Analysis of steady and unsteady aerodynamic loads on the Ariane 5 lauch vehicle rear part during flight ascent

Analyse des charges aérodynamiques stationnaires et instationnaires sur la partie arrière du véhicule de lancement d'ARIANE 5 pendant l'ascension

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Aerospatiale Matra Lanceurs

Les lanceurs sont soumis à un champ de pression stationnaire et instationnaire en phase transsonique et à pression dynamique maximale. Ces champs de pression peuvent être très sévères dans certaines zones du lanceur, qui présentent d'importantes variations locales de géométrie. Ces variations de géométrie conduisent à des décollements dans des zones significatives des lanceurs.
Les charges aérodynamiques, qui dépendent de la géométrie, du nombre de Mach et de la trajectoire, peuvent endommager les structures ou les sous-systèmes. En conséquence, ces charges doivent être prises en compte dans le dimensionnement des lanceurs.
Cet article se limite aux charges aérodynamiques appliquées en phase transsonique, sur la partie arrière du lanceur ARIANE 5. Il traite des campagnes expérimentales (sous la responsabilité d'Aérospatiale dans le cadre d'un contrat avec le CNES) destinées à caractériser le champ de pression stationnaire et instationnaire. Deux campagnes expérimentales ont été réalisées dans les souffleries de l'ONERA S2, en utilisant une maquette au 60^e^ du lanceur ARIANE 5.
L'expérience acquise lors des deux campagnes d'essais est d'une grande importance pour les versions améliorées d'ARIANE 5, comme ARIANE 5 Plus. Pour cette version d'ARIANE 5, la tuyère de l'étage central cryotechnique EPC est plus longue que dans la version standard, et munie d'un tore central, qui devrait augmenter localement les charges aérodynamiques.

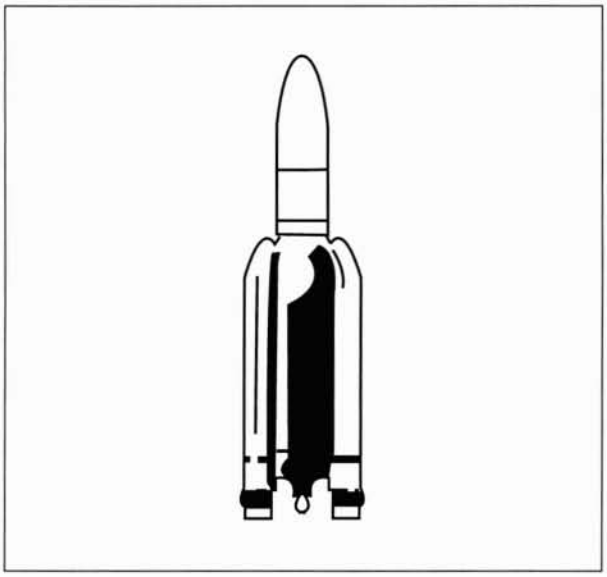
I ■ INTRODUCTION

The analysis of aerodynamic loads is of great importance in the case of ARIANE 5 rear part configuration because of (see *fig. 1*) :
– offset between the two solid propellant boosters (EAP) and one main cryogenic stage (EPC) nozzle exit planes,
– existing protuberances. Some subsystems are mounted on the external conical part of the thrust-frame,
– EAP/EPC connection.

It has been expected that these specific features would lead to intense steady and low frequency unsteady pressure fields at ARIANE 5 rear part. The low frequency unsteady pressure loads are called buffeting loads. The steady and the unsteady pressure fields induce static loads and dynamic loads respectively, which have to be taken into account in the design of structures. The static and buffeting loads have to be estimated at two levels :
– at subsystem level. The steady and unsteady pressure fields induce loads on the Vulcain nozzle of EPC and on subsystems mounted on the rear part. These loads have to be estimated to check the design of subsystems (up to 80 Hz at one scale),
– at system level. The unsteady pressure loads excite the EPC actuators, which, in turn, excite the launch vehicle and acceleration levels are induced at the payload/launcher interface (up to 20 Hz at one scale).

Moreover, these unsteady loads have to be added to steady loads. The steady loads are due to an asymmetrical steady pressure field in the ARIANE 5 rear part.

As, nowadays, the aerodynamic loads, in a 3D configuration cannot be estimated by numerical simulations, an experimental analysis was essential.

