Acoustic Environment of the VEGA Launch Vehicle at Lift-Off

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In the frame of the VEGA program, a collaboration between AVIO and ONERA has been established to characterize the acoustic environment of the VEGA launch vehicle which will lift-off from the ex-launch pad ELA1 of the former Ariane 1 in Kourou. A test campaign has been performed in the MARTEL facility, located in the CEAT of Poitiers University, in order to perform a trade-off analysis of different configurations compatible with the existing ELA1 launch pad which will be adapted for VEGA. The tests were performed using a mock-up at the 1/33 scale and the microphones were mainly installed on the launch vehicle represented by the cylindrical Air-hydrogen combustion chamber of MARTEL. In 2004, ONERA carried out a new test campaign using the AVIO BEAT facility in Colleferro (Italy) to determine the whole characteristics of the incident acoustic field generated by the first stage P80. The tests were performed at fixed altitudes with a 1/20 scale LV mock-up equipped with a realistic solid propellant booster. Acoustic source localization has been implemented using a 26-microphone-array surrounding the fairing. Moreover, a model has been developed to simulate the incident acoustic field with the minimum number of sources. According to the third octave band, 1 to 6 uncorrelated plane waves are sufficient to reproduce the measured acoustic field in amplitude and phase.

1 Introduction

VEGA is a new small European launch vehicle that is currently in development and is financed by ESA. The first launch is planned for 2008 from Kourou space center. ELV* and AVIO** have entrusted ONERA*** with the acoustic characterization at lift-off of this new launch vehicle including two steps:

- the first involves, using MARTEL facility located at CEAT****, the optimization of the launch pad configurations, keeping in mind that the Ariane 1 ELA1 launch pad will be used. As the stagnation conditions of the MARTEL jets are not the same as the P80 motor at full scale, the absolute acoustic levels measurements are not directly analyzed and a parametric study will be performed;

- in the second step, ONERA has carried out in 2004 a test campaign at the AVIO site in Colleferro. A 1/20 scale mock-up has been specially designed and manufactured by AVIO in order to obtain the real sound pressure levels at lift-off. A dedicated P80 1/20 scaled engine has been designed, which works in conditions of fluidynamic similitude (in terms of the Strouhal number) wrt the full scale P80 engine, thus allowing the generation of the same acoustic field produced by the real Vega first stage engine.

2 VEGA test setup in MARTEL facility

The tests have been carried out in the MARTEL facility [1, 2], installed at the CEAT of the Poitiers University. A general view of the test set-up is shown in figure 1.

The central part of this facility is a jet generator made up of an Air-Hydrogen combustion chamber coupling with a convergent-divergent nozzle, which can generate very hot supersonic jets. The jet generator is hung in a semi-anechoic room. The launch vehicle body is simulated by the combustion chamber itself but it is not fully representative of the VEGA diameter.

Figure 1: MARTEL test setup

The tests were carried out with a ELA1 launch pad mock-up for several fixed altitudes simulating, step by step, the launch vehicle ascent. The stagnation conditions of the jet are 1700 K in temperature and 30 bar in pressure providing an exhaust jet velocity about 1700 m/s.
The frequency transposition between the MARTEL and the full-scale results is based on the reduced Strouhal number equal to 29 which is very close to the geometric ratio equal to 33. The acoustic measurement were mainly made using a cylindrical array composed with 12-free-field-microphones, spaced every 60° in azimuth and distributed on two levels. The location of the microphone array corresponds to the fairing level of the launch vehicle.

The main parameters were:
- a single flue or two flues,
- the presence of a flue cover to mask the acoustic sources (figure 2);
- the water injection devices to reduce the jet noise (figure 3).

3 Experimental Design technique

The measurements were performed and analyzed using an Experimental Design technique (ED). The advantage of the ED is to obtain the utmost information on the main factors with the minimum number of tests.

