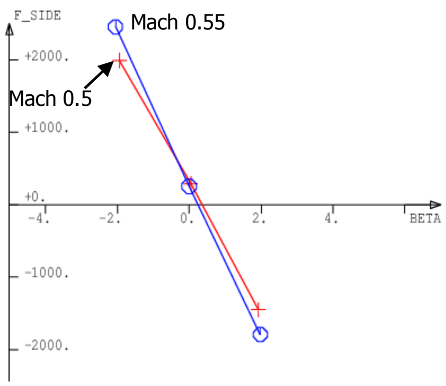

Figure 10. Global side force vs. sideslip angle

Figures 11 and 12 show the effect of the variation of angle of the movable surfaces (elevator and rudder) on the model loads (pitching moment and yawing moment respectively) at M=0.55. The model motorizations allowed performing these variations in one run around the nominal conditions.

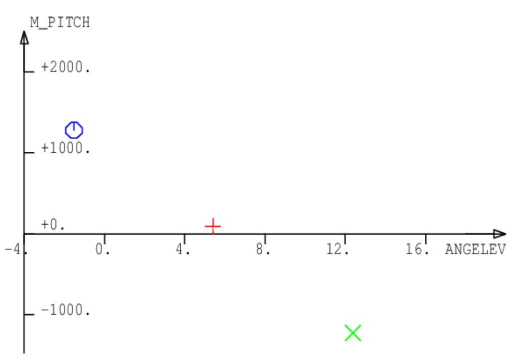

Figure 11. Pitching moment vs. elevator angle

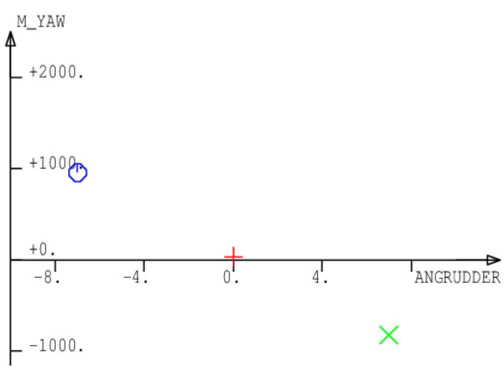

Figure 12. Yawing moment vs. rudder angle

Figure 13 shows the Mach effect on the pressure distribution on the fuselage top line between M=0.176 and M=0.55 for the nominal conditions. The nominal conditions are γ=0° from M=0.176 up to M=0.441, γ=-4° at M=0.5 and γ=-8° at M=0.55.

