SEMI-BURIED ENGINE INSTALLATION: THE NACRE PROJECT EXPERIENCE

Jean-Luc GODARD
ONERA, 8 rue des Vertugadins, 92190 MEUDON, France

Keywords: *engine installation; semi-buried engines; project NACRE*

Abstract

This paper presents an investigation conducted on semi-buried engine installations for civil transport aircraft within Task 3.2 of the NACRE European project. The objective was to perform a multi-disciplinary analysis, considering aerodynamic, aero-acoustic, structural and certification aspects, in order to determine the viability of such engine installations. An aircraft configuration of flying wing type was considered, with high by-pass ratio engines. In a first step, the engine installation architecture was defined, with three engines partly buried in the rear part over the fuselage. Then, investigations at discipline level were conducted. In aerodynamics, the main concern is the poor intake performance due to the ingestion of the airframe boundary layer, especially in cruise: this drawback can be overcome by introduction of flow control techniques such as suction or vortex generators. In aero-acoustics, burying the engine in the airframe has a beneficial impact on engine noise propagation, but this improvement was found limited for the configurations considered in the project. In structures, burying the engine leads to a reduction of mass for the attachment structure of the engine on the airframe, that was found significant by comparison to a conventional under-the-wing installation. The certification constraints related to engine fan burst protection could be a critical point for engines close to the airframe: the experiments carried out and confirmed by computations have delivered elements to propose solutions to this concern. The investigation conducted within Task 3.2 of the project NACRE has not identified any critical point against a semi-buried engine installation.

1 Introduction and Context

Over the last years, several projects have been devoted to unconventional aircraft concepts such as flying wings [1] [2], which could be a solution for high capacity transport aircraft. On the engine side, the tendency is to increase the by-pass ratio to reduce the fuel consumption, leading to an increase of the diameters. A possible consequence is engine installations more close coupled to the airframe. In parallel to these technical evolutions, the regulations present increasing environmental constraints on noise and emissions that could drive the aircraft design towards unconventional configurations. For the engine integration, these evolutions and constraints could lead, for instance, to installations over the airframe to reduce noise. Due to the evolutions of size, a close coupled installation, with engines partly buried inside the airframe could be an optimum solution.

The NACRE European project has investigated unconventional aircraft configurations [3], and Task 3.2 was devoted to the analysis of semi-buried engines installations. The NACRE (New Aircraft Concepts REsearch) project was aimed at investigating, developing and assessing the new technologies that are required for new aircraft concepts, designed not only to fulfil operational efficiency targets, but also to respect the constraints in term of environmental impact. The investigations were performed at a component level (wing, fuselage, engine integration). The technologies considered covered a wide range of disciplines such as aerodynamics, acoustics, materials, structures, engines and systems. Numerical as well as experimental investigations were conducted. At the end of the project, a multidisciplinary assessment was performed for different aircraft concepts. Inside the project, Task 3.2 aimed at investigating the problems raised by semi-buried engine integration on a flying wing type configuration and the final objective of this Task was to assess the viability of such engine installations.

Generally speaking, the integration of engines on aircraft is carried out taking into account the following technical aspects:

- The general architectures of the aircraft and engines considered;
- The flight mechanics aspects (distribution of mass, application of engine thrust, control surfaces);
- The aerodynamics aspects (interference between engine and airframe and the consequences on intake efficiency, drag and thrust);
- The aero-acoustics aspects (engine noise sources, noise propagation and airframe shielding effect);
- The material and structural aspects (structure to attach the engine on the airframe, aero-elastic aspects);
- The safety and certification aspects (fire protection, fan burst containment, bird ingestion).

These different aspects were more or less considered and assessed within Task 3.2, through numerical activities. For certification aspects, high energy material tests were also carried out.

Compared to conventional under-the-wing engine installations, semi-buried installations present the following advantages:

- It is a solution to the increase of engine diameter;
- The pitching moment due to the thrust should be reduced, with a possible decrease of control surface areas;
- The absence of pylon leads to a reduction of mass, and aero-elastic concerns should be reduced;
- The absence of pylon and the reduction of nacelle wetted area lead to a reduction of aerodynamic drag;
- The ingestion of the fuselage boundary layer by the engine could lead to an increase of the propulsion efficiency;
- The engine noise propagation should be reduced by the airframe masking effect.

