Nationaal Lucht- en Ruimtevaartlaboratorium

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Executive summary

Steady and unsteady pressure measurements on the rear section of various configurations of the Ariane 5 launch vehicle

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Knowledge area(s)
Aëro-akoestisch en experimenteel aërodynamisch onderzoek

Descriptor(s)
Ariane 5
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pressure
unsteady loads
nozzle

Problem area
The differences in configuration of the rear section of the Ariane 5 ECA launch vehicle compared with the generic Ariane 5 launch vehicle require, in view of the buffeting phenomena observed in flight, to characterize as precisely as possible the field of steady and unsteady pressures induced by the aerodynamic flow.

Description of work
A number of wind tunnel tests were conducted for various configurations of the Ariane 5 Launch Vehicle. Steady and unsteady pressures were acquired at the nozzle of the launcher, which was extensively instrumented with miniature pressure transducers. Wind tunnel testing was required, as currently available numerical methods do not provide unsteady data for the complex shape of the nozzle and protuberances with enough confidence.

This report is based on a presentation held on the 6th International Symposium on Launcher Technologies *'Flight Environment Control for Future and Operational Launchers'*, Munich, Germany, November 2005.

Results and conclusions
From the pressures, steady and unsteady nozzle loads were calculated and transformed to non-dimensional coefficients. Comparison of wind tunnel test data with flight data gave confidence in the technique of measuring overall forces and moments if using an adequate amount of pressure transducers.

Applicability
The analyses of the pressure fields applied to a numerical model of the launcher eventually led to a new design of a truncated “optimised” Vulcain 2 nozzle. The loads on the nozzle were characterised in another wind tunnel test, which indeed showed reduction of loads. The “optimised” design was applied to the Ariane 5 launcher and led to a successful flight. All investigations have proven that the use of wind tunnels results in combination with numerical models still is a valuable, inevitable tool to attack problems.

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Summary

Over the last 5 years (1999-2004) NLR conducted a number of wind tunnel tests in DNW's High Speed Wind Tunnel in Amsterdam, The Netherlands, on a model of the Ariane 5 launch vehicle. Steady and unsteady pressures were acquired at the nozzle of the launcher, which was extensively instrumented with miniature pressure transducers. Wind tunnel testing was required, as currently available numerical methods do not provide unsteady data for the complex geometrical shape of the nozzle and protuberances with enough confidence.

From the pressures, steady and unsteady nozzle loads were calculated and transformed to non-dimensional coefficients, which enabled EADS-ST to transform them to full-scale conditions, directly applicable as input to the process of dimensioning the afterbody’s elements of the launch vehicle. The pressures served for characterisation of buffet phenomena on the rear section and for comparison with results of flight tests on the Ariane 5.

The first test results pointed out high levels of transverse loads on the nozzle. Analysis of the wind tunnel tests and flight data suggested that an organised phenomenon could result from the coupling of vortices generated near the boosters and the recirculation zones downstream the central body. The rear connection struts also might have a significant effect on the phenomenon. Different solutions were proposed to lower the loads and various options were tested.

This paper describes the various nozzle models and model components and its instrumentation as well as the difficulties encountered for the manufacturing and implementation in the launcher. It describes the test set-up for data-acquisition and the procedures for data processing. It discusses the phenomena observed and the solutions. No extensive analysis of the results is presented; only some examples are shown.

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Abstract – Over the last 5 years (1999-2004) NLR conducted a number of wind tunnel tests in DNW's High Speed Wind Tunnel in Amsterdam, The Netherlands, on a model of the Ariane 5 launch vehicle. Steady and unsteady pressures were acquired at the nozzle of the launcher, which was extensively instrumented with miniature pressure transducers. Wind tunnel testing was required, as currently available numerical methods do not provide unsteady data for the complex geometrical shape of the nozzle and protuberances with enough confidence.

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Ref	year	month	Configuration	WT	testID
<#1>	1997	Feb	Ariane 5 Vulcain 1 Jet simulation	PHST	6101
<#2>	1999	Oct	Ariane 5 Evolution + Vulcain 2: base characterization	HST	9005
<#3>	1999	Dec	Ariane 5 Evolution + Vulcain 2: base characterization	SST	9501
<#4>	2001	Jan	Ariane 5 Plus + Vulcain 2: attenuation devices / not completed	HST	0018
<#5>	2001	May	Ariane 5 Plus + Vulcain 2: twin-sting configurations	HST	1011
<#6>	2001	Sep	Ariane 5 Plus + Vulcain 2: attenuation devices	HST	1025
<#7>	2001	Nov	Ariane 5 Plus + Vulcain 1: base characterization	HST	1027
<#8>	2004	Jun	Ariane 5 Plus + Vulcain 2 Optimized: base	HST	4008
<#9>	2004	Jun	Ariane 5 Plus + Vulcain 2 Optimized plus skirts	HST	4012

To simplify reading the document, the tests discussed and referred to have an additional reference corresponding to the indication of column 1.

1 Introduction

In the preparation phase of a new nozzle for the Ariane 5 launcher, two types of tests were performed to investigate buffeting in the rear section of the launcher: a campaign without jet simulation and a campaign with jet simulation.

In the first campaign (<#1> test), with jet simulation, at NLR's Pilot High Speed Tunnel the model was instrumented to measure unsteady pressures in the base area of the launcher. Despite the limited number of measurements comparison of the response calculations of the Vulcain structures, performed with the pressure fields defined on the basis of the test results, and the vibration measurements of the exit cone performed during flight 502 gave satisfactory results. Gimbal loads and moment values obtained by integrating the pressure fields, which were introduced in the various models for calculating the response of

the servo actuators made it possible to make an *a posteriori* forecast of flight 501. The comparisons however showed very conservative forecast levels (~30 % on actuator loads).
Results from the second campaign at ONERA, without jet simulation, in which instrumentation was limited to an unsteady balance, making it possible to determine gimbal loads, compared to the flight 502 results, made it possible to yield an *a posteriori* restitution of the forecast levels on actuator loads to ~18 %. Furthermore results of the test campaign with jet simulation did not show any significant influence linked to the presence of the jets
In view of these tests and even more early tests it seemed justified to secure and refine the estimates by new, extensive steady and unsteady pressure measurements, using a larger number of sensors to:

- specify the pressure fields for dimensioning the exit cone and thermal protections more accurately,
- increase integration precision for be gimbal loads and moments predictions,
- investigate geometry modifications in the rear section between the two versions of the launcher.

The measurements should cover as best as possible the flight envelope in terms of Mach number, angle of attack and angle of sideslip.
The need to fulfil these goals resulted in the design and fabrication of a 1:60 scaled model unit of the exit-cone and thermal protections of the new Vulcain 2 engine, which could be implemented in the existing scaled model of the launcher used to conduct the above mentioned tests. Since the upstream section of the launch vehicle was expected to have a very limited influence on the base phenomena being studied, updating the geometry of that section of the model was excluded.
Tests started in 1999 with the “original” Vulcain 2 nozzle at the end of the Ariane 5 launcher (<#2> test). However, the results showed high levels of transverse loads on the nozzle, as will be pointed out in the chapter of tests and test results. Different solutions were proposed to lower the loads and were investigated. Parallel to the preparations of these tests also a model of the Vulcain 1 nozzle was designed and fabricated to be tested in the same year for comparison with in-flight measurements on the full-scale Ariane 5 Launcher with Vulcain 1 nozzle. The Vulcain 1 data were necessary and used to quantify the confidence in the wind tunnel results. Since none of the investigated solutions, tested up till then, was able to reduce the nozzle loads to an acceptable level, it was decided to also test a “truncated” version of the Vulcain Mk. 2 nozzle.
Recapitulating the above briefly, three different nozzle units (Figure 1) were designed and manufactured as discussed in chapter 2 and tested. A chronological description of the various tests and test results will be discussed in chapter 3.