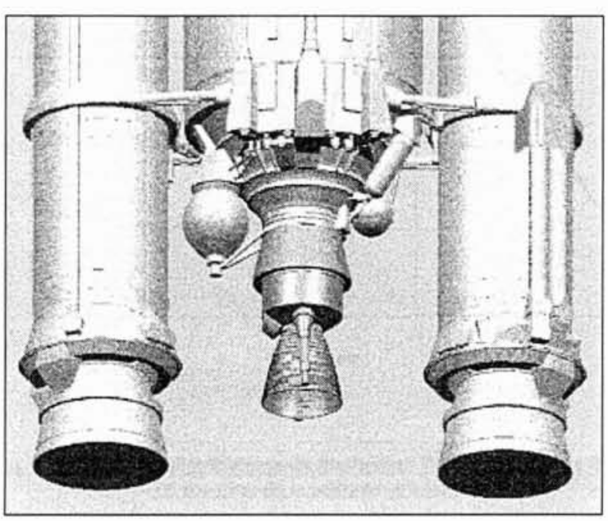


1. ARIANE 5 launch vehicle

II ■ DESCRIPTION OF THE PROBLEM

The flow at ARIANE 5 rear part is very strongly tridimensionnal and unsteady. Its tridimensionnal character is due to :
- the two solid rocket boosters,
- the rear attachment system of EAP composed of simple and double struts,
- protuberances existing on EPC rear part and thrust frame, as shown in *figure 2*.

Numerical analysis and displays show that two phenomena drive the flow characteristics :
- the development of the mixing area, which appears at EPC bottom, creating a separated flow up to the EPC nozzle,
- the drive, to EPC base, (low pressure area) of a part of aerodynamic flow, which goes along the EAP solid rocket boosters. The skirting of struts and annular protuberance on EAP leads to increase the non uniform character of the flow.



2. View of ARIANE 5 rear part

III ■ DESCRIPTION OF TESTS

Two main campaigns have been performed in S2Ma wind tunnels of ONERA (MODANE) on mock-ups. The objective of the first campaign was to measure the steady and unsteady pressure field applied to the EPC nozzle, subsystems mounted on the launcher and to the thermal protection.

The second campaign has been performed, in order to measure directly the unsteady loads, in terms of forces and moments, applied to the composite nozzle and thermal protections. The frequency range for these tests was up to 50 Hz at one scale.

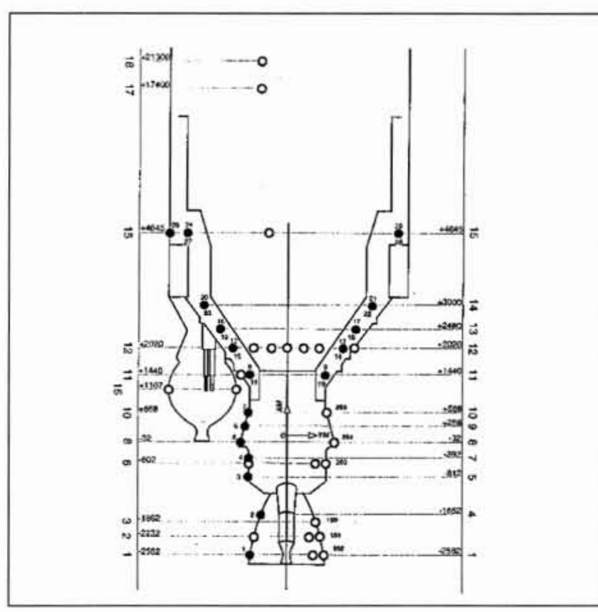
3.1 First campaign

A 0.017 scale model of the ARIANE 5 launcher, held by a lateral sting upwards EAP, has been tested from Mach = 0.5 up to 2. This mock-up was representative of the complex geometry of launch vehicle rear part (protuberances, EAP/EPC attachments), but the simulation of engine jets was impossible because of the test instrumentation. 28 steady pressure measurement and 27 unsteady pressure measurement (Kulite XCQL-062) have been flash mounted according to the repartition shown in *figure 3*.

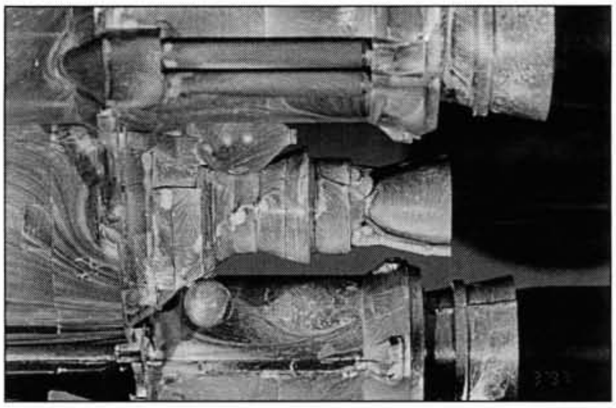
In order to get sufficient test data, in spite of the small number of measurements on the mock-up, a rotating device of the composite nozzle and thermal protection has been implemented. The corresponding 14 unsteady measurements and 7 steady measurements have allowed the characterization of pressure field in performing four different test runs (that is to say four different positions of the nozzle for each sensor).