On the other side, the following drawbacks can be identified:

- The constraints due to burying can lead to a more downstream engine position on the airframe, less efficient on flight mechanics side;
- The engine close to the airframe leads to significant aerodynamic engine/airframe interference effects;
- The boundary layer on the airframe can be swallowed by the engine intake, with worse engine operating conditions;
- The engine close to the airframe leads to more vibrations and noise in the cabin;
- Certification regulations (fire, fan burst containment) could be more difficult to fulfil due to the proximity of the engine to the airframe;
- Engine maintenance could be more difficult due to a more limited access to the engine.

The activities performed within Task 3.2 of the project NACRE are presented in the next paragraphs. They were conducted according to the following methodology:

- In a first step, the general architecture of the semi-buried engine installation was defined at a pre-design level, considering the most important objectives and constraints;
- In a second step, more precise investigations were performed at discipline levels, in aerodynamics, aero-acoustics, structures, certification aspect, on more detailed designs to evaluate the viability of such engine installations, to identify possible critical points and to deliver some quantitative data allowing for a further global assessment.

2 Engine installation

2.1 Aircraft configuration

The aircraft baseline configuration is a flying wing. It was defined by the project manager Airbus within another Task, aimed at selecting the reference aircraft of the project, on which innovative technologies would be applied within other tasks such as Task 3.2. This shape, derived from the ones defined within the previous European project VELA, is a long range aircraft (7,500 Nm range) of high capacity (750 seats), flying at a cruise Mach number 0.85. The main geometrical characteristics are: a wing span of 100 m, a fuselage length of 62 m and a reference surface of 2,000 m^2. The maximum take-off weight is 700 tons. The initial VELA configurations had engines installed under the wing, as well as vertical tail planes on the central part of the body (figure 1): these elements have been modified within the NACRE project.

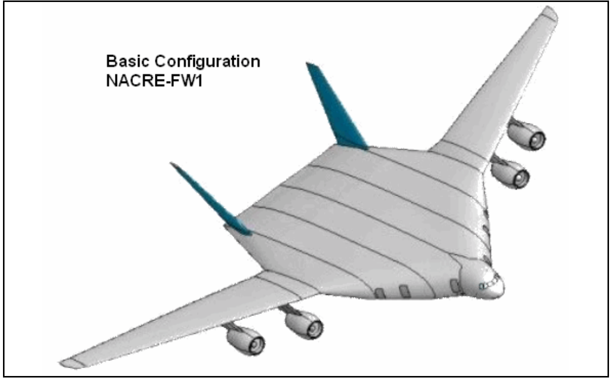


Fig. 1. Baseline aircraft configuration

2.2 Engine configuration

Taking into account the specifications delivered by the aircraft manufacturer, MTU defined generic engine concepts. Because the number of engines was not prescribed, MTU proposed two sets of engines, both fulfilling the requirements:

- 156,300 lbf SLS thrust engines for a three engines aircraft configuration;
- 117,200 lbf SLS thrust engines for a four engines aircraft configuration.

A pre-design analysis led to the following characteristics for the set of three turbofans (four turbofans in brackets):

- Conventional advanced high by-pass ratio turbofan architecture;
- By-pass ratio 9.0;
- Fan diameter 3.58 m (3.12 m);
- Engine length 6.0 m (5.2 m);
- Weight 30,500 lbs (22,900 lbs).

MTU evaluated the performance data in terms of thrust or consumption for different operating conditions for the isolated engine. MTU delivered also acoustic data on engine noise sources. In addition, because it was expected that semi-buried engines may operate with high levels of distortion, MTU delivered predictions on the influence of distortion on fan noise and efficiency.

2.3 Installation architecture

A preliminary design of the engine installation architecture was done first, before the detailed design performed at discipline level. This design was performed taking into account the assumptions of the project and the most critical constraints.

The assumptions have been the following ones:

- An engine installation over the airframe was desired to get the beneficial masking effect of the airframe on the engine noise propagation;
- The investigation was aimed at assessing engines semi-buried in the airframe;
- The baseline fuselage configuration was kept unchanged, although a modification of engine installation could have led to a more optimised modified shape.

The different following aspects have been considered for this pre-design work:

- The geometrical constraints;
- The safety (certification) aspects, in particular the engine fan burst containment;
- The different disciplines (aerodynamics, acoustics, structures, flight mechanics), but at a pre-design level.

A preliminary assessment in aerodynamics, acoustics and structures, has shown that it is more efficient to install the engines over the central part of the fuselage than over the wings.

With this constraint, the selection of engine positions is mainly driven by the safety aspects: to avoid any risk due to engine fan burst, the engines must be positioned downstream of the cabin and in particular of the pressure bulkhead. In addition, an engine must not be affected by such concern from another one. Figure 2 illustrates the possible fragment trajectories.

