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ENGINE SUB-IDLE MODEL

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Abstract

Modern unstable aircraft require to consider any flight operation leading to a possible catastrophic event.

Therefore semi-empirical mathematical models have been implemented either to assess the risk in advance of critical flight trials (e.g. engine relight) or to reduce the number of high demanding trials.

Engine Sub-Idle model has been designed to suit the above purpose. It provides performance characteristics when the engine thermodynamic cycle is not totally activated.

The model has been focused on forces and moments balance applied on the engine to enable to withstand aircraft systems loads and its assistance/resistance characteristics.

The Engine Sub-Idle model results have been compared to the zero aircraft system loads flight results.
Engine rundown behaviour is well represented by the model in all flight conditions tested.

The engine starting performance proves that at the design point and higher altitudes/Mach the model provides good results.

At lower altitudes/Mach the model data are pessimistic in term of time to idle.

An improvement of the model data is planned and a further verification will be performed in association with the engine loaded trials.

The approach used for this specific application can be extended to other propulsion systems.

Introduction

For twin engine aircraft, intrinsically unstable, double engine flame-out event may have catastrophic implications due to

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possibility of aircraft loss of control if adequate hydraulics power supply is not provided to the aircraft flight control system.
Nevertheless experimental activities aimed at Propulsion System Development and Integration include flight tests with a potential for double engine flame-out occurrence, namely in flight relight trials.

These tests are required before approaching flight tests where engine flame out can happen, i.e. severe engine handling at extreme condition or severe hot gas ingestion due to armament firing.

To understand the engine ability to relight and to support adequately aircraft Flight Control System needs during the relight attempt, a dedicated engine simulation model was implemented.

The engine simulation model evaluates live engine, engine rundown/windmilling and starting performance.

Engine rundown and windmilling performance are derived from the engine design characteristics and on Ground and Altitude Test Facilities data.

The engine dynamics during relight is analytically computed using spool equations based on engine starting capabilities and the HP shaft mechanical loading including aircraft services capabilities.

In advance of flight test activity a comprehensive session at the simulator facility with the pilots has provided sufficient confidence on the real aircraft operation behaviour.
The results of the engine model have been compared to the test results

Engine Model

The engine considered is:

A low bypass ratio two spool turbofan afterburner engine consisting of a three stage fan, a five stage high pressure compressor, an anular combustion chamber, a single stage cooled high pressure turbine, a single stage cooled low pressure turbine, an afterburner and a convergent - divergent nozzle.

This engine is connected to the aircraft gear box via Power Of Take (POT) shaft.

Engine model is one of the several aircraft systems model which form the real time simulation programme (see fig.1).

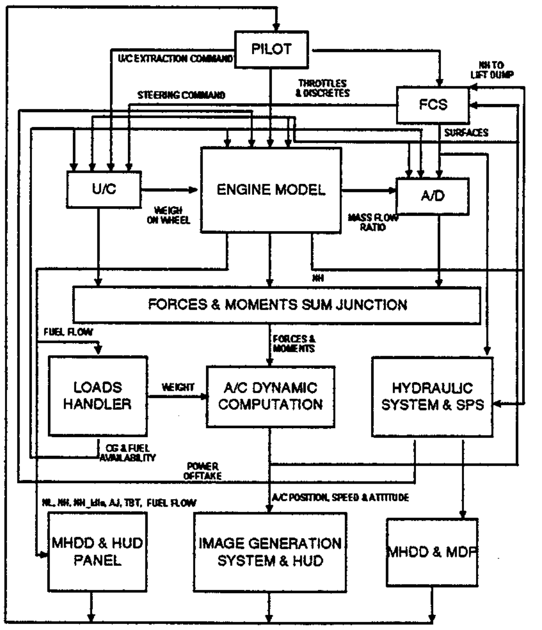

fig. (1) Engine simulation model lay-out

For what concern the engine type under discussion, the model evaluates both live engine performance and engine Rundown/Windmilling.

The live engine performance is computed through interpolations based on steady-state and transient data bank derived by the engine Performance Computer Programme (Engine Computer Deck).