Tests have been performed in different configurations (Mach number, angle of attack and sideslip) of the ARIANE launcher flight domain. Some tests have been conducted without protuberances, in order to point out their influence on the pressure field.

The repartition of steady pressure measurement is as follows:
- one meridian with 7 measurements on the EPC nozzle and the engine thermal protection,



3. Location of pressure measurement.
○ Unsteady pressure measurement
● Steady pressure measurement



4. View of the mock-up in wind tunnel

5. Characterization of the aerodynamic flow in wind tunnel

- four meridians with 4 measurements on the thrust frame,
- five measurements at EPC bottom.

The repartition of unsteady pressure measurement is as follows :
- eight measurements on the EPC nozzle,
- six measurements on the thermal protection,
- seven measurements on the thrust frame,
- two measurements on the SSHel spherical protuberance,
- four measurements on EPC.

3.2 Second campaign

As written before, the objective of this second campaign was to measure directly the unsteady loads that applied to the composite nozzle and thermal protections, in terms of forces and moments. A 0.017 scale model, held by two stings at EAP base comprised a dynanometric balance allowing measurement of unsteady loads up to 1 000 hertz (17 Hz at one scale). Inertia forces have been taken into account to estimate unsteady forces and moments. However, this test was complex for the following reasons :

– the balance must be designed to avoid a first flexural mode much higher than 1 000 Hz, to get data up to 1 000 Hz,

– the balance must be sufficiently sensitive and, consequently, not very rigid to get the required accuracy.

Annular cold jets around the stings represented the EAP jets. A cold jet represented the EPC jet. A view of the mock-up in wind tunnel is given in *figure 4*.

IV ■ MAIN RESULTS

4.1 Steady and unsteady pressure field at rear part

The various tests performed have allowed the characterization of the aerodynamic flow as shown in *figures 4 and 5* (Mach 0.7) for null angles of attacks.

• The analysis of the steady pressure field points out a separated flow on the thrust frame, with a progressive recompression along the nozzle. Some test configurations of Mach numbers and angles of attacks point out that reattachments of the external flow occur on the nozzle on some meridian plans.

Figure 6 shows an example for a 1.15 Mach number and a null angle of attack. This figure displays :

– The Cp steady coefficient along the four meridians from EPC at the left-hand side to the nozzle at the right-hand side, see *figure 4*.

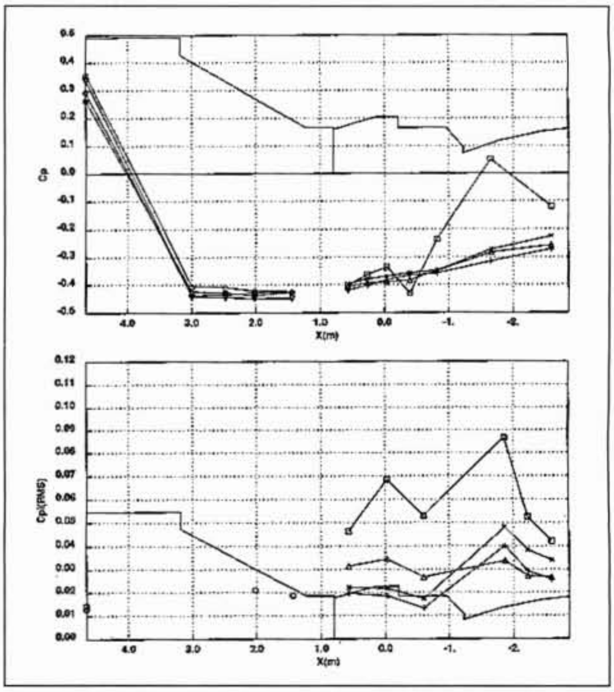
– The Cp unsteady pressure coefficient along the same meridians, *figure 5*. A simple shape of the ARIANE 5 rear part is recalled above the drawings.

The asymmetries of the flow, which can even observed for null angle of attack, are amplified for some configurations of angles of attack and side slips. These asymmetries lead, consequently, to important loads on subsystems. This phenomenon appears only in the transonic phase. An important reduction of steady and unsteady loads has been observed during tests for Mach numbers higher than 1.3.