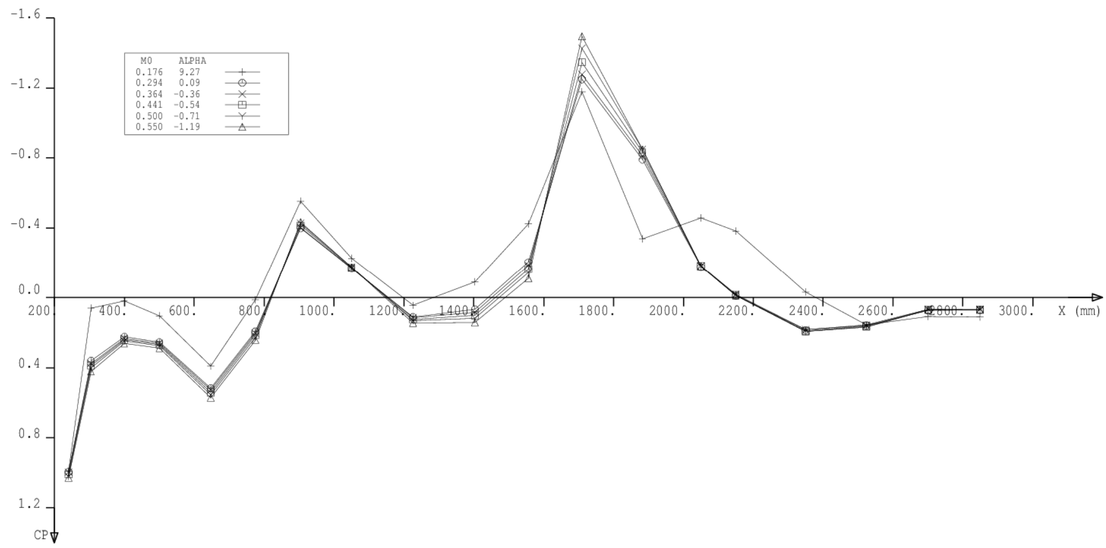

Figure 13. Pressure distribution on the fuselage

Figures 14 to 17 show the Mach effect on the pressure distribution on the left wing between M=0.176 and M=0.55 for the nominal conditions. Dotted lines correspond to the suction side of the wing and full lines correspond to the pressure side. On the suction side, the pressure coefficient reaches Kp=-2.5 at M=0.176 and AoA=+9.27°. At higher Mach number, the angle of attack is lower and so the minimum pressure coefficient remains between -2 and -1.5. A detachment is to be noticed at M=0.176 on the wing suction side at y=-280mm.

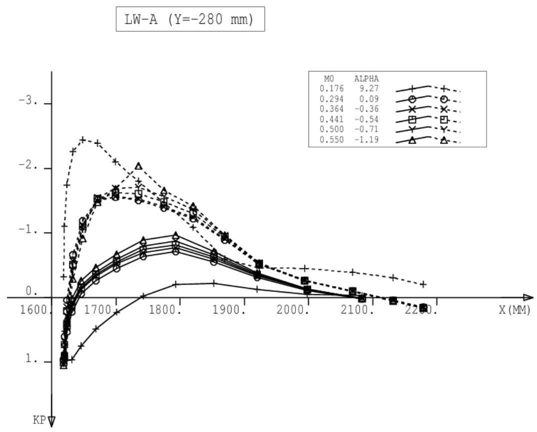

Figure 14. Pressure distribution on the left wing at y=-280mm

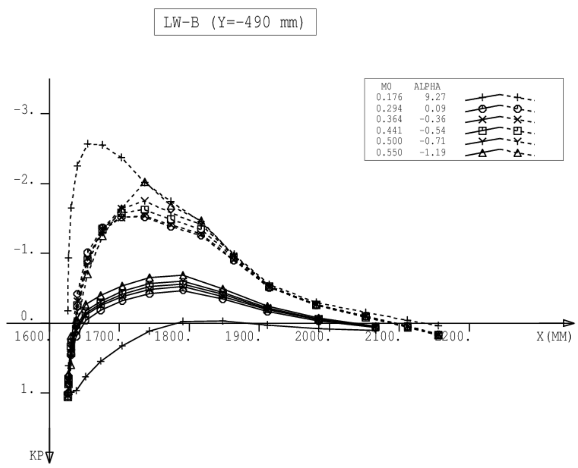

Figure 15. Pressure distribution on the left wing at y=-490mm

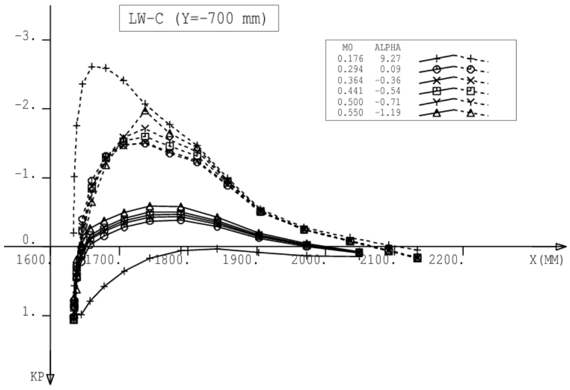

Figure 16. Pressure distribution on the left wing at y=-700mm

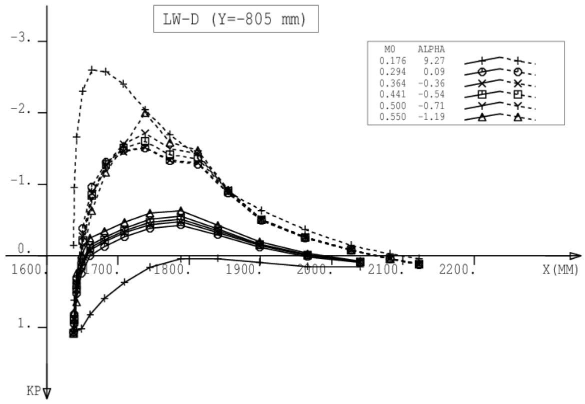

Figure 17. Pressure distribution on the left wing at y=-805mm

5.2 Vibrations

In order to evaluate the Mach number effect on the vibration levels which occurred in S1MA, the analysis of unsteady pressure measurements has been done. This analysis has been done on the leading edge sensors (9915, 9919, 9923, 9927 and 9931) but also on the trailing edge (9920 and 9928) and the nacelle (9943). The sensor locations on the tiltable wing and the nacelle are presented in Figure 18.