The engine rundown and windmilling performances are derived from the declared engine characteristics. The engine dynamics during relight is analytically computed using spool speed equations.

The engine simulation model is shown in the following para's.

Steady-State performance in sub-idle

Before describing the engine sub-idle model, it is necessary to define the forces applied on the engine which are parts of the forces and moments used for computing the aircraft dynamics.

Considering the engine in steady-state conditions and in order to evaluate the forces applied on the engine it is necessary to calculate the engine mass flow.

The mass flow is calculated using the following equations:

$$ETA = f(WAT, Mach) \qquad \text{fig.(2)}$$

and

$$\dot{m}\frac{\sqrt{T}}{P} = f\left(\frac{PT2}{PS0}, Z\right)$$

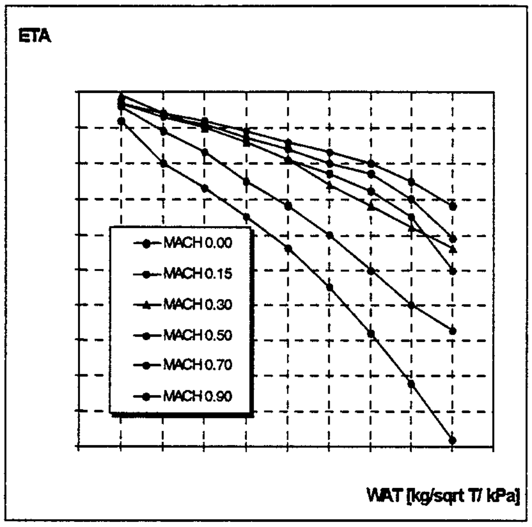

fig.(2-a) Subsonic Recovery Factor

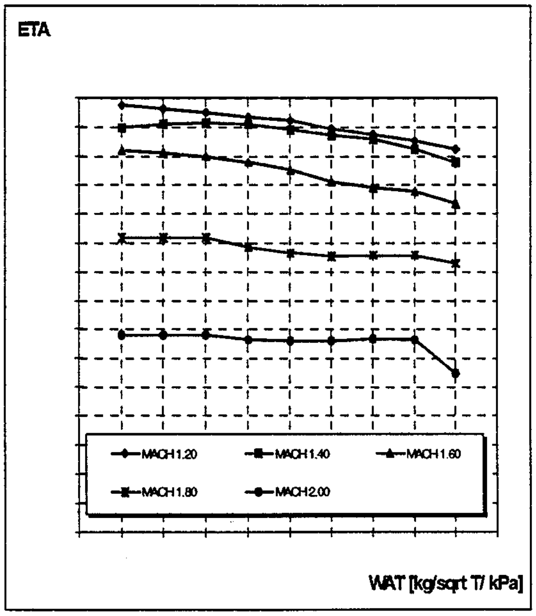

fig. (2-b) Supersonic recovery Factor

and with an iteration process the correct value is computed.

Consequently from $\dot{m}$ we can obtain the Force F_{RAM}

The intake drag value is a function of the mass flow ratio as in fig.(3).

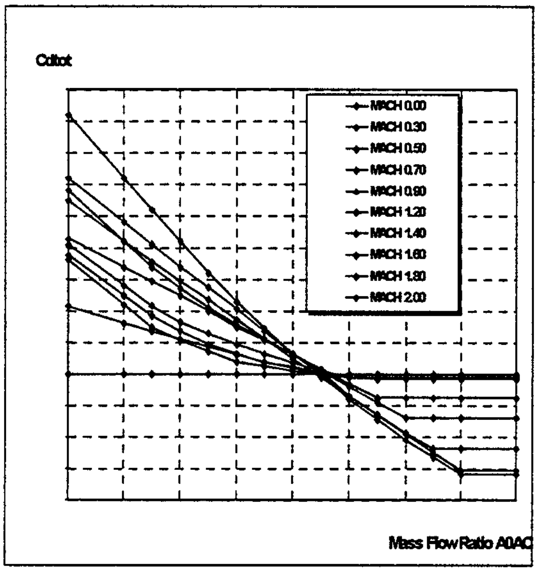

fig.(3) Intake total drag coefficient.