4.2 Power spectral analysis

4.2.1 Characteristics of the fluctuating pressure environment

Throughout the atmospheric flight, the unsteady external pressure field applied to the structures is broadband and ran-



6. Steady and unsteady pressure coefficient along the launcher rear part

dom. The parameter needed to describe this pressure field is the cross power spectral density. This parameter will be required for estimating the structure response to a field of fluctuating surface pressures. Obviously, a complete determination of the cross power spectral density of the applied pressures requires a great number of transducers. So, in most cases, some assumptions are made :

- the power spectral density of the applied pressure is constant on some finite surfaces of the structure,
- the pressure correlation pattern is rectangular so that the pressure correlation coefficient can be written in a separable form as follows :

$$C(x, x', y, y', \omega) = C(x, x', \omega)\, C(y, y', \omega)$$

where x, x' and y, y' are M and M' points coordinates along the x– and y– axes respectively of the excited structures and with :

$$C(x, x', y, y', \omega) = \frac{S(P(x, y, t) \bullet P(x', y', t), \omega)}{\sqrt{S(P, \omega)\, S(p', \omega)}}$$

where, $S(P(x, y, t) \bullet P(x', y', t), \omega)$, $S(P, \omega)$ and $S(p, \omega)$ are the cross and mean-square spectral densities of the applied fluctuating pressures respectively. These hypotheses, mainly the second one, of course, may not be satisfied in complex cases, such as the case considered in this paper. In very complex cases, the pressure correlation pattern cannot be considered rectangular.

Anyway, in cases where the number of measurements is not sufficient to have a complete and reliable understanding of the pressure field, it is necessary to develop, if possible, analytical models of the unsteady pressure field. These analytical models are derived from test results. These analytical models can provide data at points, where there no measurement.

4.2.1 Longitudinal correlation function

The correlation functions are important parameters, to estimate the unsteady loads applied to the structures. The analysis of tests results has shown that the following model fits well the measured longitudinal correlation functions (real part) :

$$C(M, M, \omega) = exp\left(\pm \frac{\xi}{L_1}\right) cos\left(\frac{2\pi f \xi}{U_1}\right)$$

with :
ξ : longitudinal distance between points of interest,
f : frequency,
U_1 : longitudinal propagation velocity of perturbations,
L_1 : correlation length in the longitudinal direction.
U_1 and L_1 are estimated from experimental data. It has been pointed out that the longitudinal propagation velocity is linked to the convection velocity U_{00}, according the formula, which is a classical one :

$$U_1 = 0.8\, U_{00}$$

4.2.2 Circumferential correlation function

The aerodynamic flow is very complex in the circumferential direction. So, analytical expressions of the circumferential correlation function could not be derived from test results. Consequently, correlation functions directly measured have been used for calculating the response of structures to buffeting loads.

V ■ COMPARISON WITH FLIGHT RESULTS

In flight, it is clearly not possible to implement a sufficient number of steady and unsteady pressure measurements, to characterize the aerodynamic environment. As a consequence, the only way to check the validity of the methodology of establishing the steady and unsteady loads before flight, is to compare the predicted effects of this loads on the launcher with the in flight measured ones, when measured.

Comparison between predicted and measured values during 502 ARIANE 5 flight have been made regarding :
– the loads induced in the actuators of the EPC nozzle,
– the acceleration on the nozzle.

5.1. Loads induced in the EPC actuators

5.1.1 Dynamic loads induced in the actuators of EPC nozzle in the frequency domain

The unsteady pressure environment induces dynamic loads on the EPC nozzle. These loads, in turn, induce forces and moment at gimbal point, which is the attachment of the EPC nozzle to the rear of the central stage. The loads applied to the nozzle have to be countered by the two U and V actuators. The pressure inside actuators is measured in flight. Consequently, knowing the actuator area, it is possible to estimate the in flight forces in the actuators, see *figure 7*.

The forces created by buffeting loads in actuators have been estimated before flight in a numerical closed loop analysis, using dynamic forces and moments at gimbal point estimated after the test analysis from the second campaign test results.