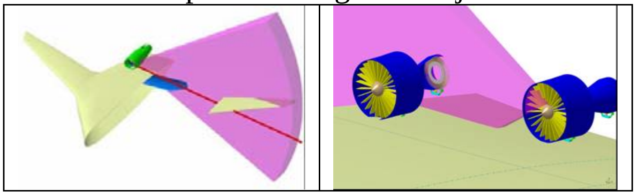


Fig. 2. Possible fragments trajectories

An engine installation with four small engines, quite close to each others, makes this certification constraint quite a critical point. So, a three big engines installation was preferred, presenting also other advantages, for instance in aerodynamics. This installation is presented in figure 3, with one engine in the symmetry plane, the two lateral ones more upstream to reduce the consequences of fan burst and to maximise the acoustic masking effect.

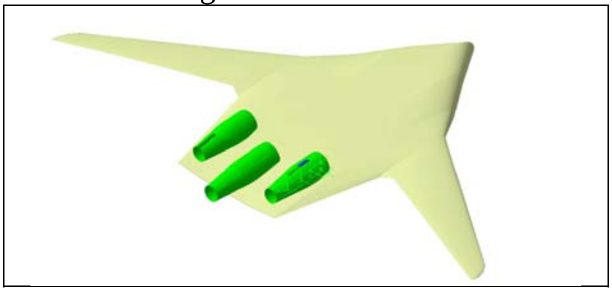


Fig. 3. Engine installation architecture

Another consequence of the certification constraint is the decision to suppress the vertical tails (figure 1) and to replace them by crocodile ailerons.

In the following paragraphs are presented more detailed investigations at discipline level.

3 Aerodynamics

3.1 Analysis of phenomena

In aerodynamics, burying the engine leads to a decrease of the wetted area and a reduction of drag. But, the engine/airframe interference phenomena are of higher intensities, generating drag or a loss of thrust. In addition, the boundary layer developing on the airframe can be ingested by the intake and the flow entering the engine is highly non-uniform and presents high levels of distortion [4]. This topic, specific to semi-buried engines, was investigated within the NACRE project.

In a first step, the design of different reference nacelles, corresponding to different burying levels along the vertical direction inside the airframe, was performed. Two levels, equal to 8% (figure 4) and 15% of the engine fan diameter were selected as possible realistic values. Then, the intakes have been assessed with RANS computations for different flight conditions: take-off (Mach= 0.10), climb (Mach= 0.25) and cruise (Mach= 0.85). For these conditions, the boundary layer swallowed by the intake had a thickness equal roughly to 0.8 m or 20% of the fan diameter. The assessment was based on the following intake performance coefficients: recovery coefficient Eta (average total pressure in fan plane divided by freestream total pressure) and distortion coefficient DC60 (maximum average value of total pressure in a 60^o sector minus minimum similar value, divided by freestream total pressure).

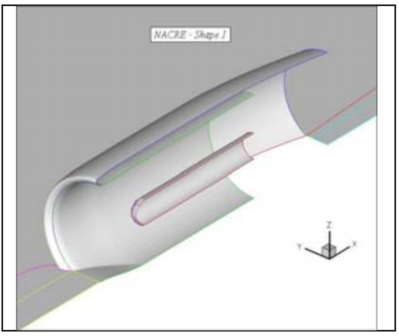
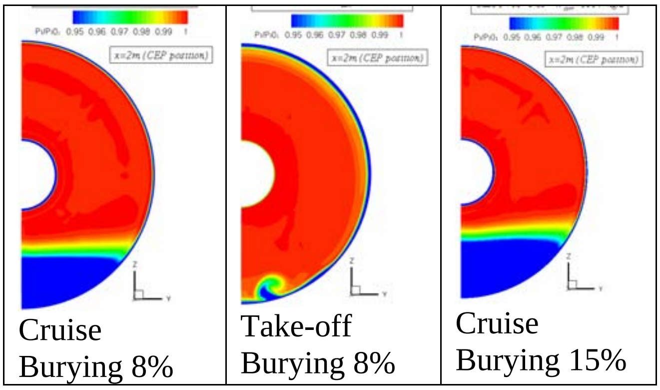


Fig. 4. Semi-buried (8%) intake configuration

The cruise condition appears as the most critical one, with Eta= 0.974 and DC60= 0.34 for a burying by 8%, whereas Eta is close to 1 and DC60 close to 0 for the other aerodynamic conditions. The non-uniformity and distortion in the flow are illustrated by the total pressure distributions in the fan plane (figure 5).

