MACH NUMBER CONTROL IMPROVEMENT IN ONERA S1MA LARGE TRANSONIC WIND TUNNEL

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ABSTRACT

Improvement of wind tunnel productivity and data base quality is a key issue within a worldwide competitive environment where cost savings are crucial. As a consequence, accurate Mach number control for large wind tunnels is essential. Indeed, a significant part of the tests performed in these wind tunnels deals with civil aircraft for which test matrix consists in a large number of polar in angle of attack at different Mach numbers. During pitch motion, pressure losses change in the wind tunnel inducing Mach number drifts which are penalizing both for data base quality and test productivity. Then, without a powerful Mach number controller, measurements as pressure distributions are not provided at the requested Mach number and additional polar are needed for load interpolations.

Since the 50's, successive improvements have been implemented in the ONERA S1MA Mach number controller, but in 2007 it appears that traditional "tools" for Mach number control have reached their limits.

Then ONERA, on the framework of the 7th European Programme, launched in 2008 the study of a new S1MA Mach number controller based on hard and software improvements. This work is part of the European project ESWIRP (European Strategic Wind tunnels Improved Research Potential) which deals with the improvement of European strategic wind tunnels (DNW LLF, ETW and ONERA S1MA).

For S1MA new Mach controller, the objective is very ambitious since it aims to obtain Mach number stability during a pitch polar within ± 0.001 at least up to Mach 0.9.

The first part of this paper is dedicated to the presentation of the S1MA main characteristics and to the descriptions of the former and new Mach number regulators. The second part refers to the different phases of simulation and experiments done to optimize the new regulator. The third part deals with the presentation of the results obtained considering both Mach number stability during a pitch polar and its consequences on aerodynamic results and test productivity.

NOMENCLATURE

M0	=	Mach number
α	=	model angle of attack
$\alpha 0$	=	specific value of the model angle of attack used for Mach control
RPM	=	fan speed, Revolution per Minute
PI0	=	Wind Tunnel stagnation pressure
EA2	=	Wind tunnel main air intake
EAR	=	Wind tunnel air intake dedicated to Mach control

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1 ONERA S1MA TRANSONIC WIND TUNNEL

For 60 years, the ONERA S1MA wind tunnel is still the largest sonic tunnel ever built, with a test section 8m in diameter and 14m long. No other wind tunnel in the world is capable of generating wind speeds up to Mach 1.

Each contra-rotating fan (15m in diameter) is directly driven by one Pelton turbine (total hydraulic power 88 MW). This direct hydraulic drive is a great advantage from the viewpoint of facility's overall energy efficiency and for environment concerns allowing S1MA to be considered as a "green" test facility.
Three interchangeable test sections are available. Then, one test is carried out while two others are prepared which enables good tunnel productivity.

Reynolds numbers for full models of civil aircraft are around 5 millions while they reach 7 millions for half models and 18 millions for large scaled wings.

Typical tests, carried out in S1MA, are full and half model tests, laminarity tests, missiles at scale 1 with engine on, helicopter main rotors and store separation studies with a CTS device. High pressure air distribution (200 bar, 17 kg/s) enables aero acoustic propeller tests including CROR configurations.

2 S1MA FORMER MACH NUMBER DRIFT

As model measurements depend strongly on the Mach number, it is important to keep it as constant as possible during the acquisitions even if the model angle of attack changes (typical tilting speed of 0.2°/s in S1MA).

During aircraft tests, the model is pitched through a series of angles of attack at a requested Mach number (pitch polar). In the test section, air flow is fast and model drag strongly changed with pitch angle. Drag increase induces a loss in the stagnation pressure across the wind tunnel. The stagnation pressure disturbance then propagates downstream to the fans and sets up a dynamic unbalance on their equilibrium. Finally, if an efficient Mach number controller is not implemented, a Mach number deviation, from the requested set point, is observed.

Typical Mach number drifts are around: ±0.007 at Mach number 0.7 and ±0.030 at Mach number 0.94.