2 Nozzle models, instrumentation and test set-up

The need to investigate geometry modifications in the base area of the launcher, to specify the steady and unsteady pressure fields for dimensioning the exit cone and thermal protections and to increase integration precision for be gimbal loads and moments predictions, eventually resulted in the design and fabrication of three nozzle units.
The rear of the model, but mainly the nozzle units were extensively instrumented with very small flush mounted cylindrical differential unsteady pressure transducers (Kulite XCQ-92-062-10D) up to a maximum of 144, which was imposed by the maximum number of channels that could be connected to the standard tunnel cabling facilities. Locations of the transducers and the corresponding reference areas were chosen such that the effects of the increase of the area of the nozzle, the presence of the torus and other nozzle details on the aerodynamics in the base area of the nozzle could be investigated. As reference signal an identical transducer, mounted in the tunnel side wall, was measured as well. Local model accelerations in y- and z- direction were measured with 4 Endevco 2222 C accelerometers, 2 in front and 2 in the aft part of the model to monitor and compensate model vibrations. As a consequence 149 unsteady signals were acquired for each data point during wind tunnel testing.
From the unsteady pressure transducers also static pressures could be derived. For all Vulcain 2 tests also 18 additional static pressures distributed over Helium Sphere, Booster modules, HP vessel and GAM bottle (the hydraulic tank for Vulcain actuators activation), were measured. Since the upstream section of the launch vehicle was expected to have a very limited influence on the base phenomena being studied, updating the geometry of that section of the model was excluded. Adaptations had to be made to the forward connection struts of the boosters (made hollow and reinforced). The rear section of the central body was adapted to make it compatible with the Ariane 5 Evolution version. The forward connection struts of the boosters had to be hollow to conduct the reference pressure tube and the electrical wiring of the transducers. The model was supported in the nozzles of the boosters by a twin sting (bi-dard), which was mounted on one of the standard model supports of the tunnel.

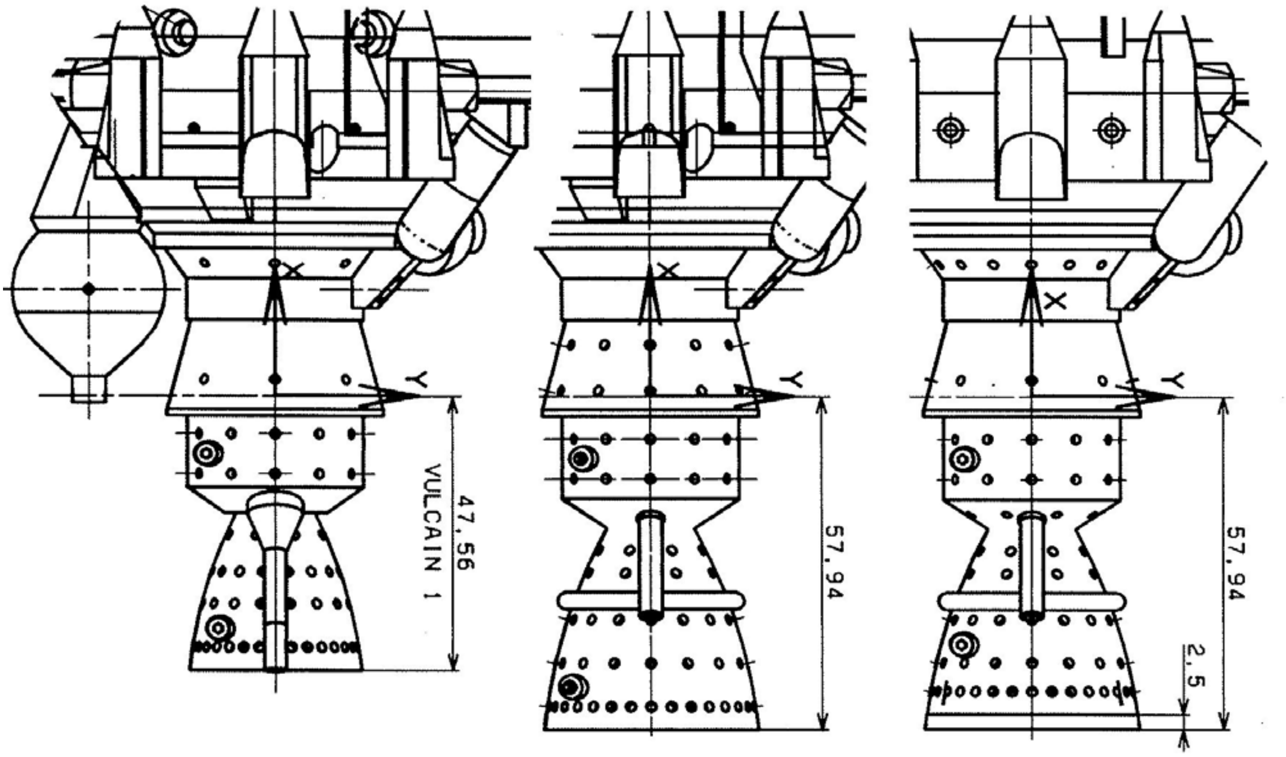

Figure 1 : The three nozzle models: Vulcain 1, “normal” Vulcain 2 and “truncated” Vulcain 2

The majority of the data was measured in the High Speed Wind Tunnel (HST) of the DNW foundation (Duits-Nederlandse Windtunnel / German-Dutch Windtunnels).
The High Speed Wind tunnel [1][2] is a variable density, closed-circuit wind tunnel with a test section width of 2.0 m. Top and bottom walls can be adjusted to obtain a test section height of either 1.60 m or 1.80 m. The tunnel is calibrated for the velocity regime ranging from M=0.2 to 1.3. The stagnation pressure can be varied between 25 and 390 kPa. An adjustable nozzle is followed by a test section with solid side walls and movable slotted top and bottom walls (about 12 % open).
For higher Mach numbers initially measurements were also conducted in the Supersonic Wind Tunnel, SST [3], a blowdown type wind tunnel having a width of 1.2 m and a maximum height of 1.2 m (<#3> tests). Compressed dried air (600 m3) of 4000 kPa (40 bar) is provided to range velocities from Mach 1.2 up to Mach 4. Maximum stagnation pressure is 1470 kPa; maximum running time is approximately 40 s.