With appropriate statistical processing and with only 16 tests, it was thus possible to obtain the results equivalent to 128 tests while taking into account the effects of interaction between the parameters. The Taguchi Experimental Design model was chosen because it is the best way of dealing with factors having more than 2 levels and it is quite convenient in case of clearly identified factors. According to the main parameters to study we have considered:
- 2 levels for the flue factor A (A1 single flue, A2 double flues);
- 2 levels for the flue cover B (B1 without cover, B2 with cover);
- 2 levels for the water injection C (C1 without water, C3 with water);
- 4 levels for the altitude of the launcher (D1 : 0m, D2 : 10m, D3 : 25m, D4 : 50 m).

The experimental design analysis can integrate the interaction (non linear behavior) between two parameters. The interaction, considered as unknown, must be taken into account. The experience gained with Ariane 5 [3, 4] leads us to identify 3 major interactions between:
- flue cover and water injection (BC);
- flue cover and altitude (BD);
- water injection and altitude (CD).

The figure 4 presents an example of the overview results in graphic form with the parameters effect and the interactions effect for the OASPL value. The experimental design process is based on an additive law of several parameters effects.

Based on these results, it is possible to calculate any combination of the 4 main factors A_i, B_j, C_k, D_l by adding the effect of each factor and each interaction. So, we can obtain the acoustic levels corresponding to the 32 combinations.

In order to evaluate the performance of the experimental design method, additional tests have been performed allowing the comparison of launch pad configurations not included in the ED. The discrepancy is very small and less than 1 dB. This point confirm than the ED method is reliable and can be advantageously used to obtain a very good estimation of any configuration not tested experimentally.

4 MARTEL acoustic results analysis

The analysis of Martel test results, has allowed the qualitative evaluation of the effects induced at lift-off on the fairing section of the launcher by the selection of
different configurations of the launch pad. These are expressed in terms of differences of dB (DdB) of the measured acoustic levels and are generated by specific changes in the selected critical factors (number of flues, etc.), which have been considered singularly and in combination. The major effects in terms of attenuation of the acoustic levels are achieved by combining together the different factors, the interaction resulting in an amplification of the attenuation effect of the order of two or three times the one produced by the same factors separately.

The main results can be resumed as follows:
- **effects of number of flues**: no significant differences, in terms of SPL measured between the configuration with single or double flues (SPL < 1 dB);
- **effects of covering of the flues**: maximum reduction of the SPL levels of 1-2 dB in the low frequency range (up to 150 Hz);
- **effects of the water injection**: maximum attenuation of the SPL from 1 to 4 dB, which is mostly effective in the low frequency region;
- **effects of LV altitude**: the investigated altitudes correspond in full scale to 0m, 10m, 25m and 50m; the results show an increase of the SPL with quote up to 25m, followed by a strong reduction of the acoustic levels for higher altitudes;
- **effects of interaction cover + water injection**: this combination produces a strong reduction (from 3 dB up to 10 dB) of SPL in all the octave bands;
- **effects of interaction cover + altitude**: this combination gives the maximum efficiency at low altitudes (reductions up to 4 dB up to 25m in full scale), becoming ineffective for higher altitudes;
- **effects of interaction water + altitude**: mostly efficient at low altitudes; maximum noise reduction at 0m (of the order of 4 dB). For altitudes above 25m the effect of the water injection is negligible.

Some examples of the results of the MARTEL facility tests are reported in Figure 5.

From these results it has been derived the Launch Pad reference configuration for the successive tests in reduced scale c/o the AVIO “BEAT” test facility, which is: two-ducts, without water and without covering of the flues.

This choice is determined by the aim to be conservative, which means to select as a reference the worst possible configuration in terms of noise generated at fairing level (i.e. total absence of any acoustic damper). The double duct configuration, moreover has been selected wrt to the single duct for the intrinsic symmetry of the acoustic field it provides on the launcher surface.

