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Wind Tunnel Tests at High Alpha And Criteria to Predict High Alpha Behaviour

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Summary

This paper presents the results of a rotary balance test campaign accomplished on the same model in different wind tunnels. The test campaign was aimed to verify the reliability of results, and to evaluate the extent of the difference that may be ascertained.

The results of the test performed with a newly developed test rig, the High Amplitude Oscillatory Coning Motion Balance (HOACMB), are also presented as well as the method to obtain dynamic derivatives with the data from the test and a comparison between the results from the HAOCMB test and that from forced oscillatory test.

Finally a simulation program (AIRSIM), able to perform six D.O.F. simulations in quasi real time, is presented. With this program, it is possible to perform the flight simulations and to have a final validation of the aerodynamic data collected from the various wind tunnel test rigs.

List of specific symbols

ω	Rotary rate about wind vector	b	Wing span
ϕ	Rotary angle about rotary axis	V	True air speed TAS
ε	Angle from body axis X to rotary axis	$\delta r, \delta a, \delta e$	Controls deflection
$C\phi$	Moment coefficient about rotary orientation	Cm,Cl,Cn	Pitch,Roll,Yaw moment coeff.

Introduction

In the last few years the importance of collecting data obtained from wind tunnel test on rotary balances to study high alpha behaviour has been recognised. Such tests, in fact, permit the aircraft aerodynamic data to be defined as a function of alpha, beta and $\omega b/2V$ (nondimensional rotation speed). It is not possible to accurately estimate the high angle-of-attack behaviour of an aircraft based only on the aerodynamic data as a function of alpha and beta alone, obtained from the fixed balance tests. Only the knowledge of the behaviour of coefficients as a function of the variable $\omega b/2V$ leads to a correct identification of the typical characteristics of high alpha behaviour.

This document contain the results of rotary balance tests accomplished on a model representative of a general aviation aircraft in different wind tunnels and with different apparatuses. The aim of this work is to familiarize the user with the data obtained from the rotary balance. In this respect the model choice proved to be particularly lucky, as NASA has intensively tested this configuration and published the results of the wind tunnel tests and flight tests of both the aircraft and the radio-controlled model [1], [2], [3], [4], [5].

A method to use rotary balance tests to predict high alpha behaviour is described and the comparison between prediction and flight test results are presented [6], [7], [8].

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Moreover, some results from a newly developed test rig, the High Amplitude Oscillatory Coning Motion Balance (HAOCMB) are presented and are compared with the results of tests performed on some models with both oscillatory and rotary balances. The HAOCMB rig appears very attractive because of its ability of rolling, yawing, pitching and rotating about the wind vector as well as any other orientation. These results promise the ability to integrate the data from rotary balance and forced oscillatory test results in future applications [9], [10].

Finally, a computer program (AIRSIM) which is able to perform accurate six-degree of freedom simulation is presented. This program has proved essential to this work because the validation of the wind tunnel data was mainly obtained performing simulations and comparing the results with dat from the flight test [11], [12].

This approach gave us a degree of confidence in performing the wind tunnel tests, and in choosing the best way to prepare the mathematical model, the aerodynamic data base and generally in using data coming from wind tunnel tests in the most significant manner.

Rotary balance test with a General Aviation model

The model was manufactured by Harbin Aerodynamics Research Institute Center (China) based on drawings shown in the NASA report [1]. The choice of this model was determined by the possibility of using the results from NASA rotary balance tests to verify the good quality of the results obtained with a new balance developed by the specialists of the Chinese Institute in 1989; see Fig.1.