Figure 2 : Model in SST / HST and close-up of Vulcain 2 Engine

The <#2> test on the Vulcain 2 (Figure 2) and the <#7> test on the Vulcain 1 (eventually performed in November 2001) were considered to be characterisation tests: the test programme was defined such that the

measurements covered as best as possible the flight envelope of the Ariane 5 in terms of Mach number, angle of attack and sideslip angle.
In 1999 the state of the art of the measurement system and software made it necessary to measure in two groups to be able to apply a sampling frequency of 12800 Hz. In 2001 and later the measurement system had evolved and all 149 unsteady time signals were sampled simultaneously at 12800 Hz in one group.
The <#6> test was split into 3 phases: in the verification phase (phase 1) the time signals were sampled with a frequency of 6400 Hz during a period of about 4 seconds for a one-to-one comparison with the verification tests of January 2001 and May 2001. In the characterisation phase and optimisation phase (phases 2 and 3) time signals were sampled with a frequency of 12800 Hz, also for a period of 4 seconds for a one-to-one comparison with the 1999 tests.
All unsteady data were measured in the 'throughput mode'. In the throughput mode raw time signals were acquired and stored directly on disk. In this way they were available for any type of post processing later on.
All pressure sensors were conditioned and amplified close to the model, using Multi Channel Conditioning Units (MCCU) or standard single channel Conditioning Units (CU). All test runs were carried out with fixed setting of the amplifiers, since autoranging each datapoint would consume too much time. The accelerometers in the model were conditioned by charge amplifiers. From the conditioning units all unsteady pressures and accelerations were connected to the multi-channel LMS SCADAS III front-end of NLR, which was controlled by a HP9000-700 C360 acquisition computer. Since acquisition and processing could not be done simultaneously on the C360, a HP9000-700 B180 computer was used in parallel for processing of stored data.
Time histories of the unsteady pressures, measured over 4 seconds, were reduced to autopowers, in power spectral densities (PSD) form, through a fast Fourier transform (FFT) and directly scaled to non-dimensional conditions using the formulas below based on the Strouhal number (St), assuming that this relationship is valid for model and full-scale vehicle (Reynolds effects are ignored).

$$PSD_{flight}(St) = PSD_{model}(f_{model}) \times \frac{V_{model}}{Q^2_{model} \times L_{model}}$$

$$St = f_{model} \times \frac{L_{model}}{V_{model}}$$

The unsteady pressures were reduced to unsteady coefficients (Cprms) by taking the overall RMS value of the auto-power spectra and by dividing the value of each unsteady pressure through the free flight dynamic pressure.
Additional to the auto-powers, the time signals were also processed to cross-powers by defining each pressure as a reference. In that way a huge amount of spectra necessary to calculate the unsteady loads became available (for example 3240 for only the nozzle). The cross-spectra were also reduced to non-dimensional conditions using the same scaling parameters as for the power spectral densities.
Spectra of the unsteady forces on the nozzle in x-, y- and z-direction were calculated by summation of the products of local pressures and the corresponding projected working surfaces. Spectra of unsteady moments were calculated by using the corresponding projected working surface multiplied with the moment arm with respect to the MRP.

3 Tests and test results

Tests started <#2> in 1999 with the "original" Vulcain 2 nozzle at the end of the Ariane 5 Plus launcher to characterise the flight envelope of the launcher. The results showed high levels of transverse loads on the nozzle. The tests also demonstrated that the loads on the nozzle could be lowered with a skirt mounted on the central body on the engine frame. At that time that solution was not suitable in terms of mass.
A working group at EADS Launch Vehicles focused on the problem of the high loads and made assumptions on the origin of the phenomenon. Analysis of the wind tunnel tests and flight data suggested that an organised phenomenon could result from the coupling of vortices generated near the boosters and the recirculation zones downstream the central body. The rear connection struts also might have a significant effect on the phenomenon. Different solutions were proposed to lower the loads.
One of the solutions was to lower the loads by adding aerodynamic devices on the boosters to disturb the organised oscillating flow in the vicinity of the Vulcain 2 nozzle. Wind tunnel tests <#4> for verification of this solution were performed with the same model (1:60) as in the previous test. Small changes were needed

to accommodate the installation of the various attenuation devices. Additional small changes were applied to improve the compliance of the launcher model with the at that time current definition of the future Ariane 5 Plus launcher.
Different aerodynamic devices, derived from three basic configurations, were planned to be tested separately under very precise conditions. One configuration was selected to carry out a complete characterisation for the same Mach numbers, angle of attack and side slip conditions as the 1999 HST test [4].
The <#4> test was not completed because reference measurements did not give the expected results. High peaks in the spectra, far higher than those observed in 1999, were found at Mach 0.70 around the buffeting frequency (Figure 3). Analysis of the results and additional investigations outside the wind tunnel supported the assumption of the existence of an acoustic source in the flow in the region of the rear end of the model and its support causing the phenomenon. However, the source of this acoustic wave became not clear and further investigation was required.

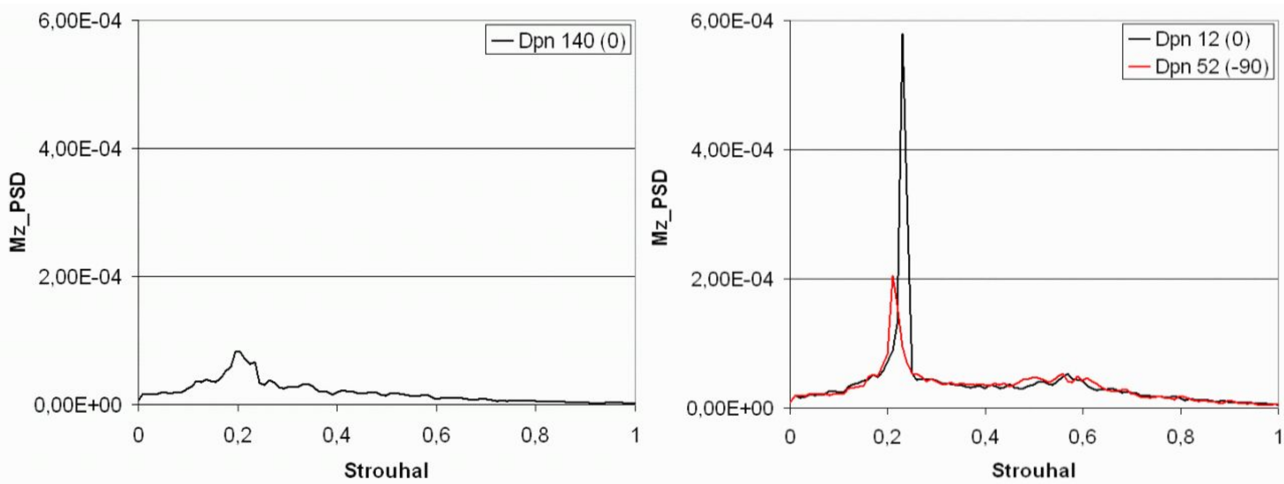

Figure 3 : Example of high loads during January 2001 tests (right) compared to 1999 tests (left)

In order to further investigate this hypothesis and, in case of confirmation, to identify the acoustic source and find a way to handle the effect of the phenomenon, wind tunnel tests <#5> were defined and performed in May 2001 [5]. Several new model components were designed and fabricated to investigate the effect on the excessive peaks in the spectra:

- Four different options of the streamline fairing at the end of the twin-sting support (Figure 4),
- New rear connection struts to enable testing of a configuration of the model, which was geometrically identical to the 1999 model.
- A new, longer twin-sting support to be tested in a later stage if the support (streamline fairing at the end of the twin-sting support) showed to have an effect.