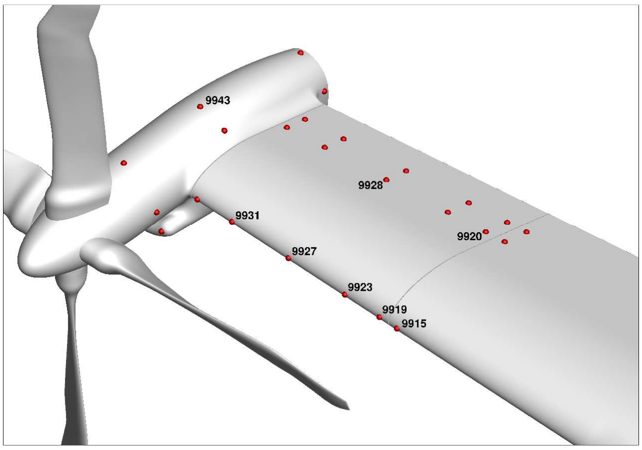

Figure 18. Unsteady pressure sensor locations on the tiltable wing and the nacelle

A Fast Fourier Transform of the pressure sensor time signals has been done for several sensors. The modulus of this FFT has been plotted function of the Mach number in Figure 19.
The first result is that 4/rev. and 8/rev. are the two main frequencies, the other frequencies presenting a very low amplitude. These two frequencies clearly correspond to the blade passage frequency and its multiple. In addition, the 8/rev. modulus is about half of the 4/rev. modulus depending on the sensor location on the aircraft.

The second result is that the 4/rev. pressure fluctuation increases with the Mach number. This can be moderated by a more detailed analysis. On the tiltable wing leading edge, the blade interaction is higher

for the AC1 configuration (M=0.176, AoA=9.9°) than for the high speed cruise configuration AC3 (M=0.55). The blade tip vortex may impact the whole leading edge because of the 9.9° aircraft AoA. But, from M=0.3 to M=0.55 the blade interaction with the tiltable wing clearly increases with the Mach number, as the rotor thrust increases. The same analysis can be done on the trailing edge part of the tiltable wing in addition to the nacelle where the 4/rev. FFT modulus is higher than all the other measurements.