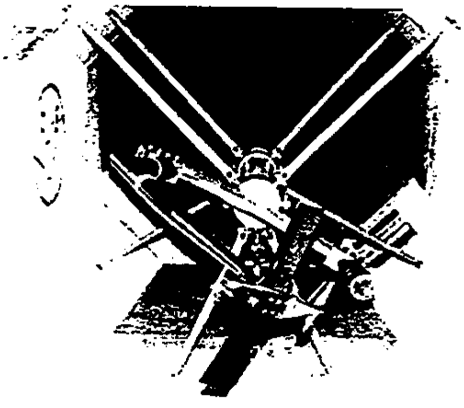


Fig.1 Rotary Balance of HARI

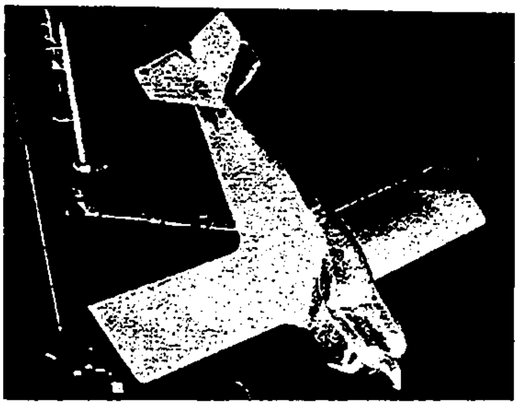


Fig.2 Test model

To obtain additional comparison data, the model was further tested on the rotary balances of Aermacchi (Italy) and of NBW-BS of DLR(Germany).

Description of wind tunnel models and tests conditions

The 1:9 scale model (see Fig. 2) used for the wind tunnel test was manufactured from composite materials, with no control surfaces. The model incorporates provisions for the attachment to the rotary balance on both top and bottom of the fuselage, and permitted very wide angle-of-attack and yaw ranges to be tested.

With a wind speed of 35 m/sec, the test were limited to angles-of-attack ranging from 8° to 82° in the HARI test, from 4° to 36° in the AEM test and from 0° to 24° in the DLR test. Also, the limit on maximum nondimensional rotation speed ($\omega b/2V$) was about 0.4.

It is pointed out that the NASA tests in reference [1] were conducted with a 1:5 scale model, a wind speed of 7.62 m/sec, and alpha values from 15° to 90° .

Fig. 3 provides a comparison of the results obtained from the tests performed in the various wind tunnels [1], [6], [7], [8].

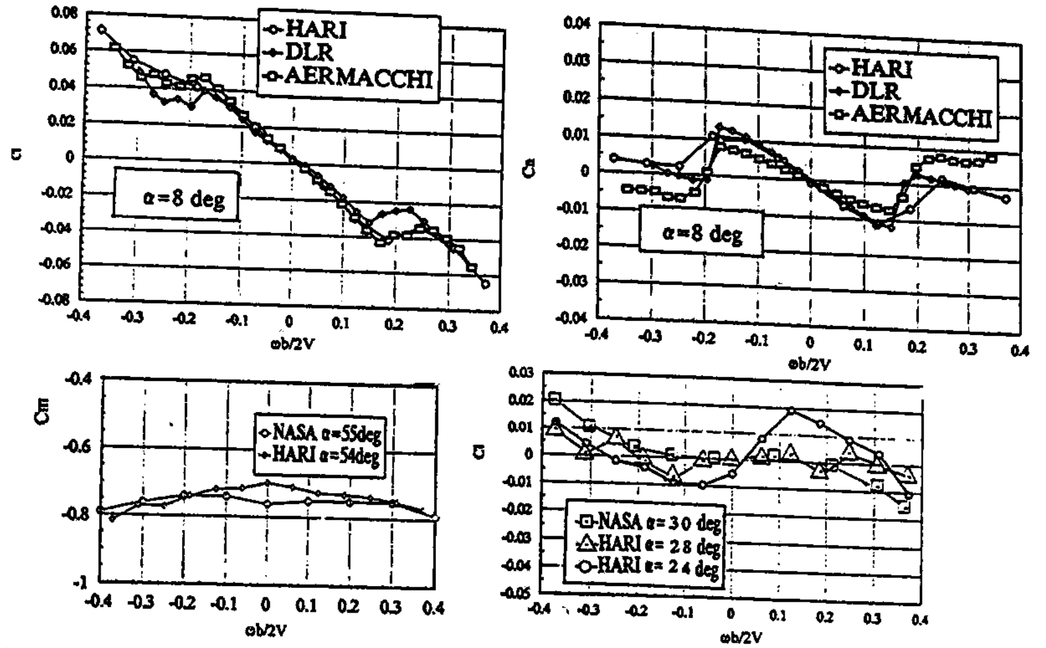


Fig. 3 comparison of rotary balance test results – coefficients are in body axes.