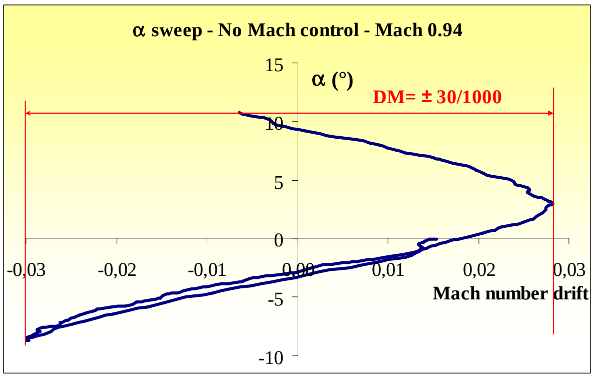

Figure 1

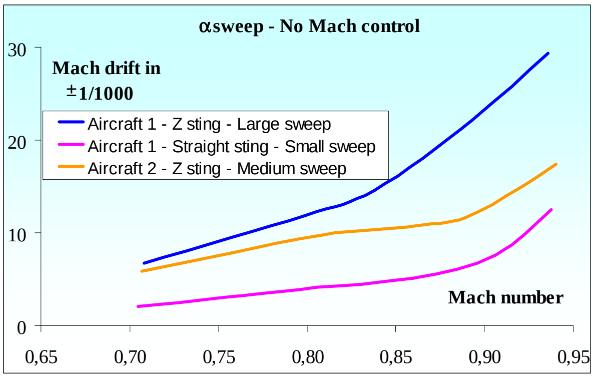

Figure 2

Figure 1 shows a typical Mach number drift at a nominal Mach number of 0.94 during a pitch polar between ± 10°. The blue curve on figure 2 shows the Mach number drifts for a civil aircraft on a Z sting for Mach numbers between 0.7 and 0.94. The pink curve represents the Mach number drifts for the same aircraft fixed on a straight sting. As straight stings are dedicated to cruise conditions, while Z stings are for buffeting configurations, α sweep are more important with Z stings (±10°) than for straight stings (±5°). This is the reason why, for the same aircraft, Mach number drifts are lower with the straight sting.

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To conclude on figure 2 the orange curve represents the Mach number drifts for another civil aircraft fixed on a Z sting. Compared to the blue curve, as α sweeps are small, the orange curve is under the blue one.

A perfect Mach number controller has to cancel these drifts but, of course, residual drifts will still be present and it was important to estimate their foreseen levels. Then, the Mach number stability, in a favourable configuration, was measured during six minutes with constant stagnation temperature, fan's RPM and model angle of attack.

Maximum improvement achievable can be illustrated by the gap between the Mach drift without controller (orange curve) and the Mach stability in steady conditions (green curve) as shown on figure 3.

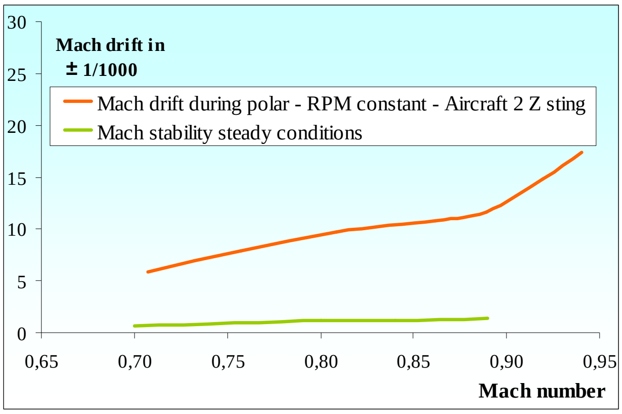

Figure 3: Comparison between Mach drifts without Mach controller and Mach stability in steady conditions

3 INITIAL IMPROVEMENTS OF S1MA MACH NUMBER CONTROLLER

Until the 80s, fan's RPM was constant during pitch polars and then large Mach number deviations were observed. Then, it was necessary to acquire a large number of extra polar to provide, using interpolations, the aerodynamic loads at the Mach number requested by our Clients. Furthermore, pitch pause technic was applied to acquire data for which interpolation is not possible (CP distributions, dynamic and acoustic data…). This method, involving extra polar and pitch-pause mode, was very accurate but also excessively time consuming.

Then, between 1985 and 2006, different improvements were implemented on fan's RPM control to decrease these deviations. Figure 4 presents the original Mach number drift (orange curve), the objective (green curve) and the situation in 2006 (black curve).

As one can see, with this first Mach number controller, a significant decrease of the Mach number drifts was obtained for Mach numbers ranging from 0.72 to 0.86. Looking in detail the situation it appears that while large deviations were still observed at negative angles of attack, Mach stability was improved for positive angles. However, as in the past, the method involving extra polar for load interpolations was still applied, providing very accurate measurements. But, as pitch pause mode was really time consuming and as it was now possible, during continuous pitch polar, to acquire CP distributions, at Mach numbers not too far from the requested Mach number, pitch pause mode was used no more for pressure measurements which generates significant productivity gains.

At this stage Mach number drifts at negative angles of attack was the last problem. Mach number drifts observed for negative angles of attack are explained by the difference between the two

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transfer's functions (model incidence / Mach and RPM / Mach). Indeed, while the Mach number rapidly changes with the model angle of attack (short delay and time response), the transfer function between the fan's RPM and the Mach number is characterized by large delay and time response. This phenomenon is amplified when the angle of attack motion changes of direction. Indeed, water turbine is not able to absorb power, so decelerations are effected by decreasing the power and letting the system slow down naturally due to friction. Then of course as model starts to go back to zero incidence, the fan's RPM decreased too late generating excessive Mach number for the negative angles between -7 and -2°.