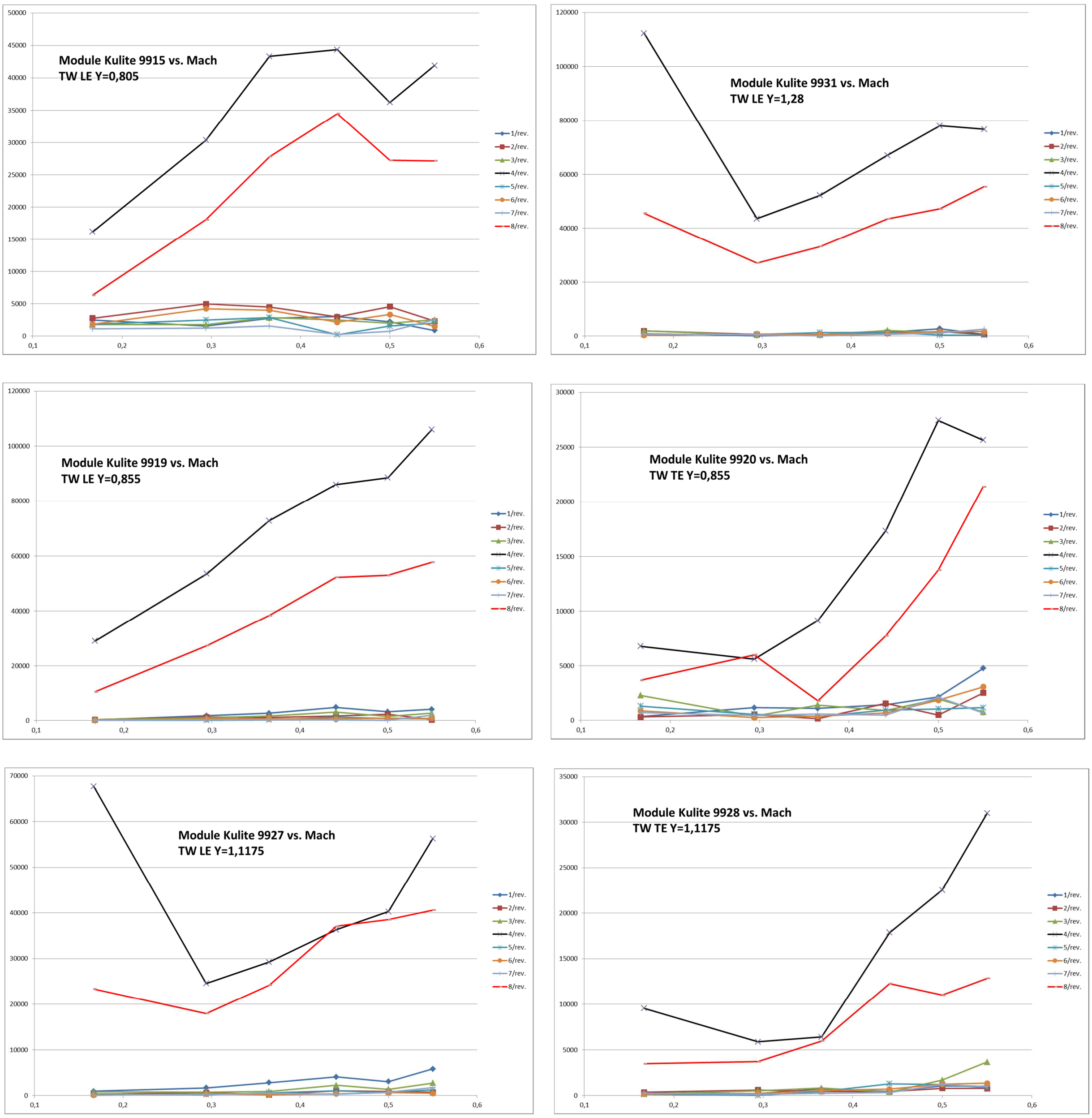

Figure 19. Unsteady pressure modules vs. Mach number

Finally, the 4/rev. interaction increases with the rotor thrust and the Mach number. There is no doubt that this rotor-wing interaction is the source of the high 4/rev. vibration level that occurred in S1MA wind tunnel measurement at high speed. It may be that this aerodynamic excitation coincides with a structural mode of the model and that such high vibration levels would not appear at scale 1.

5.3 High Speed Assessment

During the ONERA S1MA wind tunnel tests, from M=0.176 to M=0.441, the model has been trimmed with the previously described standard procedure. Therefore, the rotor thrust compensates the complete aircraft drag and a direct assessment of performance is possible. Power coefficient and efficiency vs. thrust coefficient are presented in Figures 20 and 21. For each nominal configuration (large symbols), a sweep in collective pitch has been done (small symbols) and allows plotting the corresponding curves. It is to be noted that the relation between thrust and power coefficients is nearly linear for every configuration.

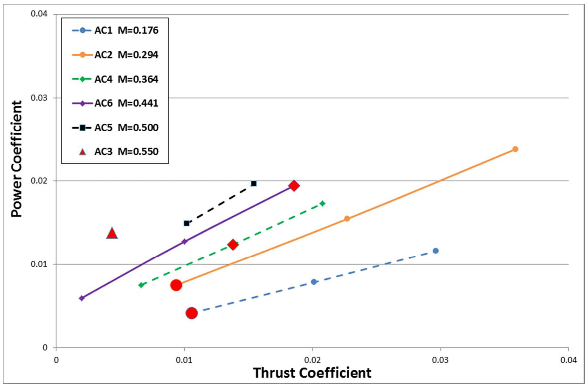

Figure 20. Power coefficient vs. thrust coefficient

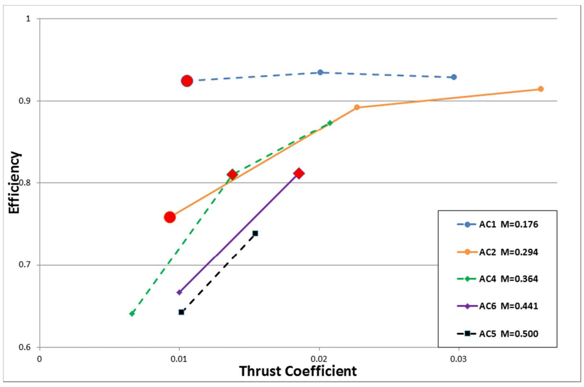

Figure 21. Efficiency vs. thrust coefficient

At M=0.5 and M=0.55, high nacelle 4/rev. vibrations occurred during the tests. Therefore, the thrust required to compensate the drag was not reachable in order to mitigate the risks. Finally, the model was trimmed to mild descent flight with γ=-4° at M=0.5 and γ=-8° at M=0.55 and a direct assessment of performance was no more possible. An "extrapolation procedure" has been proposed with the objective to evaluate the power consumption for M=0.5 and M=0.55 in level flight, and is presented below. It has been checked at M=0.364 that propeller performance in low descent flight is very similar to performance in level flight.