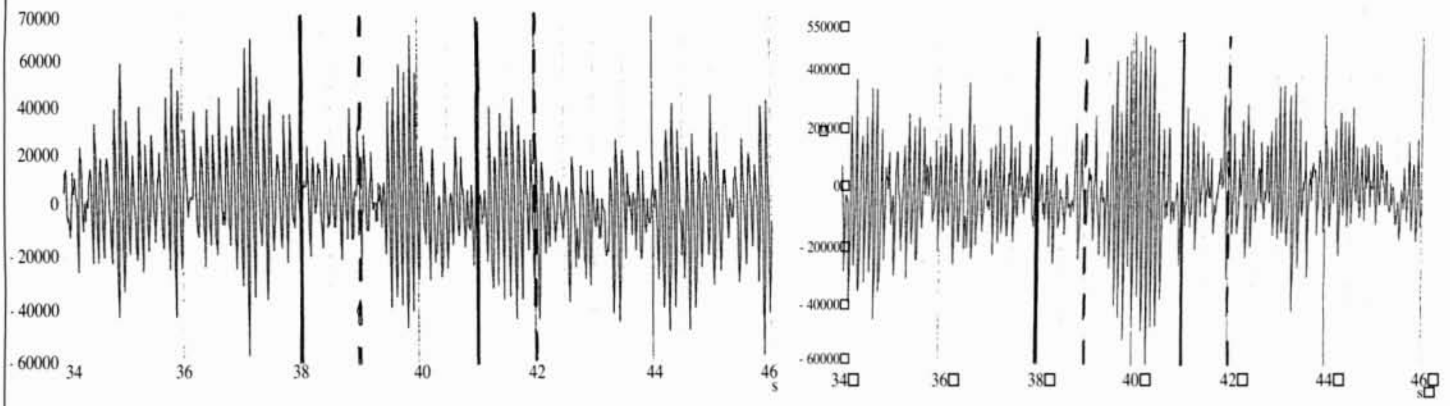
RATIO BETWEEN ESTIMATED DYNAMIC LOADS THROUGH A CLOSED LOOP ANALYSIS AND ONES MEASURED IN 502 FLIGHT (Mach 0.8)	
Power Spectral Density of loads in V actuator RMS values between 5 and 18 Hz	Power Spectral Density of loads in U actuator RMS values between 5 and 18 Hz
1.18	1.01

Table 1. - Comparison between dynamic loads measured in 502 flight and estimated ones through a closed loop analysis

The estimated loads are, consequently, very close to the measured ones. The frequencies, at which the levels are maximum, are also well restituted, as shown in table 2.

Mach 0.8	502 flight	Closed loop calculation
Pitch plane	9 – 10.2 Hz	8.5 Hz
Yaw plane	10.3 Hz	10.5 Hz

Table 2. - Comparison between frequency of highest loads occurred in flight and estimated



load in V actuator **load in U actuator**

7. Loads measured in EPC actuators during 502 flight

5.1.2 Maximum loads induced in the EPC actuators in the time domain

Without filtering, the measured loads in EPC actuators, are obviously, composed of static and dynamic loads. The hereafter presented table 3 shows a comparison between the loads in EPC actuator measured during the 502 flight and the estimated values derived from tests and a closed loop calculation.

PLANE	RATIO OF MEASURED LOADS AND ESTIMATED ONES
Pitch plane	0.88
Yaw plane	0.8

Table 3. - Maximum loads induced in EPC actuators in the time domain

Compared to the measured values, the estimated ones are satisfactory, keeping in mind the margins we take into account, when specifying loads. Notice that the prediction is pessimistic.

5.2 Acceleration on the nozzle

The accelerations on some points of EPC nozzle have been measured during 502 flight. The table 4 presents a comparison between maximum measured and predicted accelerations levels. The acceleration levels before flight have been estimated through the calculation of the response of the EPC nozzle to the unsteady pressure field derived from the first campaign test results.

RATIO OF ESTIMATED ACCELERATION AND MEASURED ONES (dB)	
Transonic phase (ovalisation modes)	1.7
Transonic phase (frequencies up to 80 Hz)	3.1

Table 4. - Maximum accelerations of the EPC nozzle

The estimated values are satisfactory, taking into account the usual margin policy. The prediction is pessimistic too.

VI ■ CONCLUSION

The methodology established for characterizing the steady and unsteady pressure field has allowed the prediction of 502 in terms of forces in EPC actuators and of accelerations of the EPC nozzle induced by buffeting loads. The predicted levels are better, in most cases, than 3 dB.

However, although the longitudinal aerodynamic flow is well understood, the aerodynamic flow in the circumferential direction is very complex and the phenomena that occurred are not understood. Consequently, numerical correlation functions from tests have been used for calculating the response of structures to buffeting loads.

The next test campaign regarding an improved version of ARIANE 5, the ARIANE 5 Plus, will allow us to have a better understanding of physical phenomena. The experience learned within the frame of these two campaigns is of great interest for this improved version.