Using the value of "Jet Pressure Ratio" fig.(4)

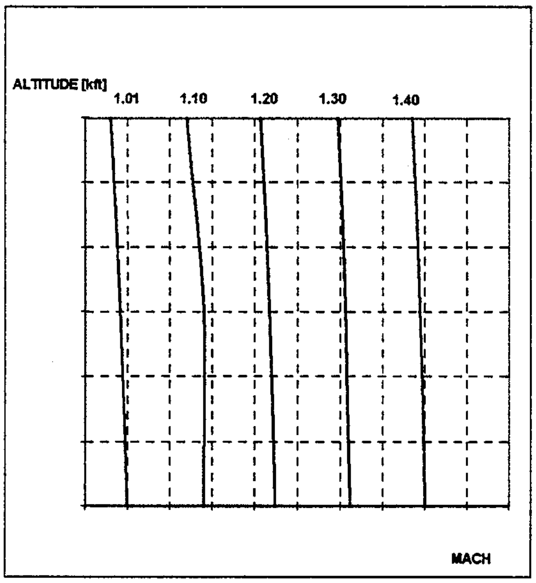

fig.(4) Nozzle pressure ratio

and using the afterbody drag coefficient from fig.(5) it is possible to calculate the value of the following forces:

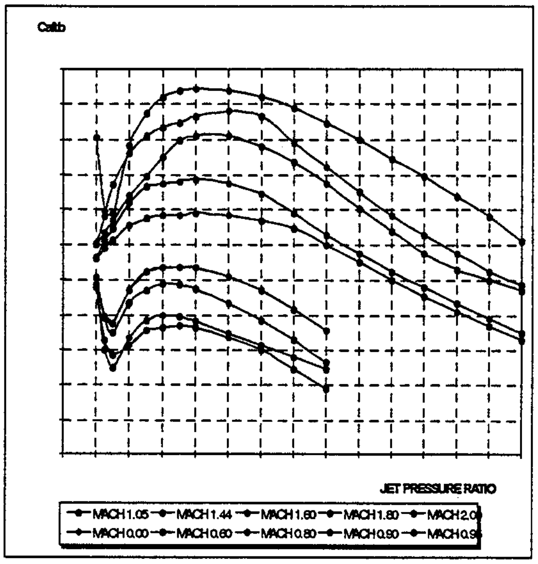

fig.(5) afterbody drag coefficient

⇒ F_{INTAKE} = Intake Total Drag

⇒ $F_{AFTERBODY}$ = Afterbody Drag

Eventually assuming negligible the Gross Thrust (F_G) we can write the equation of the forces applied on the engine which will be used in the aircraft model.

$$\begin{cases} F_G = 0 \\ F_G = F_N - F_{INTAKE} - F_{RAM} - F_{AFTERBODY} \end{cases}$$

Engine Run Down

In the sub-idle engine model one of the major parameter is the NH rotation spool speed with and without power off take.

Engine windmilling without power off take

After an engine shut down NH speed is running down to the stabilised engine windmilling.

NH speed is calculated from fig.(6) which shows the HP spool speed versus mach number at a variety af altitudes.

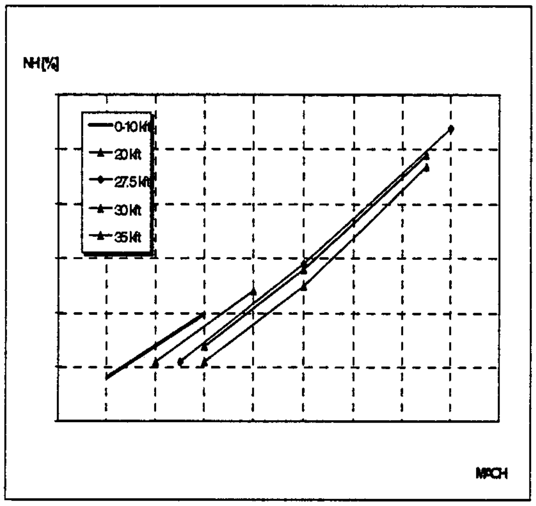

Fig. (6) Engine Windmilling data

Fig. (6) is the result of the engine tests, without power offtake, carried out on the Altitude Test Facility (ATF).