The increase of the burying level to 15% leads to a decrease of intake performance, with Eta= 0.969 and DC60=0.38 (figure 5). This parameter has a significant influence on the performance.
A variation of the boundary layer thickness has shown a roughly linear evolution of Eta and DC60 with it: this parameter has the most important influence on the intake performance. This statement shows the importance of a correct selection of the engine position on the airframe.



Cruise Burying 8%

Take-off Burying 8%

Cruise Burying 15%

Fig. 5. Total pressure in fan plane

Although the intake performance was considered acceptable for the engine, these unusual and bad values led the participants of the project to consider additional ways to improve this performance.

3.2 Improvement of performance

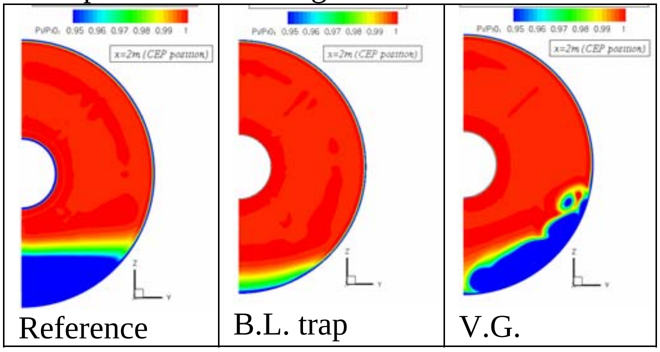
Two different methods have been considered: the modification of the intake shape and the introduction of flow control techniques.

The reference intakes considered previously have circular cross sections, cut at the bottom by the airframe. New intake shapes were designed with modified elliptical sections, but keeping the same cross section area. The objective was to obtain different distributions of the boundary layer along the azimuth direction and to assess this effect. Unfortunately, the analysis has shown only a limited improvement of the performance coefficients.

Different flow control techniques have been introduced: suction at the wall upstream of the intake, a boundary layer trap under the intake (B.L. trap), vortex generators outside and inside the intake (V.G.). Some typical values of the performance coefficients are presented in the following table, for the intake buried by 8% in cruise conditions:

	Reference	B.L. trap	V.G.
Eta	0.974	0.996	0.982
DC60	0.34	0.02	0.12

The improvements are illustrated by the total pressure distributions in the engine fan plane (figure 6). For the suction technique and the boundary layer trap, the gain is directly due to the suction of a part of the boundary layer, which is not swallowed any more by the intake. With the vortex generators, the gain is on one side due to a partial deviation of the boundary layer on both sides of the intake, and on the other side due to a more regular distribution of total pressure loss along the azimuth direction.



Reference

B.L. trap

V.G.

Fig. 6. Total pressure with flow control

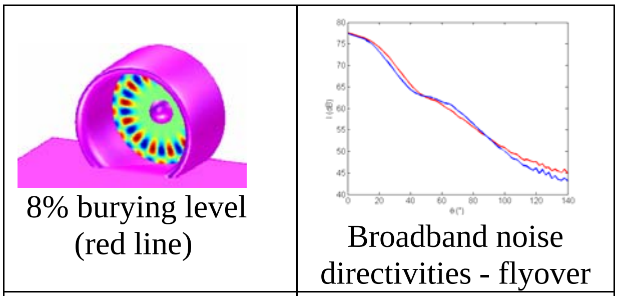
The flow control techniques seem to be a promising way to reduce the drawbacks due to the ingestion of the fuselage boundary layer by the intake, with significant improvements of the performance. But a global balance has to be done at aircraft level, considering in particular the energy necessary to operate the systems, the increase of mass and the complexity induced by these technologies, before taking the decision to introduce it on aircraft. Vortex generators seem to be quite promising devices due to their simplicity and because it is a passive technique.

4 Aero-acoustics

4.1 Preliminary comparison of configurations

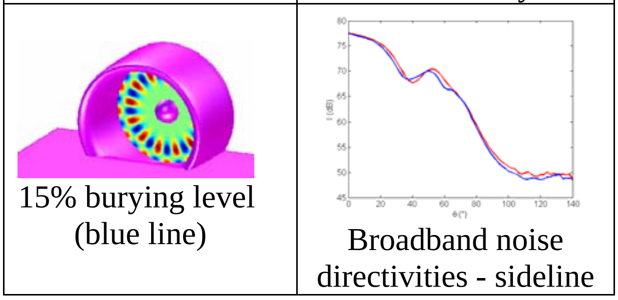
In aero-acoustics, the engine fan noise propagation through the intake has been investigated. The configurations designed within the aerodynamic activities, with different burying levels and different cross sections, have been assessed. The fan noise source characteristics were delivered by the engine manufacturer as a list of modes with their amplitudes. The first computations were performed with BEM methods, without taking into account the aerodynamic flow.