Trying to find the acoustic source was done with an acoustic array (Figure 5). The array was placed at the location of the starboard window of the HST test section. The array consisted of 29 Endevco type 8510-B2 (2 psi) pressure transducers, implemented in a circular disk that replaced the starboard window, normally used for mounting half-models. The array disk itself was mounted in a turntable that could be rotated, enabling array measurements in a forward and aft position The size of the starboard window, the number of available transducers and the frequency range formed constraints in defining the acoustic array, i.e. the definition of transducer locations that give minimum spurious side lobes. For this an optimisation routine for minimising side lobes [6] was used.
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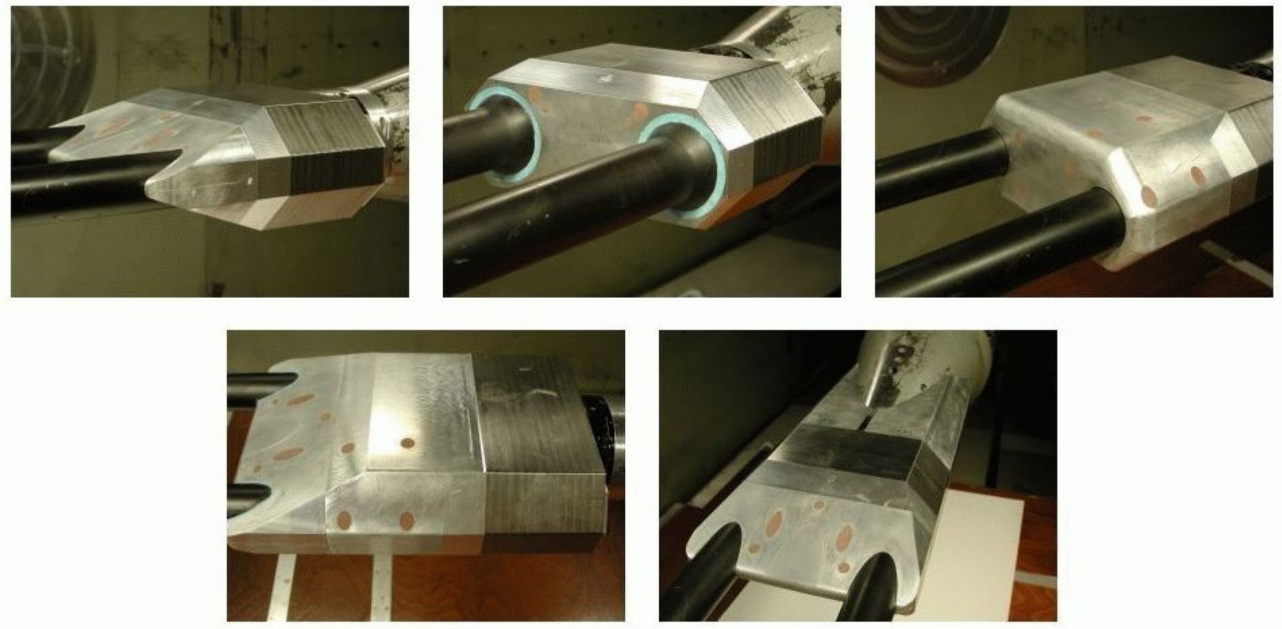

Figure 4 : Streamline fairings of twin-sting support

The time signals of the array transducers were recorded simultaneously for 20 seconds at a sampling frequency of 6400 Hz by the GBM VIPER of NLR. The system is a multiple channel data-acquisition and online processing system, consisting of a Master PC and so called Viper Units, which are PCs with multiple channel units that provide conditioning of the transducers, channel signal amplification, analogue high pass and low pass filter, analogue to digital conversion, digital filtering and storage of the signals on hard disk [7][8]. The advantage of recording and storage of the time data is the possibility of further data processing or reprocessing of any type at any later stage. For this test the data processing was done directly after storage of the time signals on a processing PC.
The software that was used for locating noise sources is called SOLACAN[1], developed at NLR.
With the array transducer pressures as input the SOLACAN software localised acoustic sources, using a conventional focusing method. The sources (uni-directional monopoles) are assumed in isolated points of a defined surface, the so-called grid points and scanning surface. From a dedicated optimisation routine based on measured cross powers and estimated transfer functions between grid points and microphones one can retrieve the source power of the local monopole.

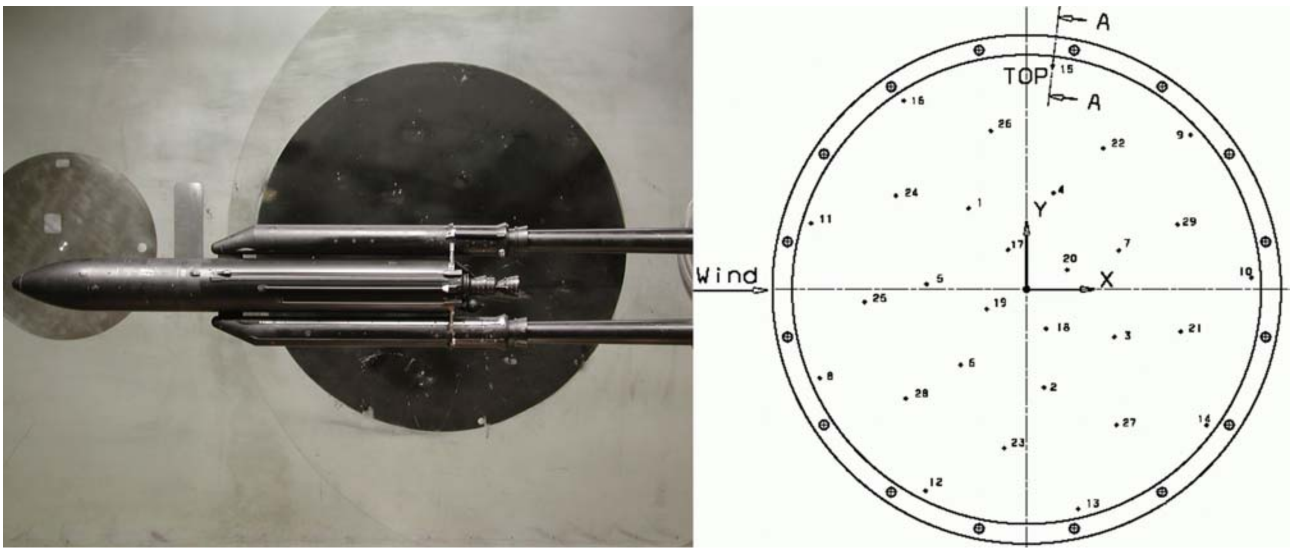

Figure 5 : Acoustic array in HST side wall window (forward position)

[1] SOLACAN: acronym for SOurce Location by an ACoustic ANtenna.