Engine Windmilling with power off take

After an engine shut-down/flame-out the aircraft requires from the engine an amount of power off take to guarantee an adequate aircraft control/stability during a descent windmilling condition, trying to relight at least one engine.

The loading system keeps, during engine run down, the torque from the engine which reduces with the corresponding NH.

The equilibrium between the energy taken from the engine mass flow and the energy required from the aircraft control system determines the engine spool speed.

Being not available experimental data from engine manufacturers, we found appropriate to use the estimated curve showing the effect of power offtake on engine spool speed during windmilling fig. (7).

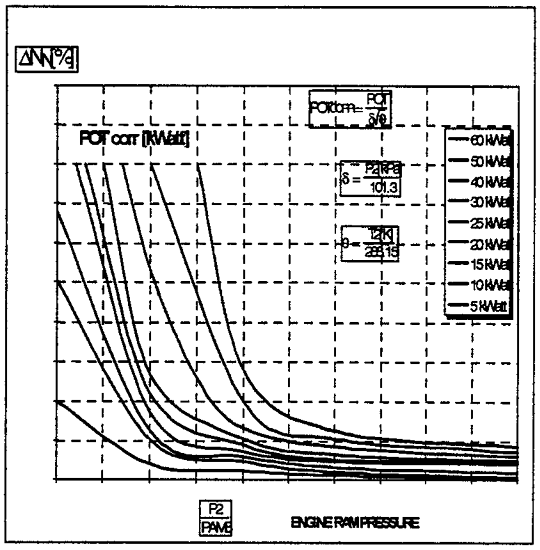

Fig. (7) Estimated windmill rundown with power off take.

Therefore, after an engine shut down, stabilised NH speed is in accordance with fig. (6); and the additional drops of NH, in presence of mechanical loads, are estimated from fig. (7) as:

$$NH_{LOADED} = NH_{UNLOADED} - \Delta NH$$

Engine dynamics

After an engine shut down, the NH speed is running to the stabilised engine windmilling spool speed.

If the engine is turned off at NH over idle, the engine speed decay is divided into two phases:

run down $\Rightarrow (NH\%)_{idle} < NH\% < (NH\%)_{shutdown}$

windmill $\Rightarrow (NH\%)_{idle} > NH\%$

Dynamics during run down

If the engine is turned off when its NH is over idle, a linear decay of NH is assumed at the fixed rate of:

$$\frac{\partial(NH)}{\partial t} = -7$$

derived as an average from engine bench testing.

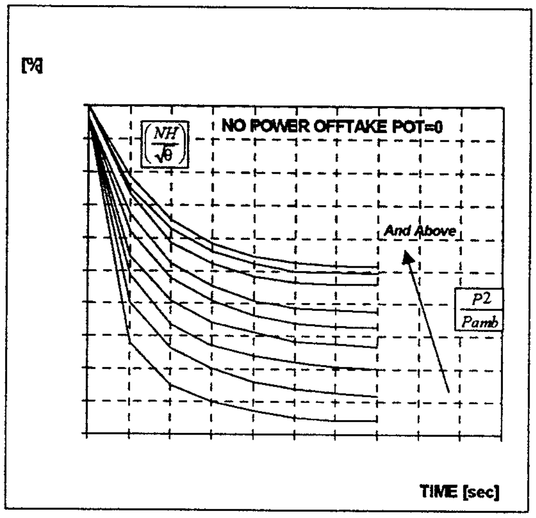

Fig.(8)Estimated windmill rundown speed unloaded

Engine rundown below idle down to windmilling speed is computed using NH decay of fig(8) and the effect of power extraction determines the stabilised windmill engine spool speed (taken from experimental data fig.6).

Engine starting

Engine dynamics during engine relight phase will be computed by integration of the torque acting on the engine spool:

⇒ Total mechanical torque extracted from the engine(PTOTORQ).

⇒ Total engine torque with the ram and loads effect (HPTORQ).

The only data available to us, engine torque during starting, are the resistance/assistance curves fig(9).