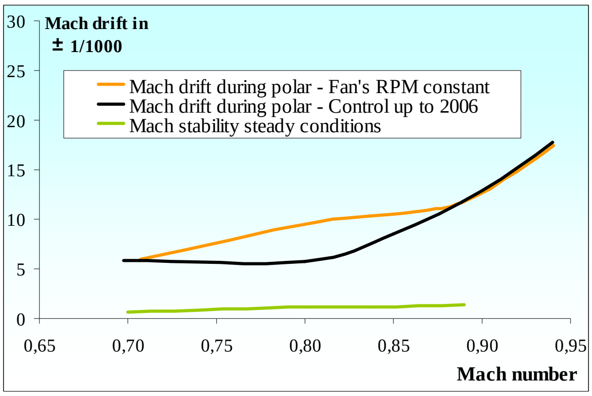

Figure 4: Mach number drift in 2006

Considering this draw back it was obvious, that an additional device, with a transfer function involving short delay and time response between action and Mach response was mandatory. The ideas to use an air intake to generate pressure losses opposite to the ones induced by the model incidence was seducing since such air intakes, named EA2, were already available in S1MA to control the total temperature.

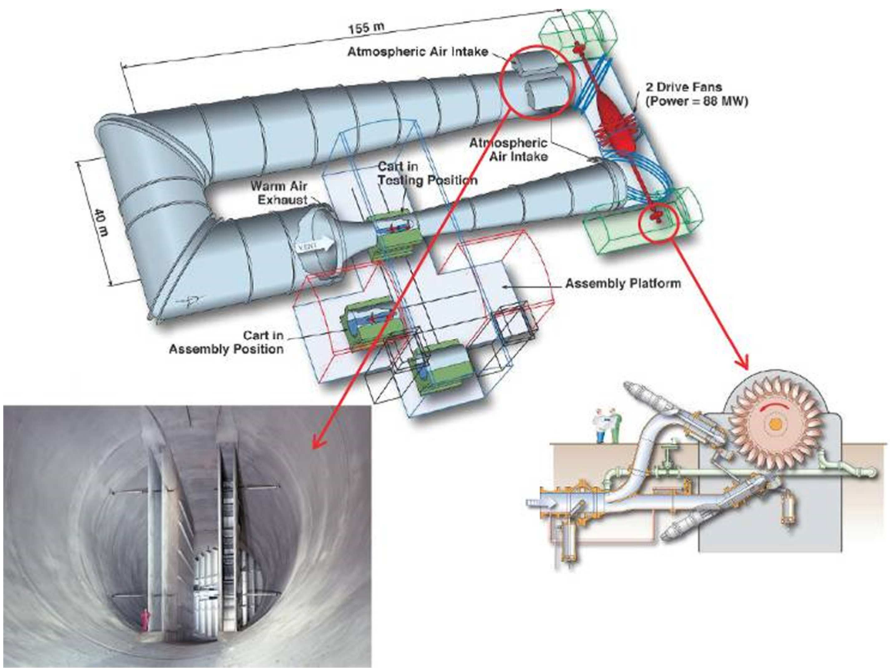

Figure 5: Mach number control using fan's RPM and large air intakes.

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The idea, symbolized on figure 5, was to use both RPM variations and air intake opening to control the Mach number. Air intakes were used to create, with a short time response, pressure loss variations opposite to the ones generated by the model pitch motion and RPM was used to generate pressure rise, with a longer delay, to keep the air intakes far from their mechanical stop.

With this controller developed in 2007, Mach number drifts for Mach numbers above 0.85 were significantly decreased as shown with the blue curve on figure 6 (drift decreased from 17/1000 to 5/1000 at Mach number 0.93).

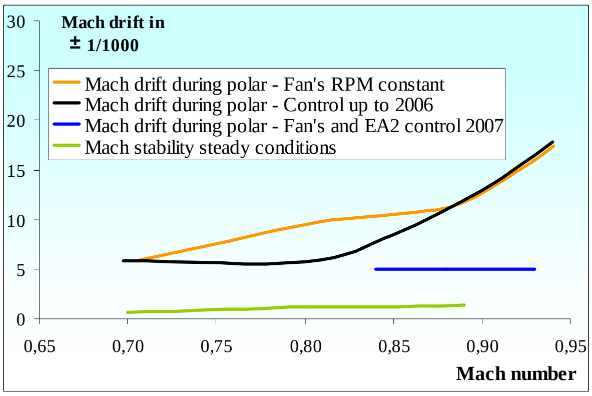

Figure 6: Mach drift in 2007

However, the Mach number drifts were still far from the expected objective (comparison blue / green curves), the regulation robustness was not satisfactory, some pumping phenomena were observed and last but not least as the drift reductions were obtained with large motions of the EA2 air intakes, which cinematic was not built to withstand large and repetitive motions, a failure probability was high.

4 S1MA NEW MACH NUMBER CONTROLLER

Previous experiments demonstrate that an accurate control of the Mach number in S1MA was possible. As a consequence, ONERA launched in 2008, on the framework of the 7th European Programme, the study and the manufacturing for a new Mach number controller.

Based on the previous developments with large air intake, the idea was to use fan's RPM control to compensate large pressure losses with some time delay in association with a dedicated air intake which can generate limited but fast pressure variations in phase opposition with those of the model during its pitch motion.