Testing the 4 different options of the twin-sting support streamline fairings showed the following.
With a wedge support a dipole is observed that radiates towards the walls. The levels recorded on the tunnel wall show a maximum that is higher than on some positions on the nozzle. Thus the influence of the acoustic source on the model pressures can not be excluded. The acoustic source can also have influenced the unsteady flow (interaction). The effects of the acoustic source reflecting on the slotted tunnel top and bottom wall (height 1.8 or 1.6 m) versus the solid sidewalls (width 2 m) causes the different results for the model at $\varphi = 0°$ and $\varphi = 90°$.
The blunt body support gave a reduction of the pressures observed on the wall and also on the nozzle. The source plots made with the acoustic array showed a monopole source about 0.2 m behind the nozzle. The blockage of the blunt body support may however have influenced the flow around the nozzle and it therefore seems not a suitable alternative to the wedge shape support.
From these tests it was concluded that Z-shaped support beams (Figure 6) that lower the position of the “wedge support” would certainly be beneficial. It would result in a reduction of the acoustic dipole source, because the “wedge support” would then not be impinged by disturbances in the flow behind the model.
The question that still remained unsolved was why the excessive loads were present in the results of the 2001 tests (January and May) and not in the results of the 1999 tests though, at least in the May tests, a geometrically identical model was tested. What probably happens is, that the disturbed flow, shed from the base area of the nozzle and impinged on the wedge-shaped support triggers, depending on model geometry, flow conditions and model angles, a “go – no go” phenomenon, resulting in an acoustic dipole source. The triggering of this phenomenon can also be influenced by the roughness of the model. For the <#2> and <#3> tests the nozzle was painted dull black while the rest of the complete model was blank. For all latter tests the model(s) were completely painted black and additional roughness was present at the rear area of the boosters because of covers and plasticine at places where the attenuation devices could be positioned.

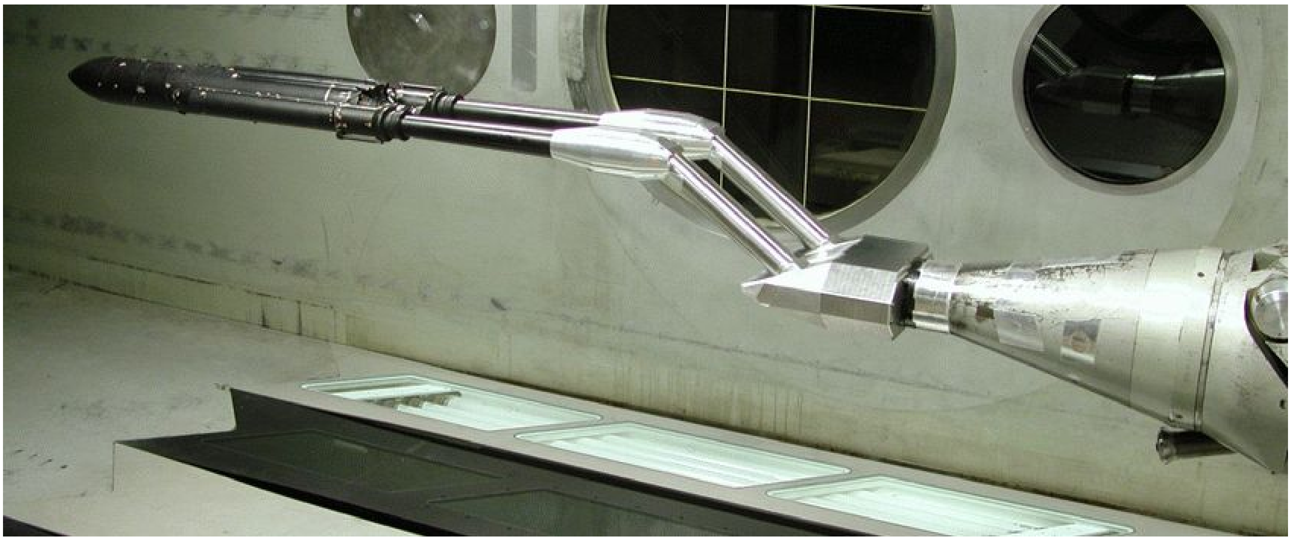

Figure 6 : Ariane launcher on Z-shaped twin-sting support

A Z-shaped twin-sting support was designed and fabricated and was tested <#6> in September 2001 [9]. The campaign started with a verification phase in which several simultaneous measurements of array transducers and model transducers showed that the effect of the acoustic source was reduced in such a way that it did not influence the model pressures. Figure 7 (upper part) shows acoustic source images of the straight (left) and Z-shaped (right) support for the same test conditions and some typical array transducer spectra (lower part).

Since the outcome of the verification phase showed results different from the 1999 results, EADS decided that a new characterisation phase for the “new” nominal configuration was necessary. The comparison showed that the influence of an acoustic source was also present in the 1999 results, though not so pronounced as in the <#4> and <#5> tests [5]. The phenomenon was not detected at that time since comparisons were only performed at Mach 0.9, were the phenomenon is not visible.

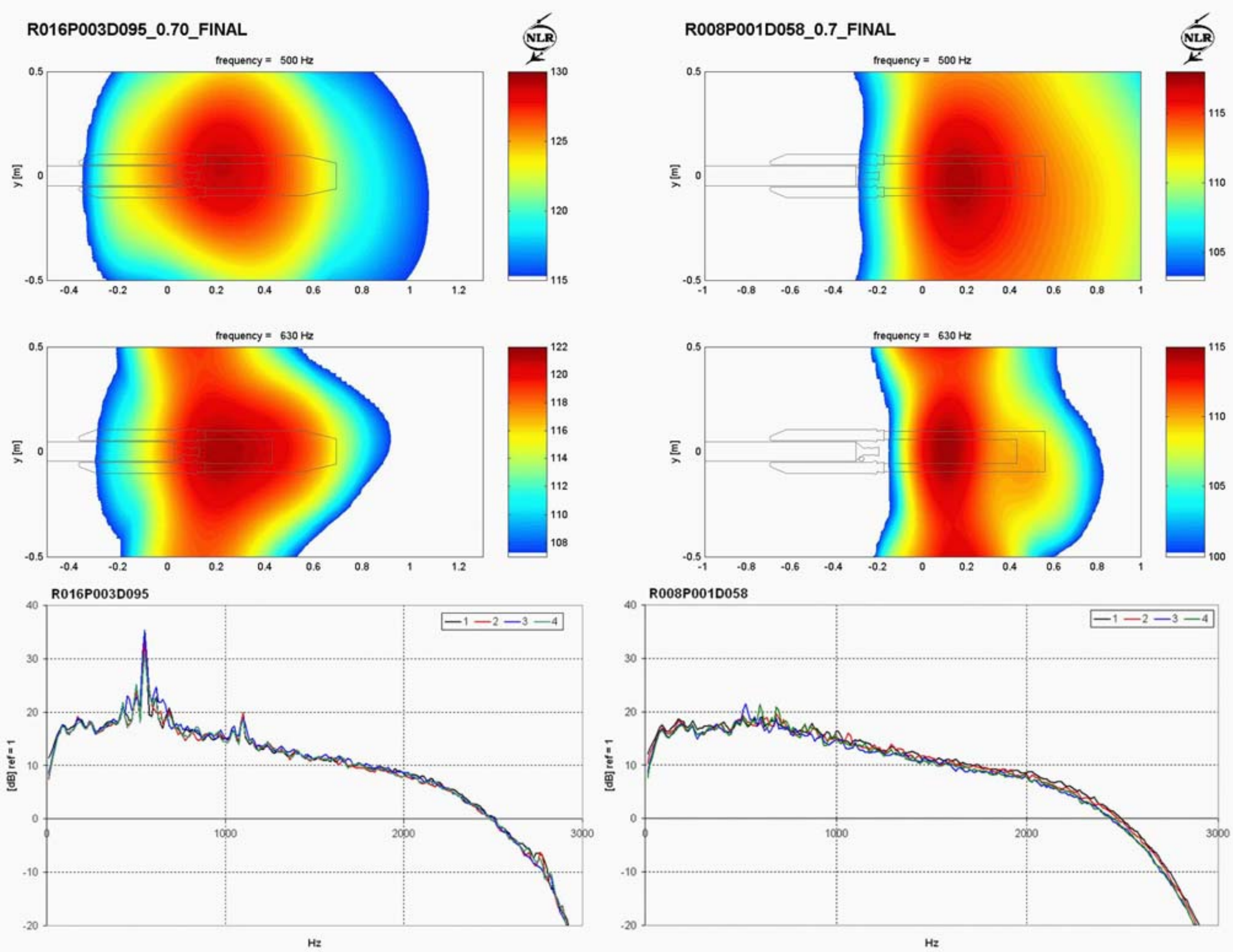

Figure 7 : Acoustic array results for straight (left) and Z-shaped (right) twin-sting support