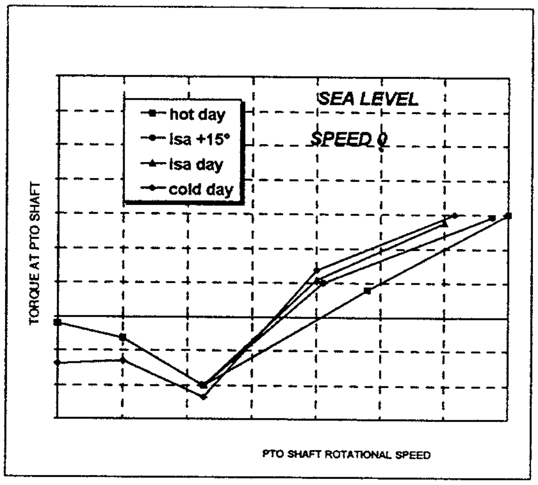

fig.(9/1)Resistance/Assistance characteristics

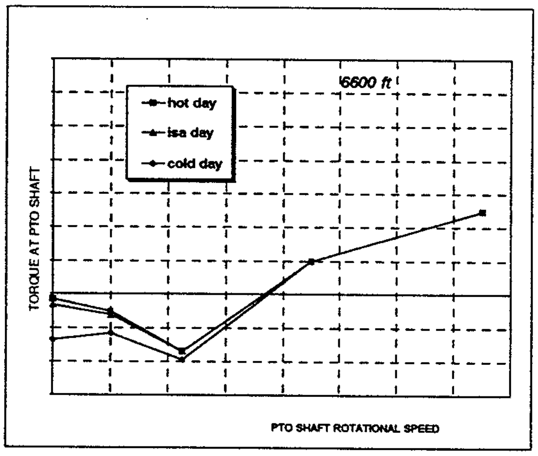

fig.(9/2)Resistance/Assistance characteristics

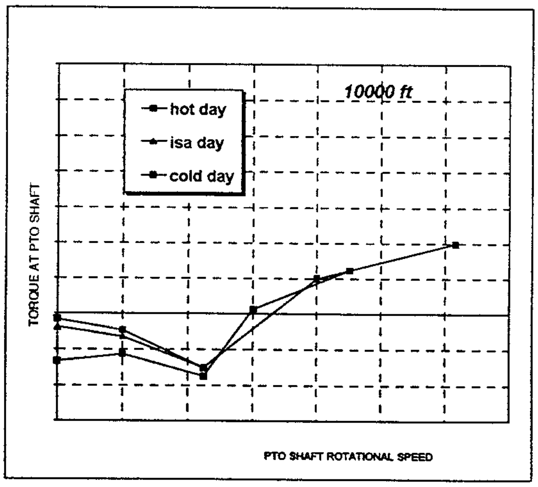

fig.(9/3)Resistance/Assistance characteristics which, being based on static conditions, do not take into account the effect of the aircraft speed.

To take into account the ram and loads effect we made the following assumption:

⇒ HPTORQ = RAMTORQ + ERATORQ + DELTATORQ

Where the RAMTORQ is the resistance/assistance torque evaluated at the stabilised NH windmill;

⇒ RAMTORQ = -ERATORQ

and ERATORQ is the resistance/assistance torque computed at the actual NH, assuming that the resistance assistance characteristic at Mach>0 is the same of that at Mach=0 with a simple translation of the axis origin making the zero torque corresponding to the known stabilised windmill NH.

Based on engine manufacturer data we know that at windmilling speed the engine is able to produce a mechanical power as indicate in fig.(10);

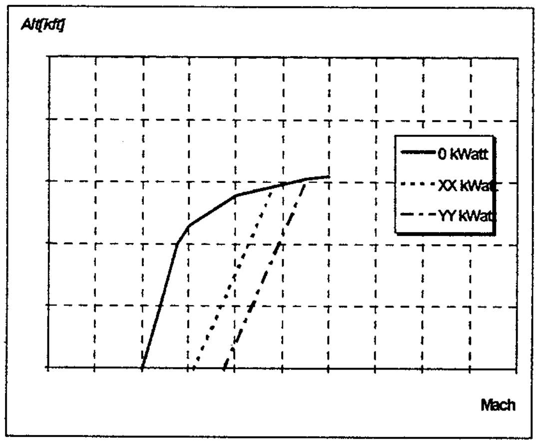

fig.(10) Relight boundary

so we can assume an addition torque DELTATORQ derived from the above figure:

⇒ DELTATORQ = f(Mach;Alt)

Dividing the total torque by the HP rotor inertia we can compute the $\delta(NH)/\delta t$ and consequently the NH behaviour during the starting phase.