It is apparent that the results are practically identical. As far as the comparison with the NASA results is concerned, the small deviations noted can be ascribed mostly to the different model used, while the differences between the AEM, DLR and HARI data are not such as to significantly affect the estimated aircraft behaviour.

The phenomena, which are typical of the behaviour of this configuration at high angle-of-attack, are:

- Strong variation of pitching moment with variation of the nondimensional rate of rotation (ωb/2V)
- autorotation phenomena at stall

These phenomena are reproduced in a very similar manner in all cases.

Aerodynamic data obtained from the wind tunnel tests

The model built by HARI was not fitted with control surfaces; therefore, the tests conducted permitted only the stability characteristics to be assessed.

In particular, it was possible to obtain the following coefficients as a function of alpha, beta and ωb/2V:

CL, CD, Cy, Cm, Cl, Cn

The effectiveness of the flight controls can only be obtained from the test performed by NASA, and enable us to have a fairly complete aerodynamic data set. The contributions due to the acceleration in alpha and beta and to the rate of rotation, which are not aligned with the wind axis, are missing. These contributions were estimated by calculations at low angle-of-attack and extrapolated or even neglected at high angle-of-attack.

Mathematical model and simulations

The aerodynamical data necessary for the simulations were managed according to the mathematical scheme, as follows:

$$Cn = Cn\beta \times \beta + Cn\delta r \times \delta r + Cn\delta a \times \delta a + Cnp \times (pb/2V) + Cnr \times (rb/2V)$$

A similar structure has been applied to CD,CL,Cl,Cm and Cy.

The various coefficients were obtained from the wind tunnel tests. Whenever possible, an attempt was made to linearize the behaviour of the coefficients with beta and $\omega b/2V$. The simulations were performed using the six DOF simulation program AIRSIM. The matching between simulations and flight test results are presented in Figs.4.