Compared to the large air intakes, this air intake, named EAR, has the following advantages:

- it is located in front of the fans (see figure 7), then its efficiency is higher than for an air intake settled after the fans,
- its cinematic is designed to withstand a very large number of open / close actions,
- Control reactivity is improved.

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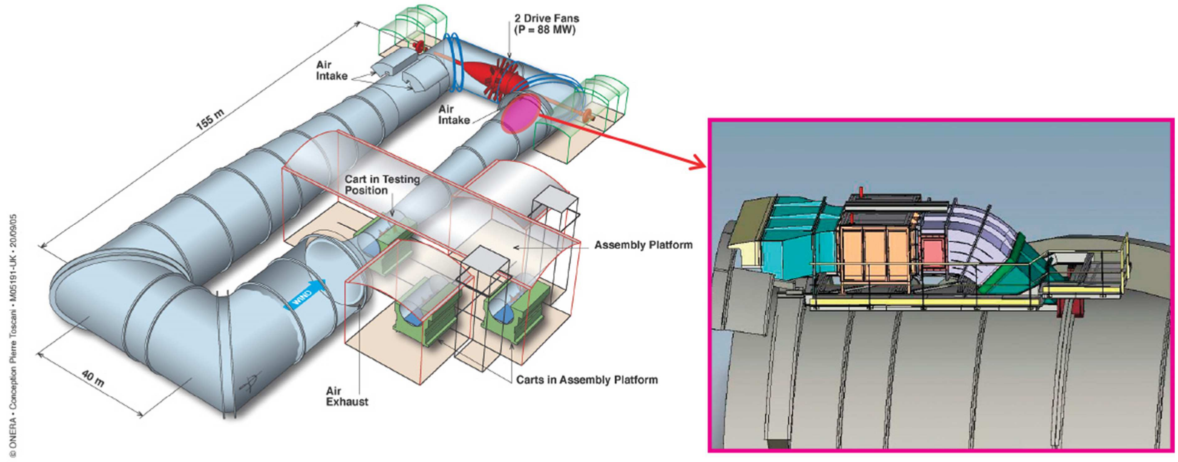

Figure 7: S1MA new air intake for Mach number control

This air intake works by aspiration with a maximum of 6 000 Pa between atmospheric pressure and wind tunnel internal pressure. Taking into account previous regulation with the wind tunnel main air intake located downstream the fans and considering theoretical gain achievable with a new air located upstream the fans, ONERA dimensioned the new air intake with a frontal upstream surface of 6 m^2. Mass flow introduced is controlled thanks to the opening of two vertical shutters. Air is introduced in the aerodynamic circuit just in front of elbow n1 with an angle of 45°. The global mass of the air intake and associated shelter for mechanism and control system devices is 15 tons.

4.1 Transfer functions involved in Mach number controller

Even if promising results were obtained in 2007 (blue curve on figure 6) it has to be noticed that controller adjustments were carried out at that time with empirical procedures only.

As the gap, between the 2007 Mach drifts (± 0,005) and the final objective (around ± 0,001 up to Mach 0.9) was large, to go on with empirical adjustments was not adequate and then an approach of using parameter identification for modelling has been selected.

These identifications consisted in applying determined entries and observing associated responses in amplitude, delay, time response and non-linearity.

To design the Mach number controller of S1MA, three transfer functions have to be determined:

- Transfer function between the model pitch angle and the Mach number response,
- Transfer function between fan RPM command and the Mach number response,
- Transfer function between the air intake (EAR) opening and the Mach number response.

4.2 Transfer function between model pitch angle and Mach number response

Input criterion of the transfer function must be simple, sturdy and linked with the pressure loss generated by the model pitch. Considering references [1], [2], [3] and in house experience, ONERA defined a criterion named wbis.

Considering that induced drag variation is predominant during a pitch polar and is mainly proportional to the square of the angle of attack, the use of a criterion involving a component in $(\alpha\text{-}\alpha0)^2$ seemed to be promising. On figure 8, the parabolic curve represents the Mach number drift versus the model angle of attack during a pitch polar performed with no Mach control. $\alpha0$ is the point located in the horizontal plane of symmetry of the curve. On figure 9, when Mach drift is plotted versus $(\alpha\text{-}\alpha0)^2$ are straight line is obtained.