Relight simulation

To study the effects of a double engine flame out to the aircraft systems, a dedicated activity has been performed.
One of the early tests performed out consists on shutting down the engine and achieving the stabilised NH windmill and restarting the engine, without loads, within the relight envelope; the typical manoeuvre is showed in fig.(11).

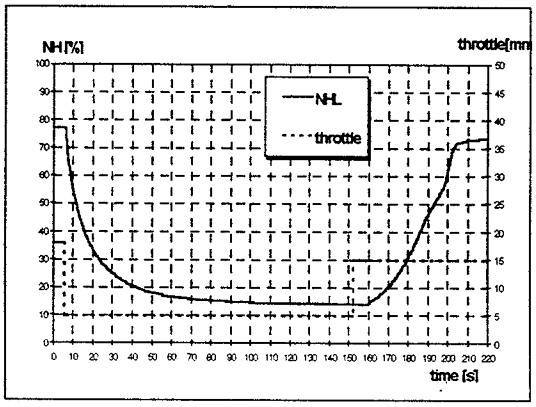

Fig.(11) Typical Manoeuvre

The results of the engine model have been compared to the available flight test results.

Flight test result

The engine in flight relight tests (unload) were carried out at flight condition selected in the windmill relight envelope.
The trials have been performed starting from the most favourable zone of the windmill relight envelope (19000ft/M 0.8) and proceeding up to the other tests points.
From the engine sub-idle model point of view in the following

figure are showed the comparison between the engine simulation model and flight test results.

Comparison

The engine in flight relight test with power off take extraction from the engine will be carried out in the future, however the typical engine shut down and relight characteristics obtained with the above descripted model is showed below.

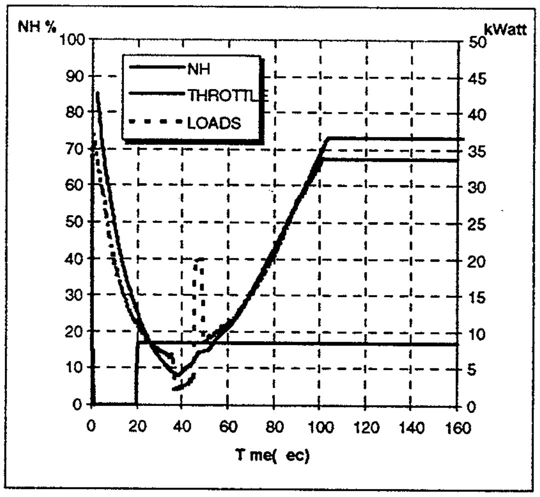

fig.(12) loaded relight (Model)

The comparison between the simulation and the experimental data has been carried out on the unloaded cold relight test points, in order to examine the behaviour of the engine rundown and the starting phase.

Engine rundown

Figures from 13 to 16 show the comparison between the simulated engine rundown and experimental data.
For these relight points, the analysis shows a good agreement between the two trends.
In fact, the decay on NH and the asymptotic NH value are in good agreement.