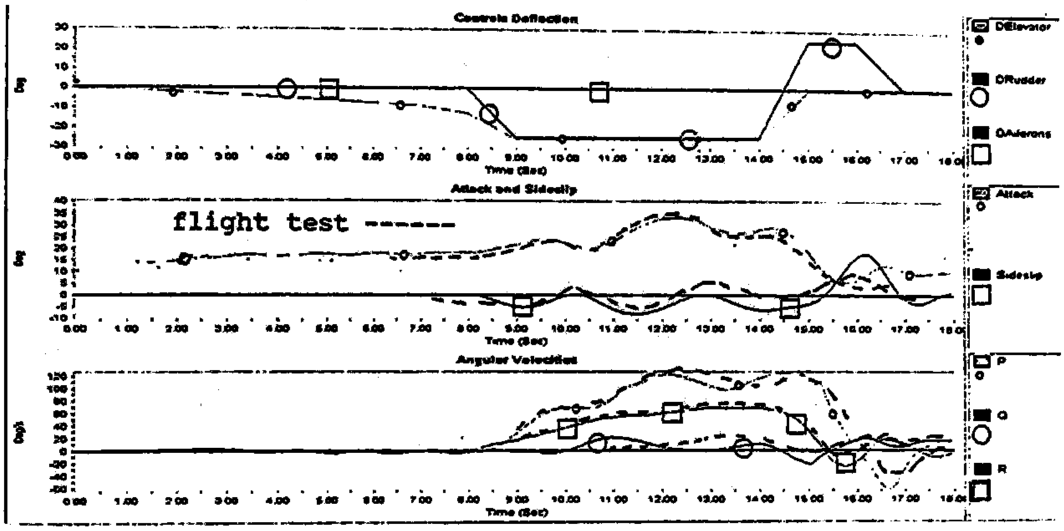


Fig. 4a Time history of spin entry, two turns and recovery

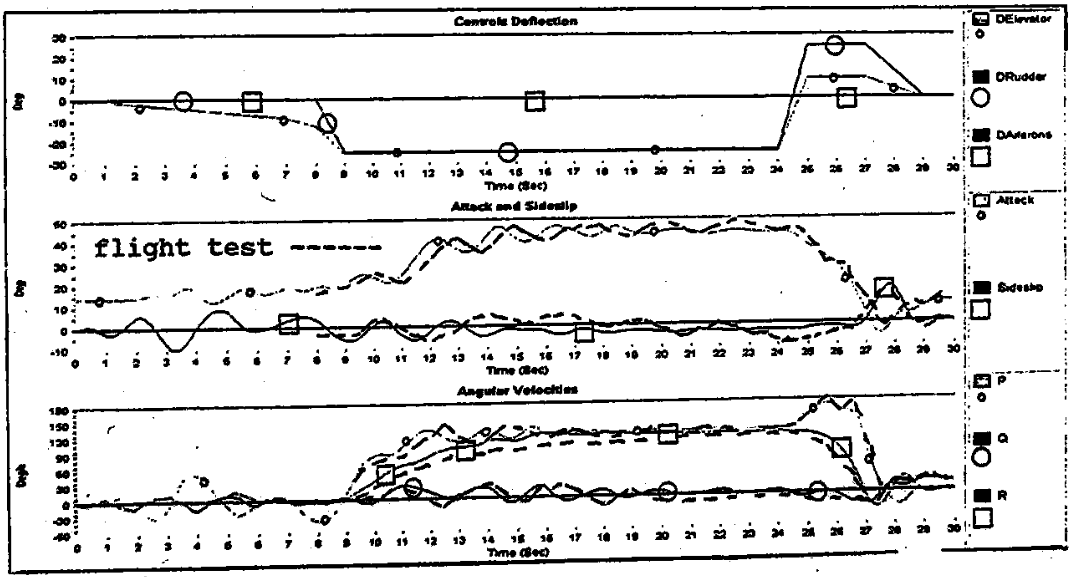


Fig. 4b, time history of spin entry, six turns and recovery.

This matching represents, in our opinion, the best validation of the wind tunnel data.

The matching is very good indeed and so the criteria used to perform the wind tunnel test and to manage the aerodynamic data proved to be reliable.

We believe and can reasonably state that the accuracy provided by the tests accomplished on a rotary balance is very high, allowing to satisfactory estimate the aircraft behaviour at high angle-of-attack and in developed spin.

Conversely, neglecting the $\omega b/2V$ dimension may result in a flawed, or even erroneous forecast of the aircraft behaviour.

The High Amplitude Oscillatory Coning Motion Balance (HAOCMB)

This balance is a dynamic test apparatus recently built in the FL-8 low speed wind tunnel of Harbin Aerodynamic Research Institute. FL-8 is a closed recirculating low speed wind tunnel; the test section is octagonal and the size is 3.5 m x 2.5 m. The maximum free flow speed is 70 m/sec.

HAOCMB is shown in Fig.5; it consists of the turn table of the test section, a gearbox, a motor and a set of support rods for fixing the test model. The driving motor is a disk shaped AC electrical motor of 2.2 kW; the maximum rate is 1450 rpm. The gearbox ratio is 1:7.5 and the gearbox is fixed by two supports to the upper and bottom turn table. The turn table can move from –180° to +180°. Two angled variable joints were designed for changing the test model attitude. The relation among these changeable angles is presented in Fig.6. The test wind speed is normally 30-60 m/s.

The main difference with respect to the rotary balance consists in the possibility to change the rotary axis orientation angle, and to obtain oscillations in alpha and beta during the rotation. The oscillatory frequency can be modulated by changing the rotational rate, and the oscillatory amplitude depends on the angle between rotational vector and wind vector.