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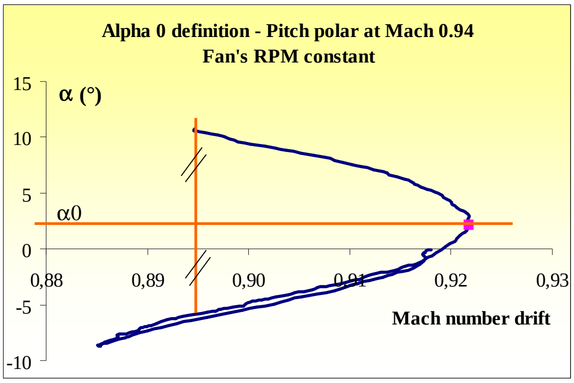

Figure 8: Mach drift without control and α0 definition

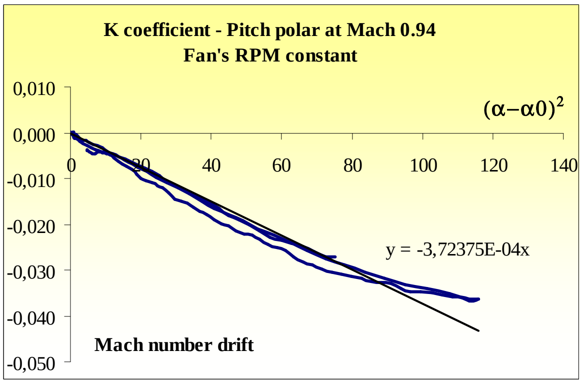

Figure 9: Mach drift versus $(\alpha\text{-}\alpha0)^2$

It was found that wbis criterion is as simple as: $wbis\ criterion = K \times (\alpha - \alpha 0)^2$ where K coefficient and α0 angle depend on the Mach number. For an optimal performance of the controller, a determination of α0 and K evolutions is necessary for each new test set up. Then, it is necessary to carry out four pitch polar at constant fans RPM, ideally, at Mach numbers around: 0.8 / 0.85 / 0.9 and 0.92. Then, evolutions of α0 and K coefficient versus the Mach number are determined and modelised with second or third order polynomial laws.

To demonstrate the quality of the transfer function determined with wbis criterion not only in amplitude but also in time, time history of the experimental Mach number drift is compared with the estimated one.

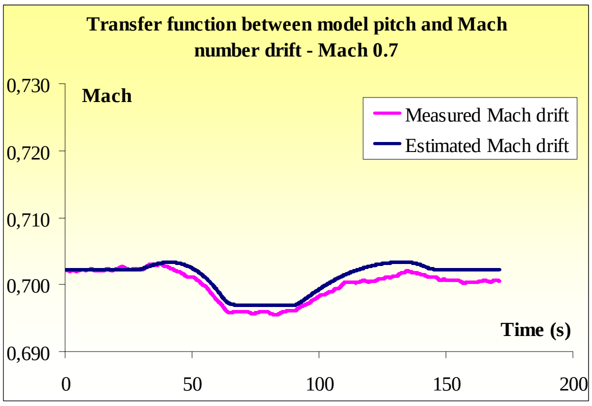

Figure 10

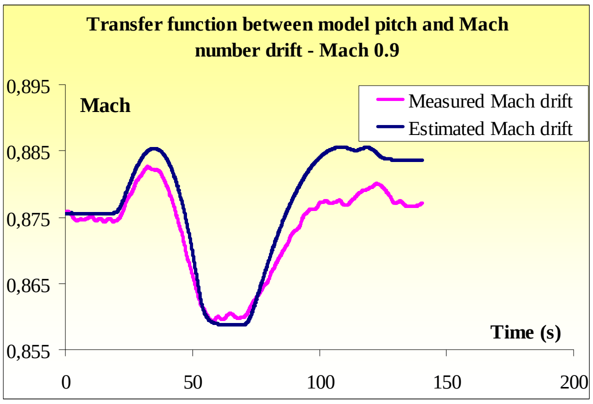

Figure 11

As shown on figures 10 and 11, a very accurate modelisation of the transfer function between model pitch motion and Mach response has been obtained.

4.3 Transfer functions between RPM command and Mach number response

To establish the transfer functions, step increases on fan's RPM were applied and induced Mach number variations were recorded. Non-linear responses were obtained then, to cover the full Mach / RPM domain, a large number of first order transfer functions were determined. One of them is presented on figure 12.

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Step responses in Mach number for a RPM command indicate a very large transport delay (higher than 5s) which confirms the necessity to add, to the fan's control, a more reactive device to compensate the Mach number drifts induced by the model pitch motion.

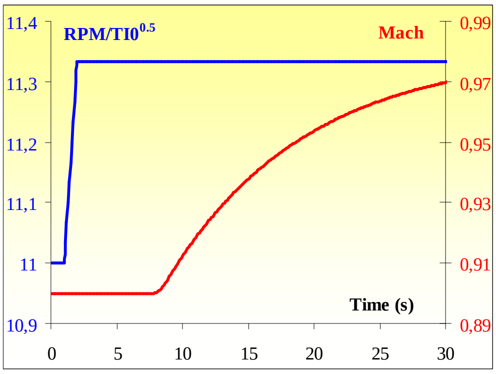

Figure 12: Transfer function RPM / Mach number

4.4 Transfer function between EAR air intake and Mach number response

Transfer functions between the EAR air intake aperture and the Mach number response depend on the Mach number. Figure 13 presents the transfer function obtained at Mach number 0.84. Transfer functions, are first order with delay and time constant between 1 and 2s.