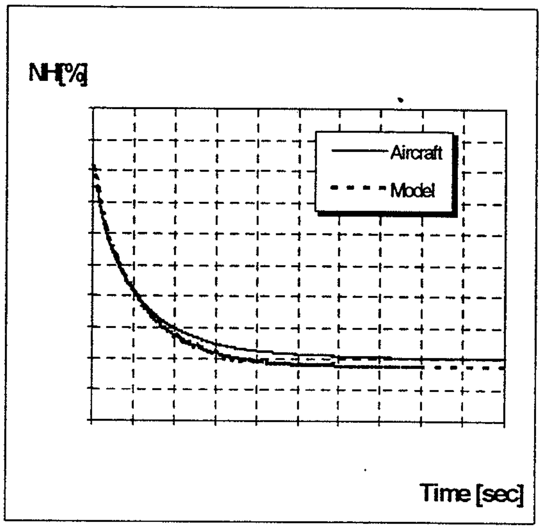

fig.(13) Mach=0.69;alt=15100

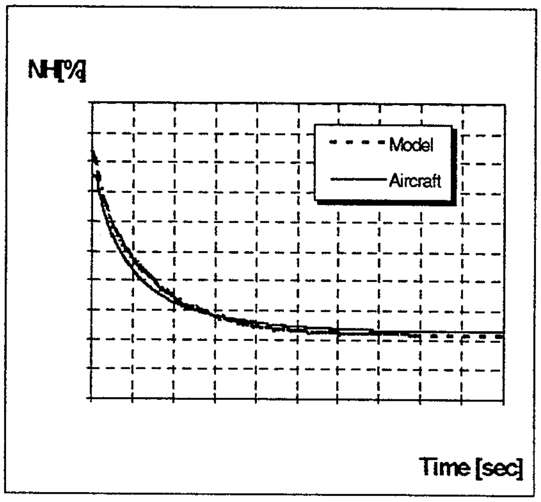

fig.(14) Mach=0.8;alt=15000ft

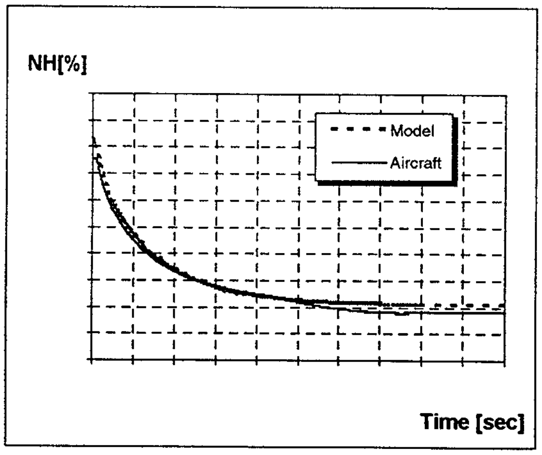

fig.(15) Mach=0.8;alt=19000ft

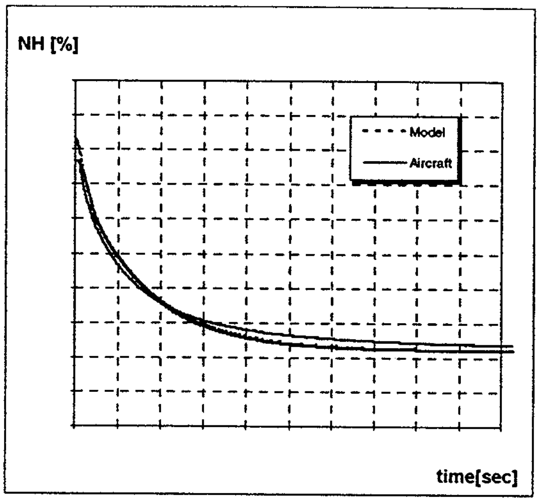

fig. (16) Mach=0.83;alt=20000ft

The fact that the predictions are in good agreement with experimental data, prove the validity of the most relevant assumptions and no corrective actions are necessary for the rundown phase.

Engine starting

For this phase the comparison between the flight test result and the model shows a good agreement.
In the point (19000ft/M 0.8) already identified as "favourable" the run up phase and the approach phase are practically the same.

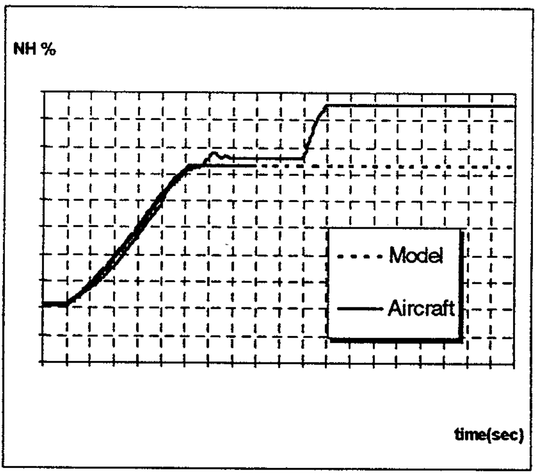

fig. (17) Engine starting
Mach=0.8;alt=19000ft

For mach and altitude higher than the "favourable" point the agreement between the curves is still the same.