At M=0.5, a sweep of two collective pitch angles has been done and allows extrapolating linearly the power vs. thrust coefficient measured values (Figure 22). At M=0.55, only one thrust has been measured and a linear extrapolation of power vs. thrust coefficient is not possible. The power vs. thrust coefficient slope function of the Mach number is evaluated. The slope function of the Mach number is almost linear, so the slope at M=0.55 can be extrapolated (Figure 23).
The slope of the power vs. thrust coefficient at M=0.5 and M=0.55 is consequently known (dotted lines in Figure 22), but the value of the propeller thrust for the trimmed condition remains unknown.

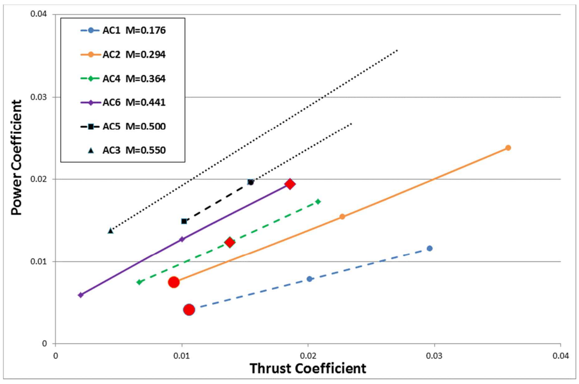

Figure 22. Power coefficient vs. thrust coefficient

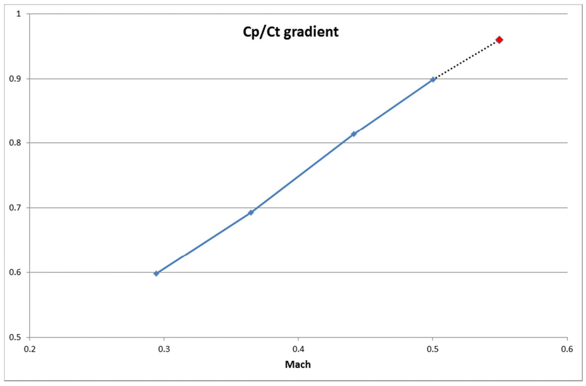

Figure 23. Cp/Ct gradient vs. Mach number

In order to estimate the thrust at M=0.5 and M=0.55, the following procedure is proposed:
- the measurements without blades provide "fuselage +stubs" drag in level flight: these measurements were done for the whole range of Mach number (including M=0.5 and M=0.55: the highest curve in Figure 24);
- the required propellers thrust values are derived from these "blade-off" measurements;
- one part of "fuselage+stubs drag" has to be compensated by propellers thrust: this part was evaluated based on AC4-AC6 configurations measurements, for which the propellers thrust in trimmed condition and the "fuselage+stubs drag" in "blade-off" condition are both known (the lowest curve in Figure 40);
- the propeller thrust vs. Mach number line on AC4-AC6 has then been extrapolated to AC3-AC5 configuration, in order to "evaluate" what would be the AC5 & AC3 target thrust coefficient (triangle curve in Figure 25). This black curve corresponds to the target Ct (corresponding to half fuselage+stubs drag) shifted on the AC4 and AC6 measured trimmed points (red curve).