The comparison of the two reference shapes, with 8% and 15% burying, is shown in figure 7. The intensities of the broadband noise (in dB) are plotted versus different directions in the flyover and sideline planes, the broadband noise being the incoherent sum of all modes. The results confirm the expected tendency, with lower intensities for a higher burying, but the differences between the two shapes remain moderate, lower than 1 dB whatever the direction considered.



8% burying level (red line)

Broadband noise directivities - flyover



15% burying level (blue line)

Broadband noise directivities - sideline

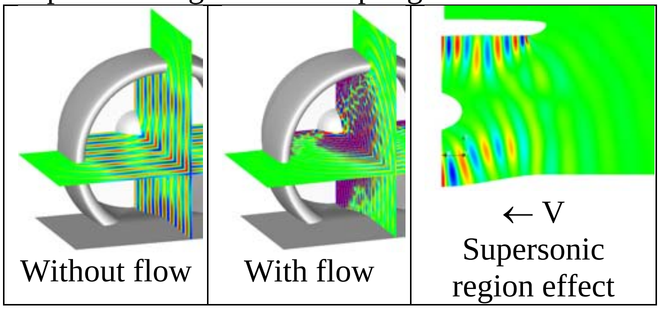
Fig. 7. Effect of burying on noise propagation

Similar computations were performed on the intake shapes with elliptical cross sections. The results showed no influence on the noise intensities in the flyover plane. In the sideline plane, limited modifications of intensities were observed, with an increase for some directions and a decrease for others, resulting in a global negligible effect.

4.2 Comparison with aerodynamic flow

Other computations were done with more advanced methods (Euler, RANS), taking into account the aerodynamic flow, to confirm the previous tendencies. The climb conditions (Mach= 0.25) were considered, as they correspond to the conditions for which noise reduction is desired. For these conditions, the engine massflow is important and the flow inside the intake is highly non-uniform, with regions with low velocities and regions with high velocities, and even with a local supersonic region close to the intake throat. Such variations of velocities and densities can have an influence on the noise propagation.

In a first step, computations were carried out with and without flow for the reference intakes. They showed a significant influence of the flow on noise propagation and two typical phenomena were noticed (figure 8): a deviation of the noise towards the top direction by comparison to computations without flow, and the attenuation due to the presence of a local supersonic region in the top region of the intake.



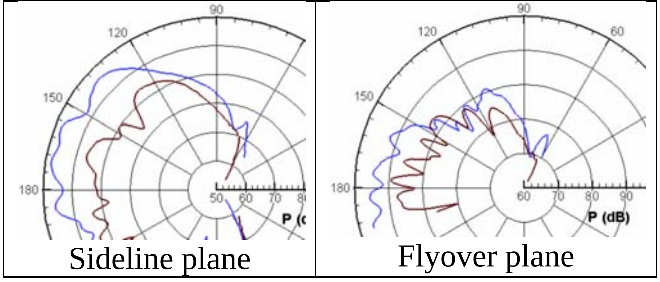
Without flow

With flow

← V
Supersonic region effect

Fig. 8. Acoustic instantaneous pressure field with and without aerodynamic flow

In a second step, the two reference shapes (figure 7) with different burying levels were compared with the flow. The plots of the RMS values of the broadband noise in different directions (figure 9) showed significant differences between the shapes, reaching 10 dB in the upstream directions. In the downstream directions, the differences are much lower. As expected, lower intensities were observed for the most buried configuration but these differences are much more important than the ones predicted without flow (figures 9 and 7). Although the lower shape of the most buried intake could reflect backward the acoustic energy and, combined with the incident waves, could provoke the attenuation, such a decrease seems too important. Additional computations for different configurations or conditions, or with other numerical codes, should be done to explain these results.