Good agreement between the experimental Mach response (red curve) and the mathematical model (green curve) validates the control algorithm introduced inside the regulator.

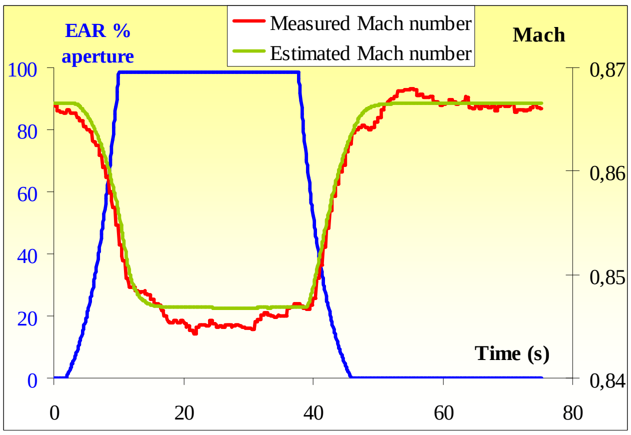

Figure 13: Transfer function Air intake / Mach number.

4.5 Regulator architecture and modelisation

As the three transfer functions involved in the Mach number controller were experimentally identified, it was possible to carry out a long and complex optimization process. Objectives of the simulations, made in Excel format, were to check the regulator behaviour, to optimize its architecture and its parameters. Of course, with this kind of simulations, large quantity of hydraulic energy are saved compared to an adjustment done with wind tunnel experimental tests only.

Regulator architecture optimized with the numerical simulations is shown on figure 14.

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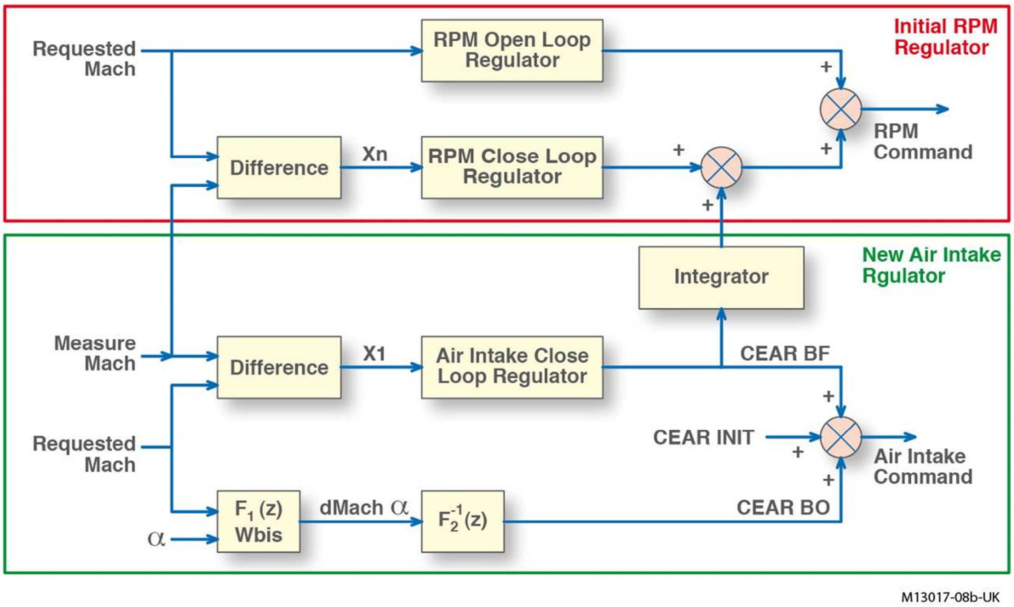

Figure 14: Mach number regulator during numerical simulations.

The regulator is divided in two blocks: the RPM regulator (red rectangle) which is similar to the former Mach number controller and the air intake regulator (green rectangle). The RPM regulator is used for large Mach number changes, from 0.7 to 0.75 for example, while the air intake regulator is used to compensate the Mach number drifts during pitch polar.

In between the two regulators, the integrator enables to adjust smoothly the RPM command (in 10 to 20s) during a Mach change in order to have the air intake aperture in a mid-position when the new Mach number is reached. Then air intake can use its complete range of motion, for Mach number control during pitch polar.

Figure 15 shows, for Mach number 0.9, the simulated Mach number drifts with fan's control only and with fans and air intake controls. These simulations clearly indicate a strong improvement on Mach number stability using the air intake.

To acquire confidence in these simulations, a comparison between simulated and experimental results was done for fan's RPM control only. This comparison is presented on figure 16. Agreement is very satisfactory.