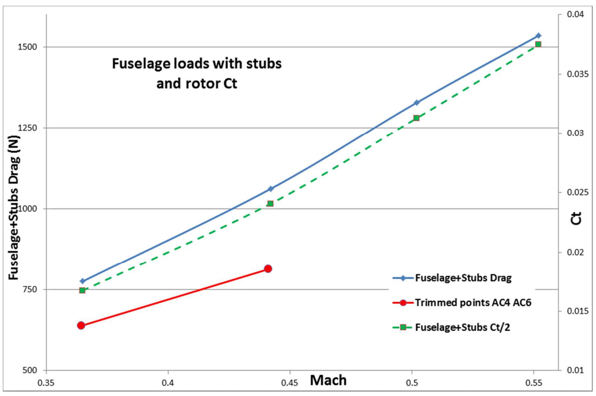

Figure 24. Fuselage + Stubs drag vs. Mach number

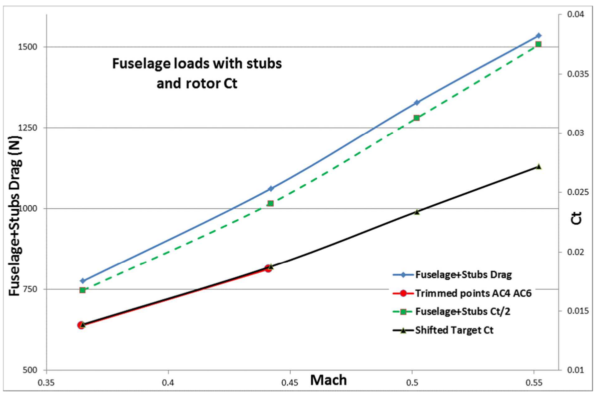

Figure 25. Fuselage + Stubs drag vs. Mach number

As a result, the target thrust is estimated for AC5 and AC3 configurations. Since the power vs. thrust slope function of the Mach number was previously estimated, the extrapolation of the power coefficient for the AC5 and AC3 configuration is possible (Figure 26). The plotting of the propeller efficiency for the complete flight domain is shown Figure 27.

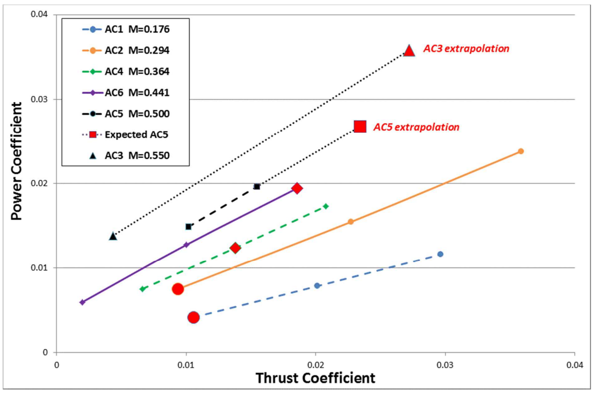

Figure 26. Power coefficient vs. thrust coefficient

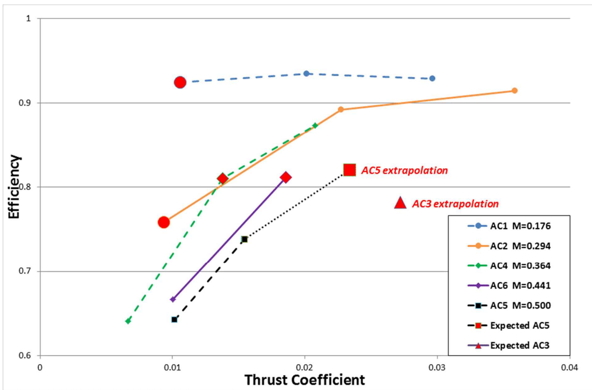

Figure 27. Efficiency vs. thrust coefficient

The power and thrust coefficients allow the assessment of the power and thrust for the ERICA concept at scale 1 in level flight at 7500m. The ERICA performance is assessed up to M=0.5. The propeller efficiency remains above 80% from M=0.364 up to M=0.5 and is 0.78 for M=0.55. This high level of performance could be lower on the real aircraft, due to the hub drag penalties linked to the gimbal hub at scale 1 instead of the reduced hinged hub in the wind tunnel.

6 CONCLUSIONS

The NICETRIP high speed tests performed on the ERICA concept of a European tilt rotor aircraft were successfully achieved in ONERA S1MA wind tunnel in May 2014. The preparation phase and the real-time monitoring means used during the tests ensured operating the wind tunnel and such a complex powered model safely.

Despite the model limitations encountered during the tests, mostly due to the vibrations linked with the 4/rev. interaction, the data post-processing led to the high speed assessment of such a tilt rotor concept. The ERICA performance was assessed up to M=0.5. The propeller efficiency remains above 80% from M=0.364 up to M=0.5 and is 0.78 for M=0.55.

The amount of experimental data recorded during the high speed tests, mostly in terms of loads and pressure distributions, represents a large data base for the ERICA tilt rotor concept.

7 ACKNOWLEDGMENTS

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