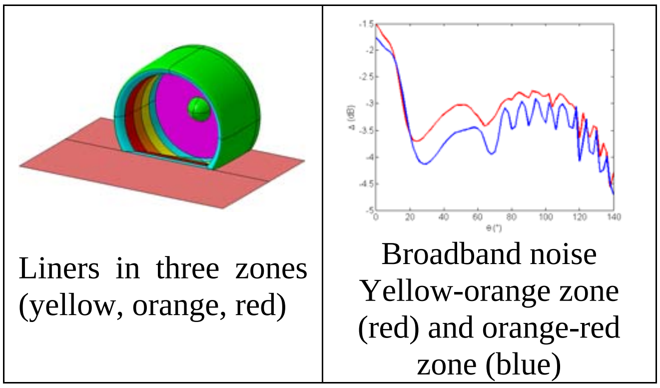
Sideline plane

Flyover plane

Fig. 9. RMS of broadband noise with flow – Burying 8% (blue) and 15% (red)

4.3 Influence of acoustic liners

The capability of acoustic liners to reduce the engine noise propagation for semi-buried intakes was also assessed with BEM computations. Different positions of the liners inside the intake were compared, keeping the same area. The optimum noise reduction was obtained for an installation in the top region and close to the lips. The intensity of the attenuation is in the order of 1 dB.



Liners in three zones (yellow, orange, red)

Broadband noise Yellow-orange zone (red) and orange-red zone (blue)

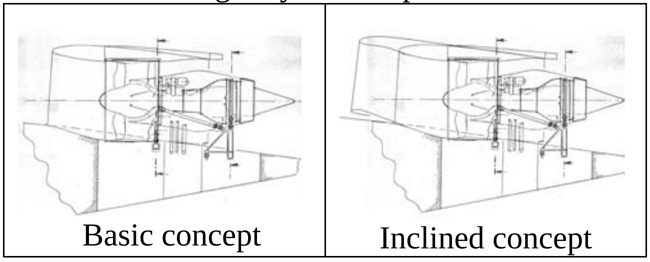
Fig. 10: Broadband noise intensity for different liner horizontal extent

5 Structures

On the structural side, the objective was to design structures to attach the semi-buried engines on the airframe, and to investigate the intake response to static and dynamic loads.

5.1 Supporting structures

In a first step, different architectures for the engine installation, corresponding to different inclined positions of the engine and different structural attachments (figure 11), were proposed and compared at a pre-design level. The most important constraints considered were an engine removal by the bottom, an easy accessibility, attachment constraints leading to an isostatic mounting, material and thermal constraints. The pre-design assessment showed the potential interest of the inclined concept with a reduction of consumption, of fan noise intensity by several dB and of engine installation weight by several percent.



Basic concept

Inclined concept

Fig. 11. Engine installation architecture

In a second step, a detailed design of the structure to attach the semi-buried engine on the airframe was carried out (figure 12). The objective was to define a structure as light as possible, respecting the constraints in terms of allowed attachment points, maximum local displacements (30 mm) and local stress (lower than material yield stress). The assessment was done with FEM computations with the NASTRAN software. The external forces acting on the structure are the engine thrust and weight and the aerodynamic forces at the airframe surface. Different aerodynamic conditions and extreme engine operating conditions were considered for the design. Aluminum alloy was selected for the elements with low stress and titanium alloy for the elements with high stress. As an outcome, the most efficient structure designed has a weight of 850 kg roughly for each engine, corresponding to 7% of the engine weight.

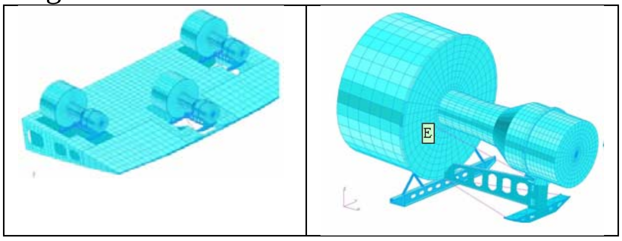


Fig. 12. Engine attachment structure

The last step was a comparison of a three semi-buried engines installation on the NACRE flying wing configuration with a conventional four small engine installation under the wings (figures 1 and 3). The global assessment took into account the supporting structures but also the reinforcement of the airframe structure in the region where the engines are installed.

For the semi-buried installation, the airframe reinforcement weight was estimated with FEM computations to 6,500 kg roughly. By adding the three engines attachment structures, the global weight penalty is 9,050 kg, without taking into account the engines weight. The FEM analysis is illustrated in figure 13 by the displacement field in cruise conditions.