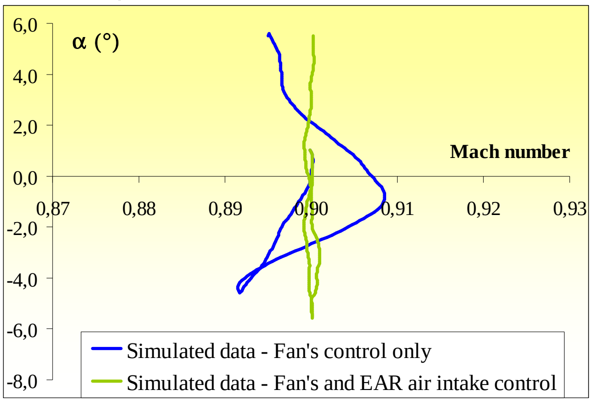

Figure 15: Simulated Mach drifts

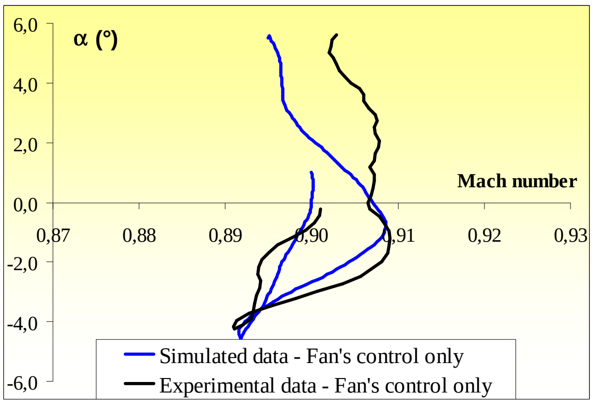

Figure 16: Comparison simulation / experience

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Even if the simulations were encouraging, it is important to remember that they can be optimistic since non linearity are difficult to capture, data used are not affected by noise measurements and extra difficulties generated by delays and time constants were not excluded.

5 EXPERIMENTAL ADJUSTMENT OF THE NEW MACH NUMBER CONTROLLER

Dedicated aerodynamic test were carried out at the end of 2013 to realize the controller adjustment, using a civil aircraft mounted on a Z sting. With the Mach controller as defined on figure 14, deviations were drastically decreased compared to 2007.

However, significant Mach number drifts were still observed in high transonic because air intake was already closed when model incidence was one degree higher than the minimum angle of attack (-4°). Then, of course, air intake could not be "more" closed; its pressure loss remained constant while the model pressure loss was still increasing which generates a Mach number decrease.

To overcome this and maintain the air intake aperture as far as possible between 20 and 80%, a significant modification of the regulator architecture was realised.

With a revised and more complex architecture (see figure 17), Mach number deviation is compensated with the open loop on the air intake but also with an open loop on RPM (dcnα box).

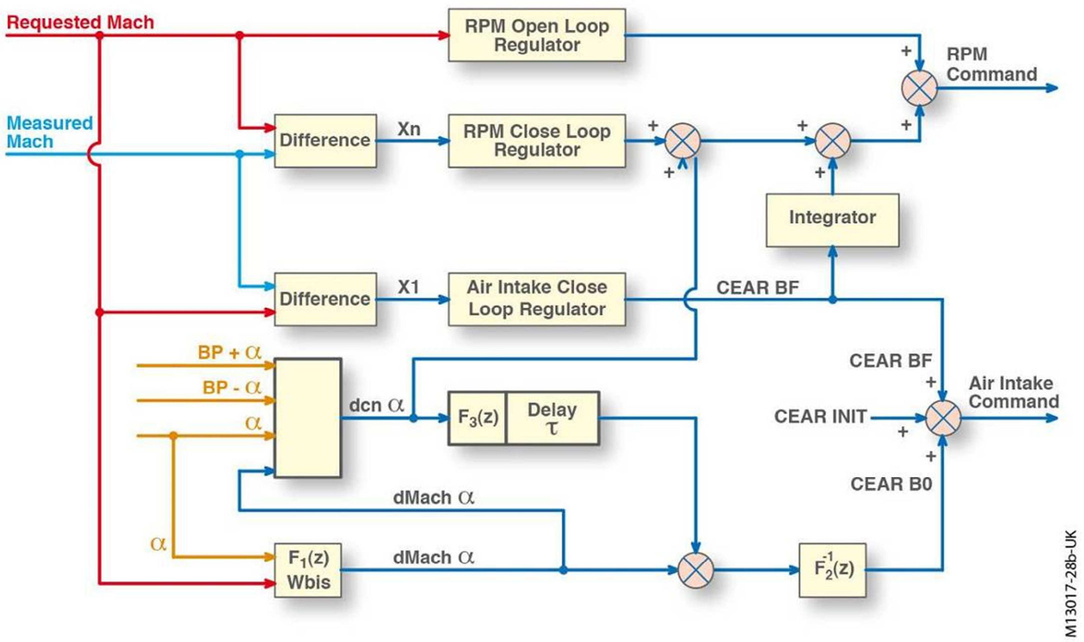

Figure 17: Final Mach number controller.

To give a rough estimate, at Mach number 0.85, a Mach number variation of 0.001 is compensated by a 4.5% change of air intake opening or a 0.1 fans RPM variation. The aim of the weighting between RPM and air intake is to compensate, with the fans, approximately 50% of the Mach number drift generated by the pitch motion.