### 5 1/20 scale tests in Colleferro

The BEAT facility (figure 6) reproduces in geometrical scale (1/20) both the VEGA ELA1 Launch Pad and the full launch vehicle mock-up. A dedicated SRM ("P80" Solid Rocket Motor) has been designed and developed in order to provide the same acoustic field generated at lift-off by the full scale Vega 1st stage SRM.

The design of the BEAT test facility has been conceived in order to allow:
- the simulation of different altitudes ranging from 0m up to 75m in full scale, reproducing the first 4 seconds of the VEGA launcher ascent trajectory at lift-off;
- the representation of different launch pad configurations, with the same versatility of MARTEL facility.

Starting from MARTEL facility test results, the main goal of the BEAT test campaign is to determine the effective acoustic levels generated at lift-off on critical sections of the launcher (mainly on the fairing and at the interstages). While MARTEL facility tests, in fact, provide useful results only in terms of variation of acoustic levels, the BEAT tests can provide the real SPL on the VEGA launcher (i.e. the same levels achievable in full-scale conditions).

The main goal of the BEAT test campaign is, then, the assessment of the final configuration of the launch-pad to be adopted for the VEGA launcher, by comparing the SPL values obtained at different altitudes with the two extreme configurations, in terms of noise reduction efficiency, extrapolated from MARTEL facility test campaign:

1: two ducts without both water injection and covering of the flues (which is taken as baseline configuration);
2: two ducts with water injection and covering of the flues.

The results of the BEAT test campaign will be used for the determination of:
- the unsteady pressure field induced by the jet plume on the launcher surface;
- the incident acoustic field;
- the simplest acoustic source model that describes the incident acoustic field on the launcher in the low frequency domain;
- the effects (on the SPL) of the introduction of noise reduction devices such as water injection and covering of the flues.

The BEAT test facility is mainly constituted by the following elements:
- a support structure (Gantry) which is capable to sustain the launcher at different altitudes during the static firing tests;
- a mock-up of the Vega launcher which reproduce in 1/20 scale its external geometry from the interstage 1/2 section to the upper part of the fairing;
- a Solid Rocket Motor designed in order to produce a jet plume characterized by the same Strouhal number of the P80 full scale engine (jet exhaust velocity: 2700 m/s, jet temperature: 3500 K);
- the 1/20 scale mock-up of the ELA1 launch pad.

The determination of the acoustic levels on the launcher surface is allowed by the introduction of 41 microphones distributed on the launcher mock-up. Other 6 microphones are installed on launch pad elements in order to measure the acoustic loads induced on ground components.

During the BEAT test campaign two different configurations of the launch pad have been tested: the baseline (two ducts without cover and without water), and the full configuration (two ducts with cover and with water injection). The Sound Pressure Levels, achieved along the launcher surface with the two configurations, have been measured at three different altitudes: 0m, 10m and 25m. At higher altitudes, only the baseline configuration has been tested.

6 Acoustic sources localization

Acoustic source localization is performed using the 26 microphones in the fairing area. The objective is to locate the directions of the incident acoustic plane waves reaching the fairing.

The incident pressure for a plane wave of unit amplitude and direction \( \vec{u} \) at frequency \( f \) and location \( \vec{r} \) is
\[
p(\vec{r}, f) = \exp[ik\vec{r} \cdot \vec{u}],
\]
with \( k = 2\pi f/a_0 \) (\( a_0 \) is the sound velocity). Because the microphones are flush-mounted on a rigid wall, they do not measure the incident field. With a good approximation, it is possible to relate simply the incident pressure to the wall pressure assuming diffraction by an infinite rigid cylinder, the radius of which is the local radius of the fairing.