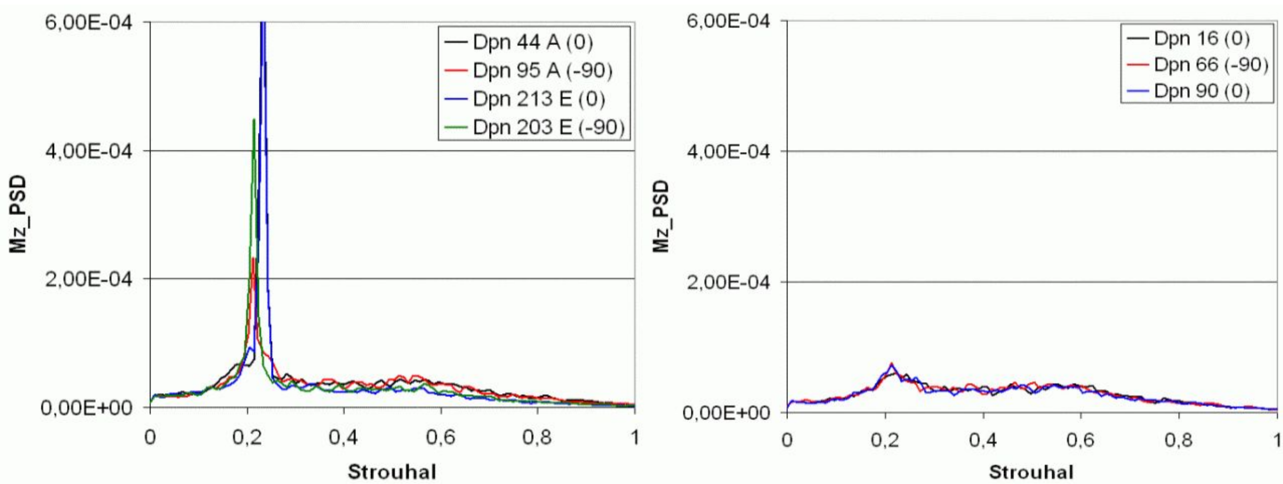

Figure 8 : Example of high loads during May 2001 tests (left) compared to September 2001 tests (right)

Starting from results of the nominal configuration in the characterisation phase, the goal of the optimisation phase was first to find out which type of attenuation device was the best. Three types of attenuation devices were investigated:

- Streamlined fairings on the rear connection struts (Figure 9),
- Fences on the boosters (Figure 10), and
- Vortex generators on the boosters (Figure 11).

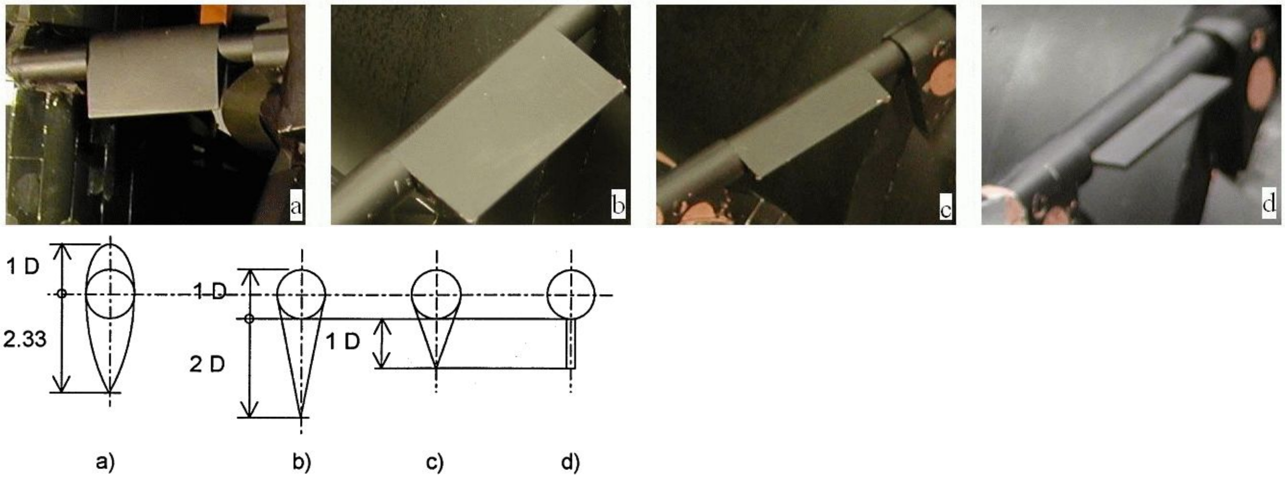

Figure 9 : Attenuation devices: rear support struts streamline fairings

As a first step, the configuration, defined as nominal of each of these types was tested for 10 conditions each, i.e. 5 fixed combinations of α and β at 2 Mach numbers.
For the 4 variations of the DAAR streamline fairings configuration "a" (Figure 9 - left) was chosen as nominal, which was tested as first configuration. Beside the nominal configuration A of the fences (Figure 10) and the clean configuration in which all gabs were filled with covers, 5 other combinations were possible.