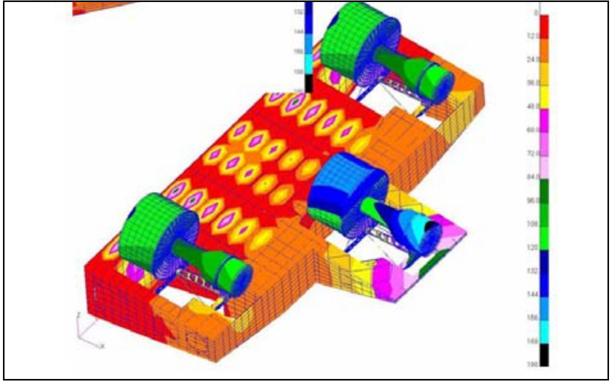


Fig. 13. Displacement field at cruise

For the under-the-wing installation assessment, it was assumed that the weight and thrust of the four engines are similar to the ones of the three semi-buried engines. The weight of the four pylons was calculated with an analytical formula already used in the former project VELA, and gave a total mass of 6,300 kg roughly. The mass of the wing reinforcement was calculated with FEM computations and was estimated to 6,400 kg. So, the total weight penalty due to this engine installation is 12,700 kg, without considering the engines weight.

Such a difference demonstrates the potential interest of a semi-buried installation on the structural side, although a complete balance at aircraft level and considering all aspects of the problem should be done before drawing definite conclusions.

5.2 Intake aero-elastic analysis

The aero-elastic response of the engine intake to the aerodynamic static loads and aero-acoustic dynamic loads was also determined. The reference intake shapes with 8% and 15% burying were considered. The analysis was performed in cruise, take-off and climb conditions. Aluminum, titanium and composite materials were considered. The loads were delivered from the previous aerodynamic and acoustic investigations. The objective was to evaluate the necessary weight for the intake to respect the displacement (2 mm max) and stress (safety factor 3 between local stress and allowed stress) constraints under these loads. The FEM analysis was carried out with the NASTRAN software.

The static load analysis showed that take-off conditions are the most critical ones. The displacement criterion is a stronger constraint than the failure or stress criterion. The less buried configuration is more critical for the failure criterion, especially with composite. The most buried configuration is more critical for the displacement criterion, especially with titanium. In the worst case, with titanium material, the stress and displacement constraints are respected with an intake mass of 150 kg (figure 14).

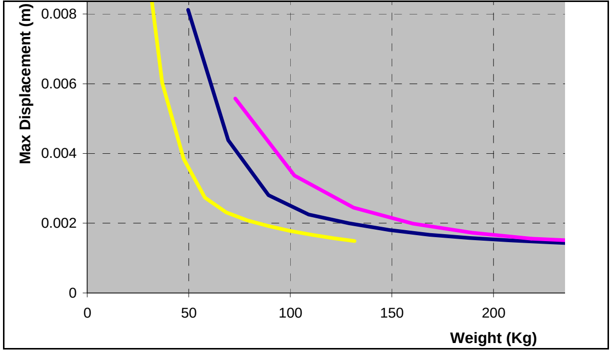


Fig. 14. Maximum displacement versus intake weight. Take-off. Aluminum (blue), titanium (purple) and composite (yellow)

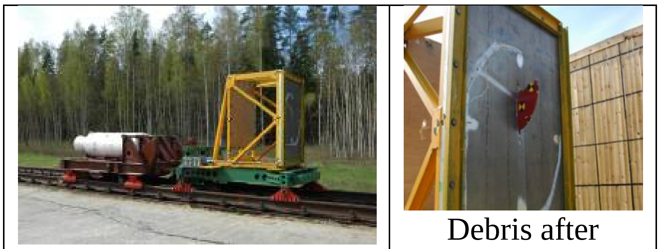
The dynamic load analysis showed a high modal density and a large contribution of circumferential modes. The most critical condition corresponds to a frequency of 100 Hz. The displacement criterion is a more critical constraint than the stress criterion

6 Certification

The engine installation close to the airframe makes the certification a critical point, in particular the topic of uncontained large fragment protection. This point was investigated within the NACRE project through tests and computations.

For unconventional aircraft configurations, the certification requests the protection of the airframe through shielding or containment of the engine disk in case of burst, with a criterion considering 1/3rd disk or smaller fragments.
Within the NACRE project, a preliminary work consisted in the selection of the engines positions on the airframe, taking into account the expected trajectories of the fragments. This selection has been presented in the paragraph 3.
In a second step, the capability of protection materials to contain or deflect high energy debris (1/3rd disk) or smaller fragments was assessed through two types of tests: high energy tests at TsAGI/GkNIPAS, and tests of small fragments in a gas gun type bench at Aircelle. The principle of these tests is to launch debris with a certain trajectory and energy on a protection material and to evaluate the energy absorbed by the material as well as the kinetics of debris after impact. The final overall objective is to estimate the protection material thickness required for containment.