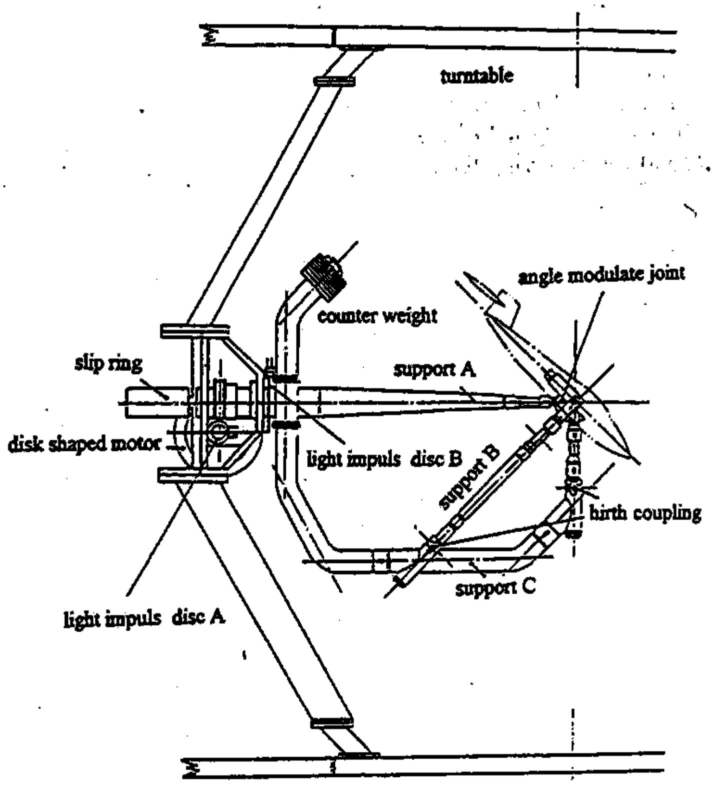


Fig. 5 abridged general view of HAOCMB

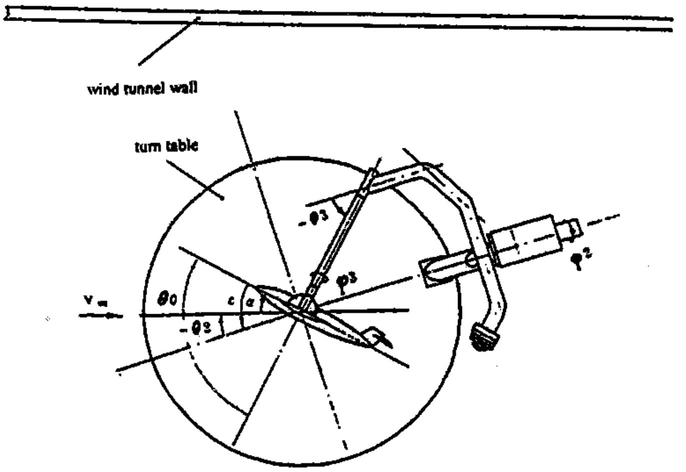


Fig. 6 sketch of configuration angles

The method used to get the model's oscillation relative to wind by constant rotation of the model avoids the interference by large inertia forces and moments as seen with forced oscillation; this is beneficial to the accuracy of aerodynamic measurements.

This apparatus is able to perform the test normally performed with rotary and oscillatory balances. By using this test platform, we can not only get useful data for the simulation of steady spin (rotation axis parallel to wind axis) but also for the simulation of spin entrance and recovery (rotation axis inclined to wind axis). What is more important is the ability to verify the aerodynamic mathematical model in order to be able to predict with good accuracy the high angle-of-attack behaviour.

Data acquisition was done by a 14 bit A/D converter with 80 KHz sampling rate. Two light impulse discs were used for triggering the beginning of a sampling set and the individual sampling points of each station. There are 256 sampling stations within one complete revolution.

Test results and discussion

Two test models, a delta wing fighter configuration J and a straight tapered wing trainer configuration K were used for the tests.

Repeatability

Seven repeated tests of model K at alpha = 8°, $\varepsilon = 10°$ show the test accuracy of the measuring system. Repeated tests were done under five rotational rates. Fig. 7 shows the root-mean-square error of a force element at different rotational rates within one revolution. Table 1 shows that the accuracy of this system is higher than that of the RB-1 rotary balance at HARI.

	σ Cz	σ Cm	σ Cl	σ Cn	σ Cc	σ Cx
GB	.001 ~ .004	.0003 ~ .0012	.0001 ~ .0005	.0001 ~ .0005	.0003 ~ .0012	.0002 ~ .0005
FL-8W.T (1995) static	.006 ~ .01	.0006 ~ .0025	.0006 ~ .0009	.0004 ~ .0008	.002 ~ .004	.0008 ~ .0021
FL-8RG-I (1990)	.0044 ~ .016	.0023 ~ .0075	.0013 ~ .0019	.00024 ~ .0008	.0039 ~ .0065	.0008 ~ .0022
HAOCMB (|Φ|< 180°	.0015 ~ .0077	.0005 ~ .0052	.00005 ~ .0007	.0001 ~ .00055	.0015 ~ .006	.0006 ~ .0027
HAOCMB (|Φ|< 30°	.0061	.0022	.00025	.00033	.004	.0015