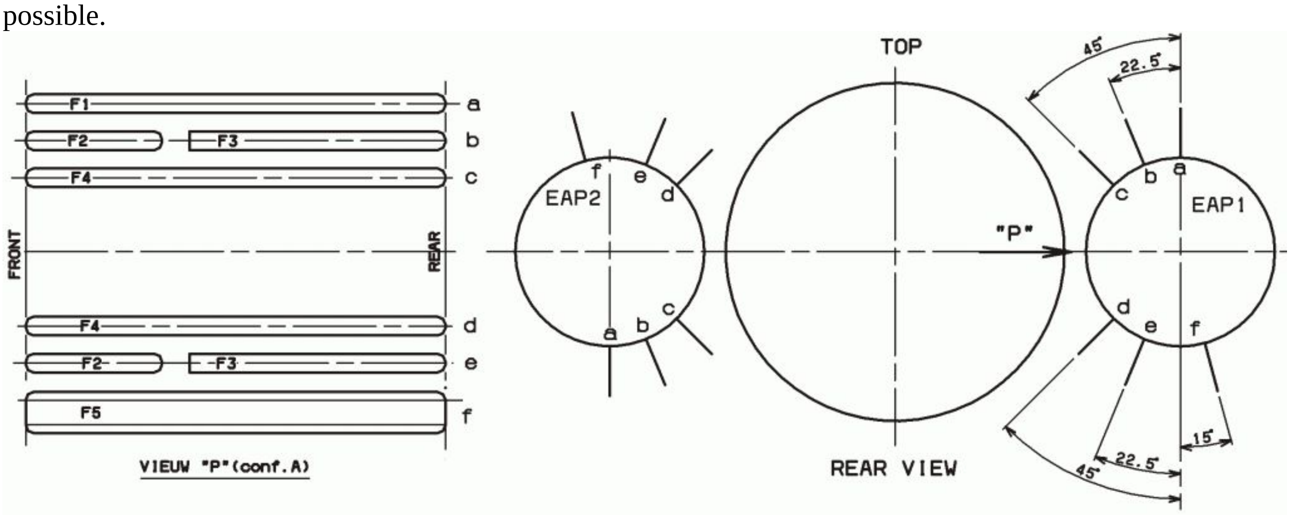

Figure 10 : Attenuation devices: fences

Two configurations of the vortex generators were tested. At first configuration A (Figure 11) was believed to be the nominal configuration. After testing this configuration, new insights caused reason to believe that the configuration B (Figure 11) was the nominal configuration. As, before the tests, the vortex rings were expected to be the "best" attenuation devices, two more configurations were present for detailed investigations (Figure 11C and D). From the test results this appeared not to be the case.

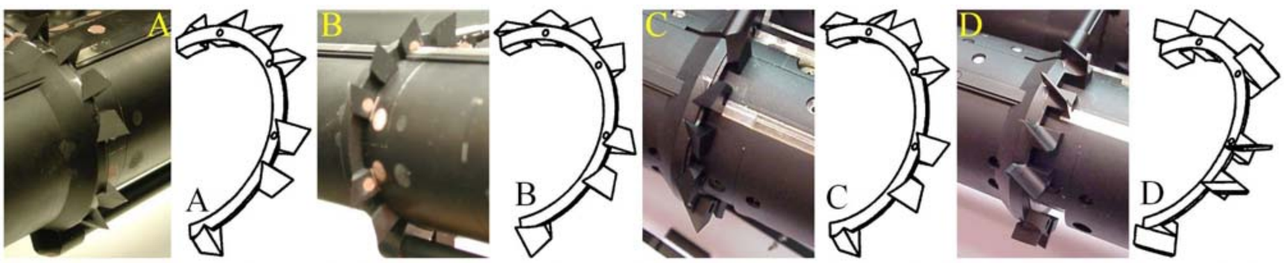

Figure 11 : Attenuation devices: vortex generators

Results of the nominal configurations, at conditions that generated the highest levels of overall moments in previous tests (Figure 12), showed that of all types of attenuation devices, the nominal DAAR configuration gave the best reduction of the levels of the overall moments.

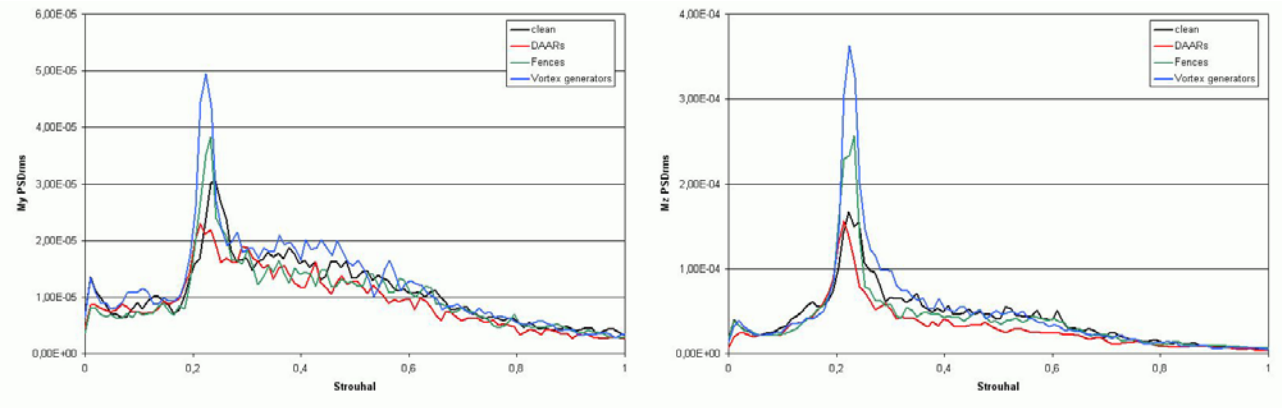

Figure 12 : Example of results of nominal configuration of attenuation devices:

Further testing of the other 3 configurations (Figure 9, b, c and d) completed the test programme. Comparison of the results of the different rear connection strut fairings led to the conclusion that the nominal configuration was best. As can be seen in above figure the differences with the clean launcher are minimal and the overall loads and moments remain at a level which was unacceptably high.
Since it was not clear how to judge the outcome of the various wind tunnel tests in relation to information gathered from actual flight measurements (no Vulcain 2 flight data were available at that time), it was decided to perform wind tunnel measurements on a model of the Ariane 5 Vulcain 1 launch vehicle, for which flight data were available. From the comparison of wind tunnel data vs. flight data of the Vulcain 1, both qualitative and quantitative knowledge and insights could be projected on the Vulcain 2 wind tunnel results, to enable a better judgement of the data. In fact the investigations on the Ariane 5 Vulcain 1 were initiated as a parallel investigation to the attenuation devices test. Design and fabrication of a new Vulcain 1 nozzle (Figure 1 left) was already completed; the investigation was not performed yet because priority was given to the Vulcain 2 investigations. The Vulcain 1 wind tunnel test <#7> was performed in November 2001 [10]. Results were produced in a similar way as for the other investigations and were handed over to EADS, who took care of further processing and analysis and comparison to flight results. How unsteady pressures, measured in flight, were used to correct or adjust the wind tunnel data and to validate the dynamic models of nozzle and engine actuators with the corrected pressure fields is discussed in [11].
From these analyses and analyses of the Vulcain 2 data compared to flight results, that had become available in course of time, confidence in the wind tunnel test results was gained.

Because of the confidence in wind tunnel test results and because the dimensioning problems (buckling, ovalisation) were still present, it was decided to make a new design in which the nozzle of the Vulcain 2 was shortened 0.15 m (full scale) compared to the previous definition. Even if this geometrical modification seems minor, the knowledge of buffeting phenomenon is not high enough to ensure to take minimal margins in extrapolating specifications from results of the <#6> tests. It was decided to validate the new design of the nozzle by performing a wind tunnel test campaign <#8> in the nearest conditions as the previous tests to facilitate comparisons.
In a verification phase results of the truncated nozzle plus extension disc (Figure 1 - right) were compared to results of the Vulcain 2 nozzle of the <#6> test (Figure 1 - middle).
Comparison of these results showed differences which could not be logically explained from the presence of the extension disk. From the difference in the Cprms curves in the region between $\varphi = 180°$ up to $\varphi = 360°$, which is the upper side of the launcher model, the LBS box (ground link pod) was open to suspicion. A closer study of the LBS box showed small but clear differences between the new LBS box and the original LBS box that was used in all previous Vulcain Mk2 tests. It was decided to replace the “new” LBS box with the original one and to redo some tests. From the results of these tests it was clear that the LBS box caused the differences. The results of the runs with the original LBS box showed reasonable comparison with the results of the <#6> test. The above event is mentioned to emphasize that small changes in the external geometry of the model can have a major impact on the data.