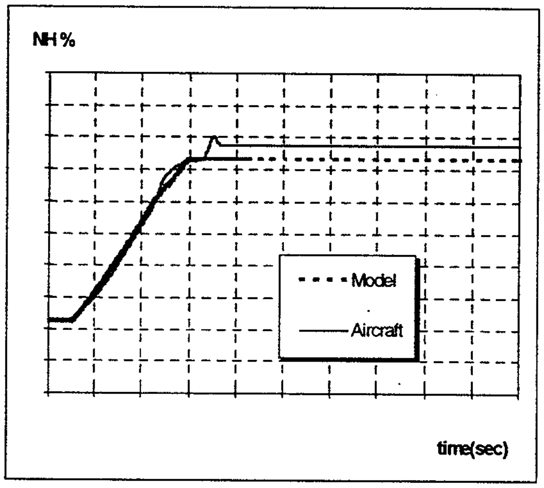

fig. (18) Engine starting
Mach=0.83;alt=20000ft

For mach and altitude below the above mentioned point there is a difference between the two curves. The engine model is more pessimistic in term of "time to idle" and the effect of aircraft speed is stronger than the altitude.

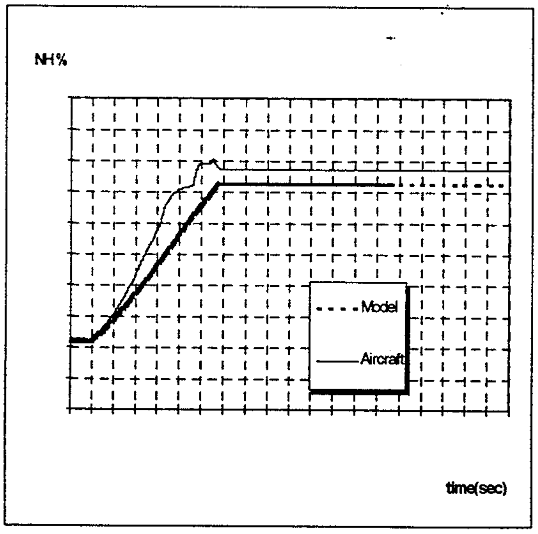

fig. (19) Engine starting
Mach=0.83;alt=15000ft

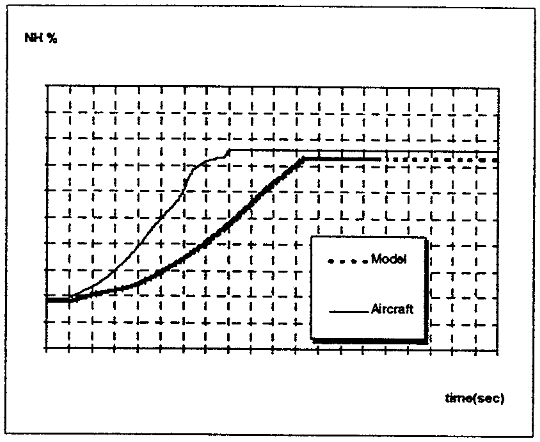

fig. (20) Engine starting
Mach=0.69;alt=15100ft

For this phase corrective actions are necessary.

Conclusion

The Engine Sub-Idle model results have been compared with the results achieved in flight, at the present only with no aircraft systems loads.
The engine rundown behaviour appears to be well represented by the model in all flight operation conditions tested.
The engine starting characteristic highlights the consideration that at the design point and higher altitudes/Mach the model provides good results. At lower altitudes/Mach the model data appear to be pessimistic in term of time to idle.
An improvement of the model inputs data is planned and a further verification will be performed in the next future when also the loads cases will be analysed.
The approach used for this specific application can be extended to other propulsion systems.