Table 1 accuracy of the wind tunnel test measurements

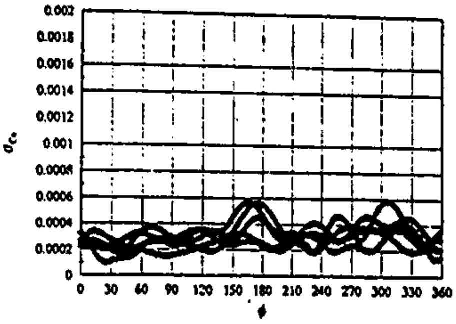


Fig. 7 root-mean-square error of an element during one revolution

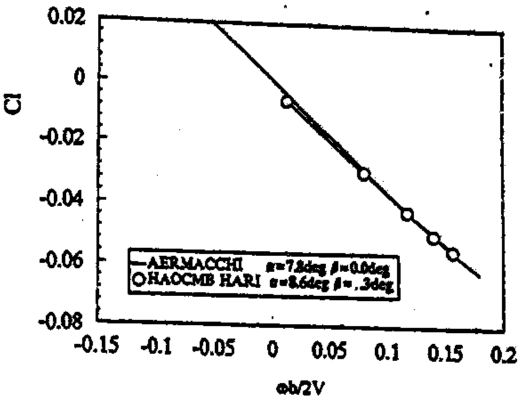


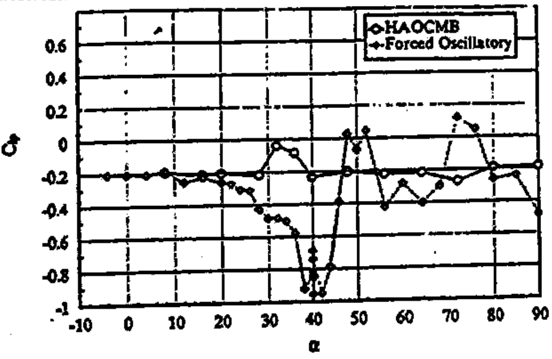
Fig. 8 comparison between HOACMB and rotary balance, rolling moment

Comparison between HAOCMB and rotary balance

When α0 = ε, HAOCMB becomes a conventional rotary balance. Fig.8 shows the result of the model K with HAOCMB of HARI, and the rotary balance of Aermacchi.

Comparison between HAOCMB and oscillatory balance

A comparison of data from HAOCMB test and forced oscillatory test on a fighter configuration is shown in Fig.9. The results are very close at lower angle of attack while in the region of 20° < α < 45°, the forced oscillation test displays an increase in rolling damping, and when α is greater than 42° the damping decreases. The results from HAOCMB are different, the damping decreases in the region 28° < α < 40°, and in other region it is very steady at Clp=-.02 like that at low angle of attack.



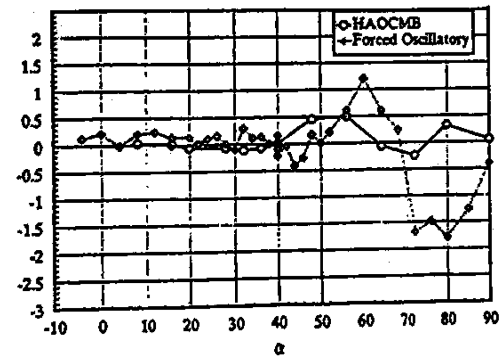


Fig. 9a comparison of test data Clp

Fig. 9b comparison of test data Cnp

According to the data available, the possible causes for the differences are:

-rolling moment is non-linear to the rolling angular displacement

-There is a small damping region at stall or post stall

Regardless of which factor dominated the difference, the force oscillation test with signal correlation processing method is restricted at high angle-of-attack. While in the HAOCMB test the variation of forces and moments with rotary rate are presented directly, the rotation rate can be higher (it can be 10 times more than that of the forced oscillatory test) and it is possible to have a higher accuracy in dynamic test.