As time delay, between RPM command and Mach response from one side and air intake command and Mach response from the other side, are totally different, adjustments were complex.

But in the end, as shown on figures 18 and 19 excellent Mach number stability were obtained.

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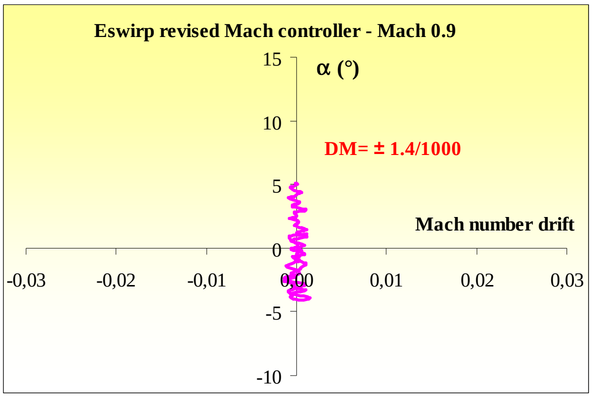

Figure 18: Mach number drifts during pitch sweep – M0 = 0.9 Final regulator 2014

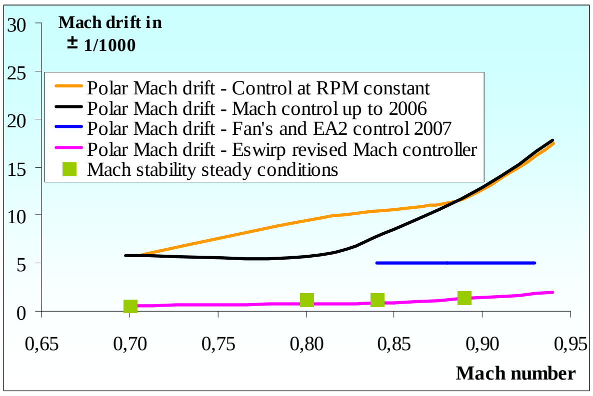

Figure 19: Synthesis of Mach number drift during pitch sweep Final regulator 2014

Even at high transonic when model pitch angle changes of direction no Mach number drift are observed and finally Mach deviations don't exceed 1.5/1000 (figure 18). Mach number drifts obtained with the final controller are synthesized by the pink curve on figure 19. This curve is superimposed with green squares which represent the Mach number stability in steady conditions. To obtain, Mach number drifts during pitch polar, as small as, natural fluctuations of Mach number in steady conditions, is a great success.

6 IMPROVEMENTS GENERATED ON DATA BASE QUALITY AND TEST PRODUCTIVITY

As said in introduction, improvement of the S1MA Mach number controller was requested to increase the quality of the aerodynamic data base and the productivity of this unique large transonic wind tunnel.

Since 2006 pressure measurements were recorded during continuous pitch polar (no pitch pause) which generated significant productivity gains, however, as one can see on the black curve on figure 19, Mach number drifts were still significant and Clients had to keep in mind this, during their analyses of the pressure data. With the new Mach number controller (pink curve), Mach number drifts are negligible which increases the data base quality and generates productivity gains on our Clients activity since it is not necessary to check, for each incidence, if the reached Mach number is not too far from the requested value. It is important also to underline that this improvement of the data base quality applied not only for the pressure measurements but also for all the measurements for which interpolation is not adequate: dynamic measurements, acoustic measurements…

Furthermore, this improved Mach number control is of great interest for wake survey tests and laminarity tests for which aerodynamic stability is crucial.

On another hand, in a period in which competitiveness is enhanced, gains of productivity on wind tunnel tests are a major concern. With the new Mach number controller, which leads to no Mach number drifts, loads interpolations are "easier" leading to the cancel of all the pitch polar which were requested for load interpolations purposes only. In the end, time necessary to acquire the same Client data base is reduced by -30%.

7 CONCLUSION

This paper presents the successful development of the new ONERA S1MA Mach number controller.

Since both systems have their own advantages, a RPM and an air intake control, are combined in the new regulator. Indeed, RPM control gives a wide range of action while air intake provides a very interesting reactivity. A very accurate identification of the different transfer functions, coupled with an

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optimized weighting between RPM and air intake open loops, leads to a high performance Mach number controller.

With the new controller, Mach number drifts during pitch polar do not exceed the natural fluctuations of the Mach number in steady conditions which is a very impressive result. For example, at Mach number 0.9 peak to peak deviation, during a pitch polar between -5° and +5°, does not exceed ±0.0015 which is ten times lower than in 2006.

This impressive improvement on Mach number stability generates an increase of the tunnel productivity of around 30% which is of great interest for the attractiveness of the S1MA World Class wind tunnel. It is equally important to underline that this Mach stability induces a great improvement of the aerodynamic data base quality for all the data than cannot be interpolated.

This new Mach number controller is now used on a regular basis in the ONERA S1MA large transonic wind tunnel, for the financial and technical benefits of all our Clients.

Acknowledgments

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