After comparison of results of the truncated nozzle plus extension disc and the original LBS box with results of the Vulcain 2 nozzle of the <#6> test it was decided to remove the extension disk and to start a complete characterisation of the steady and unsteady aerodynamic distribution of pressures of the truncated nozzle.

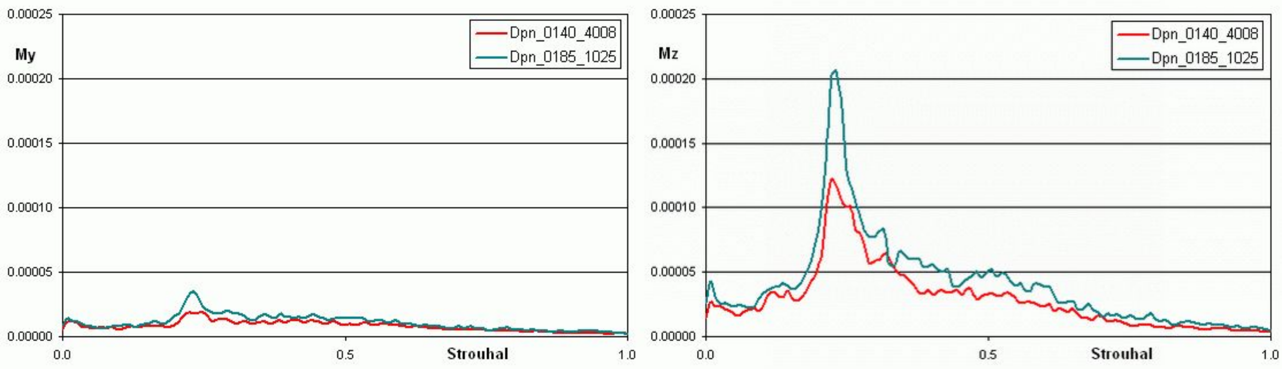

Figure 13 : Effect of truncation, truncated nozzle left, nozzle with extension disk right

From the results of these investigations it was evident that the truncated nozzle generated lower unsteady overall loads (Figure 13). This conclusion was justified in a qualitative way. Quantification of the decrease of the loads by truncating the nozzle needs a thorough investigation of the data of this test campaign, which was beyond the scope of the contract. EADS did the quantification and results were used to define all specifications in terms of loads on the different structures in the rear section of the launcher equipped with the truncated "optimised" Vulcain 2).

For minimisation of efforts and cost effectiveness, the test on the truncated nozzle <#8> (HST test 4008 [12]) was directly followed by an additional test <#9> (HST test 4012 [13]) with the object to (try to) reduce buffeting by the use of skirts.

Limited (short) skirt tests were already performed in 1999 <#2> on the previous version of the Vulcain 2 nozzle [4]. At that time it was concluded that skirts had a weak, though positive influence. In order to confirm (or not) the weak influence of the short skirt and to investigate the effect of other skirts on the new nozzle, 4 different skirt configurations (Figure 14) and their interface to the base of the Ariane 5 Launcher were designed and fabricated.

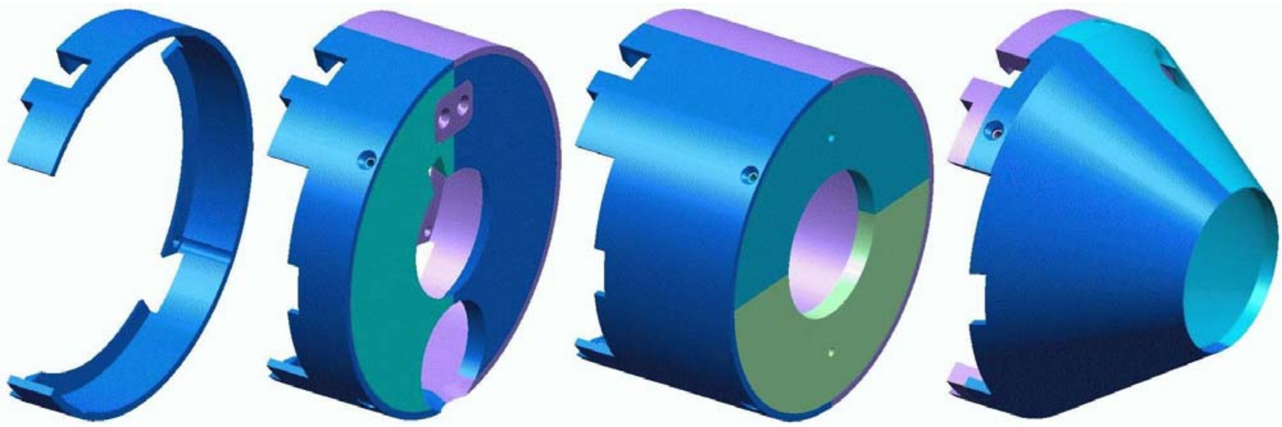

Figure 14 : Skirt variations

These configurations were:

- Short skirt configuration: 920 mm full scale, open, all protuberances present (Figure 14 - outer left),
- Middle skirt configuration: 1947 mm full scale to the end of the BME (Bâti Moteur / engine frame) cone, closed horizontally, no Helium sphere installed (Figure 14 – inner left),
- Long skirt configuration: 3389 mm full scale to the end of the PTE (Protection Thermique Etage / stage thermal protection), closed horizontally (Figure 14 – inner right), and
- Cylindro-conical skirt: 920 mm full scale cylindrical (as short skirt), then conical to the end of the PTE (diameter 2264 mm full scale), no Helium-sphere installed (Figure 14 – outer right).

For completeness and numerical validation also a smooth and symmetrical configuration, without protuberances, was tested. The stripped configuration and the effect of the 4 different skirt configurations were tested on the optimised nozzle. Though a “smooth” configuration as tested, is not an option for real flight, the test results of this relatively simple geometry will provide a good starting point for computational code evaluation for understanding the difficult turbulent flows in the region of the rear part of this type of launcher vehicles [14].
However, the conclusion from limited skirt tests in 1999 [4], that skirts had a weak, though positive influence was confirmed by the present tests. A choice for one of the skirt configurations measured in this test could not be made without a more thorough analysis.

4 Epilogue

Over the last five years a large number of wind tunnel investigations has been performed at NLR and DNW, to characterize the steady and unsteady aerodynamic pressure distribution of three Ariane 5 nozzles. In spite of the setback and the time delay caused by the acoustic phenomenon, the Vulcain 2 measurements resulted in valuable information. Unfortunately the loads remained (too) high for the various solutions tested to lower them.
Comparison of Vulcain 1, later also Vulcain 2, wind tunnel test data with flight data gave confidence in the technique of measuring overall forces and moments if using an adequate amount of pressure transducers.
The analyses of the pressure fields applied to a numerical model of the launcher eventually led to a new design of a truncated “optimised” Vulcain 2 nozzle. The loads on the nozzle were characterised in another wind tunnel test, which indeed showed reduction of loads. The “optimised” design was applied to the Ariane 5 launcher and led to a successful flight. All investigations have proven that the use of wind tunnels results in combination with numerical models still is a valuable, inevitable tool to attack problems.

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