The high energy tests were carried out with the following set-up: a protection material was installed on a moving trolley propelled by a rocket, and was impacting the debris in a stationary position (figure 15). The relative trajectories of the debris were translations or translations with rotations. Several oblique impact conditions as well as several levels of energy were investigated up to 150 kJ. Aluminum protection materials were considered.


Test set-up

Debris after impact

Fig. 15. High energy tests at TsAGI/GkNIPAS

The small fragment tests at Aircelle investigated several composite materials including typical materials used for structure.

The analysis of the tests results, including a comparison to finite element computations, was used to validate methods for sizing of containment or deflection shields. The high energy tests delivered valuable results. The analysis showed the importance of modeling the 1/3rd disks fragments shape as well as its rotation. For small fragments with lower energy, the comparison between tests and computations was done through correlation.

7 Conclusions

Within Task 3.2 of the NACRE project, a multi-disciplinary investigation was done on semi-buried engine installations for civil transport aircraft, the configuration considered being a flying wing. Aircraft architecture, aerodynamics, aero-acoustics, structures, vibrations, certification were taken into account. The objective was to determine the viability of semi-buried engine installations.

The selection of the aircraft architecture was mainly influenced by geometrical constraints and by certification aspects. A configuration with three big engines installed in the central rear part of the flying wing was chosen.

In aerodynamics, the friction drag is reduced by burying the engines due to the decrease of the wetted surface. But the main concern is the ingestion by the intake of the boundary layer developing on the airframe. The cruise conditions are much more critical than the low speed ones. The introduction of flow control techniques (suction, vortex generators) can improve significantly the intake performance.

In aero-acoustics, burying the engine in the airframe leads to a reduction of engine external noise, although this reduction was limited for the configurations considered in the project. The non-uniform aerodynamic flow seems to have a significant influence on noise directivities.

In structures, the weight of the structure to attach the engine on the airframe, taking into account the reinforcement of the airframe, is much lower for a semi-buried installation than for a conventional under-the-wing installation, in particular due to the absence of pylon.

The certification aspects are critical for semi-buried engines due to the proximity of the airframe. On one side, an appropriate selection of the engine positions on the airframe reduces the risks. On the other side, high energy material tests have been performed and have delivered valuable results to define a methodology for the design of containment or deflection shields.

As a conclusion, the investigation carried out has not identified any show stopper against a semi-buried integration of the engines in the airframe. Such architecture seems viable, although more detailed analysis with precise balance at aircraft level are necessary to confirm the advantages of such configuration.

8 Acknowledgements

This paper is a synthesis of the activities performed within Task 3.2 of the European project NACRE. The author would like to acknowledge the different contributors to the technical activities: J. Goos, J. Loerke, J.-J. Mirat, J. Ramette, Th. Surply, S. Roumegas from Airbus, P. Caruel from Aircelle, A. Gatti and M. Mucciardi from Alenia Aeronautica, G. Diodati and P. Vitiello from CIRA, S. Barré from Dassault Aviation, G. Efraimsson and N. Forsberg from KTH, S. Donnerhack, H. Klingels and P. Traub from MTU, A.-L. Delot, E. Manoha, D. Mincu and B. Paluch from Onera, J. Whurr from Rolls-Royce, S. Dron from Snecma, A. Shanygin from TsAGI.
In addition, the author would like to acknowledge the European Community, represented by D. Knoerzer, for his financial support to the NACRE project, as well as J. Frota from Airbus as manager of the project for his contribution to its success.

References

[1] Liebeck R H, Page M A and Rawdon B K. Blended Wing Body Subsonic Commercial Transport. *36th AIAA Aerospace Sciences Meeting & Exhibit*, January 12-15, 1998, Reno (NV), USA, AIAA 98-0438.

[2] Mialon B, Fol T and Bonnaud C. Aerodynamic Optimization of Subsonic Flying Wing Configurations. *20th AIAA Applied Aerodynamics Conference*, June 24-26, 2002, Saint Louis (TN), USA, AIAA 2002-2931.

[3] Frota J. Novel Concepts for Aircraft Component Technologies: The NACRE European Integrated Project. *25th ICAS Congress*, September 3-8, 2006, Hamburg, Germany, ICAS 2006-1.6-1.

[4] Plas A P, Sargeant M A, Madani V, Crichton D, Greitzer EM, Hynes T P, and Hall C A. Performance of a Boundary Layer Ingesting (BLI) Propulsion System. *45th AIAA Aerospace Sciences Meeting & Exhibit*, January 8-11, 2007, Reno (NV), USA, AIAA-2007-450.

Contact Author Email Address

Jean-Luc.Godard@onera.fr

Copyright Statement