Other results from HAOCMB

Fig.10 shows some results from the HAOCMB test. The variation of aerodynamic forces and moments versus the rotational angle ϕ and the time rate of rotational angle ϕ' can be seen. This test gives $C\phi$, the coefficients of moment about the rotary axis of the model.

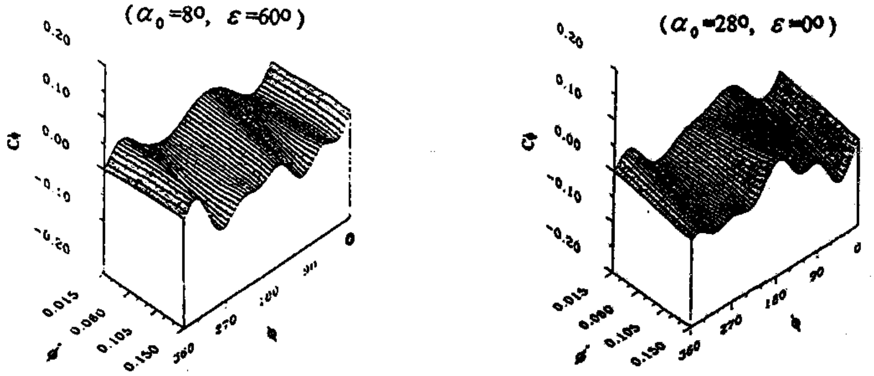


Fig. 10 Moment about rotary axis' variation with rotational angle and rotational rate

If the moment and rotational rate are in the same direction, it indicates that the aerodynamic force is pro-rotary. Actually, each value of ϕ corresponded to different α and β values. Therefore, more difference in matches of ε and $\alpha 0$ can bring out larger variation range of α and β in a test run. The derivative of moment coefficient about rotary orientation $C\phi\phi'$ is shown in Fig.11.

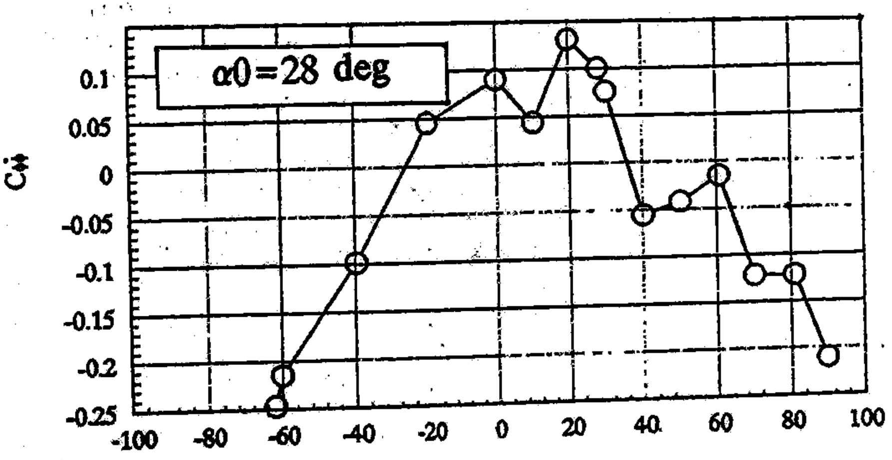
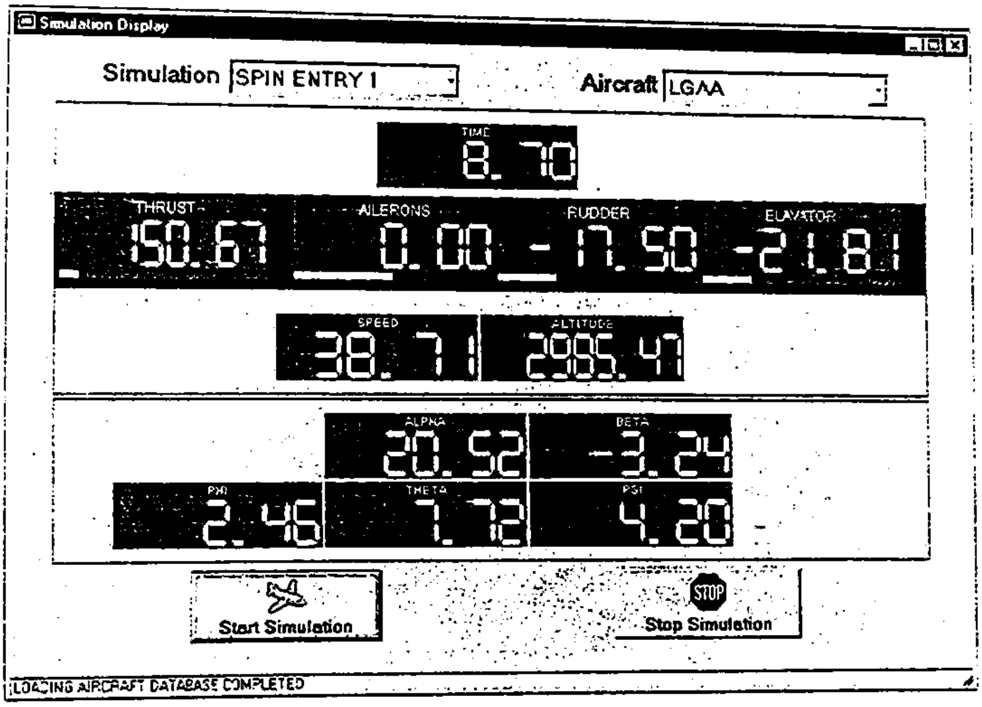


Fig. 11 $C\phi\dot{\phi}$ vs ε (α=28°)

With the new balance all the directional and longitudinal derivatives were evaluated; some of the results were published in Ref.[9], [10].

Simulation program AIRSIM

In our opinion, the best way to validate the wind tunnel test results is to show a good correspondence with the flight test results. For this work, it is necessary to have a proven simulation system able to perform the simulations in all flight conditions.
For this purpose the AIRSIM program was developed, whose control panel appears in Fig. 12.



Simulation SPIN ENTRY 1
Aircraft LGAA
TIME 8.70
THRUST 150.67
AILERONS 0.00
RUDDER -17.50
ELEVATOR -21.81
SPEED 38.71
ALTITUDE 2985.47
ALPHA 20.52
BETA -3.24
PHI 2.46
THETA 7.72
PSI 4.20
LOADING AIRCRAFT DATABASE COMPLETED

Fig. 12, AIRSIM control panel.

The program runs on a PC with Windows 95 operating system, and is able to perform a simulation in all situations including spin entry, developed spin and recovery. This thanks to the good accuracy of the algorithm used to obtain the solution to the equations of motion.
Just a few years ago, this level of performance with high-speed simulation was not possible, except on large powerful computers much more expensive than a modern PC [11].

A PC-based flight simulator like AIRSIM presents many advantages compared to conventional simulators, which require the involvement of several specialists, pilots and hardware technicians. Further, these kinds of simulators have a parameter database which is difficult to manage because it involves the hardware settings of the simulator cockpit.
Instead, AIRSIM presents a user friendly interface, with particular ease to change the database; further, the windows-like interface allows the user to change a parameter, run the simulation and view the result graphs without having to enter and exit different programs every time.

The data base editor allows the user to set different kinds of simulations with the same aircraft, and then graphically compare their results [12].

Conclusions

The rotary balance wind tunnel test performed by HARI proved to be reliable and its accuracy is very high.

The criteria used to manage the aerodynamic data and to prepare the mathematical model allow a satisfactory estimation of the aircraft behaviour at high angle-of-attack. Conversely, neglecting the $\omega b/2V$ dimension may result in a flawed or erroneous forecast of the aircraft behaviour.

The newly developed HAOCMB balance is very promising and is a big step forward from the classical rotary balance. This balance has the capability to perform steady tests, oscillatory tests and rotary tests. These tests contain extensive information so we can get data to meet the demand of various usages by a test project with a few number of wind tunnel runs, hence the test efficiency is very high. The apparatus is especially suitable for the establishment of an aerodynamical database for the aircraft's stall/departure/spin prediction, and can be a very useful tool for the verification of the CFD program and mathematical model.

The simulations necessary for the final validation of the data can be performed at low cost on a PC with AIRSIM, a simulation program able to perform the simulations in quasi real time even in critical situation such as stall, departure and spin.

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