Working in a space of dimension \( N = 26 \), the wall pressure for the incident wave is represented by a column matrix. Using classical beamforming, the localisation function is:
\[
\gamma(f, \vec{u}) = \frac{A^H(f, \vec{u})\Gamma(f)A(f, \vec{u})}{Tr[\Gamma(f)] \|A(f, \vec{u})\|^2}
\]
where \( \Gamma(f) \) is the NxN cross-spectral density matrix (CSDM) of the microphones on the fairing at frequency \( f \).
For the geometry of the array, the relevant frequency range covers the 10 third octave frequency bands from 25 Hz to 200 Hz. The localization function is normalized to its maximum value, then plotted using 10 colors between 0 and the maximum value, according to figure 7.

![Figure 7: Acoustic sources localization. Classical beamforming.](image)

7 Model for the incident field around the fairing

In complex situations with continuously distributed sources in space, which is the case for free jet noise and noise induced by interactions between a jet and solid boundaries, beamforming gives the locations of the radiating regions, but not their amplitude. To do so, we choose to describe the incident field as a set of uncorrelated plane waves. The computation of the plane waves power spectral is achieved minimizing the difference between the measured CSDM and the CSDM issued from the model.

Figure 8 shows the result obtained in the same conditions as for figure 7, with third octave band levels normalized by its maximum value. The levels are computed using 1040 source directions evenly distributed.

![Figure 8: Uncorrelated plane waves model. Map of amplitude.](image)

It can be seen that the amplitude maps are similar to localization maps, with a better resolution. The uncorrelated wave plane model being computed, it is easy to suppress all sources corresponding to spurious reflections, which are indeed not to take into account at full scale, as reflections by the gantry (see for instance figure 7).

A criterion has been chosen in order to restrict the source locations to relevant ones. It consists in defining a maximum angle around the launcher axis where the actual sources are assumed to be located, large enough in order to cover the exit of the flues. All spurious sources being suppressed this way, it is easy to compute free pressure field and wall pressure fields relative only to the realistic sources. In order to provide useful input data for vibroacoustic codes predicting the acoustic field inside the fairing, the number of incident plane waves has to be reduced. A special procedure has been implemented in order to find the minimum number of plane waves and their locations such that the pressure field they radiate on the fairing is the same (in level and relative phase) as the field radiated by the full uncorrelated plane wave model. The results (figure 9) are given for each third octave band from 25 Hz to 200 Hz, and allows to compute:
- the number of incident plane waves in the minimum model, ranging generally from 2 to about 10, with their angular direction and amplitude;
- the mean wall SPL on the fairing in the reduced model, and its comparison with the measured mean wall SPL averaged on all 26 microphones. The difference is mainly due to the spurious reflections, not taken into account as explained previously in the reduced model;
- the free field SPL on the fairing in the reduced model. The difference with the previous value is due to diffraction effects. It appears that, depending on the frequency and on the firing, the free field SPL is lower than the wall pressure one, the difference ranging from 0 to 3 dB.

![Figure 9: Uncorrelated plane waves : model with minimum number of sources](image)

8 BEAT tests acoustic results analysis

The BEAT test campaign has allowed the determination of the acoustic field generated by the first stage solid rocket motor of the Vega launcher at different altitudes above ground. The measured acoustic loads induced on the fairing sections and expressed as overall sound...
pressure levels (OASPL) vary from 147 dB to 130 dB for the different test configurations. The highest levels are registered, of course, during the tests executed at low altitudes (0m, 10m and 25m) in the baseline configuration, while the lowest levels are measured with the test at the highest altitude corresponding to 75m in full scale.

The comparison between the SPL measured in the fairing part of the launcher for all the configurations examined have been accomplished considering the average level between the four fairing sections. The results obtained for the baseline and the full configurations at the different altitudes are reported in figure 10.

![Figure 10: SPL averages on the fairing. Baseline and full configurations](image)

All the results show that the critical altitudes, in terms of SPL measured at fairing level, are the lowest altitudes between 0m and 25m (full scale equivalent) for all the frequency range. The comparison between the SPL levels measured at 0m, 10m and 25m with the two configurations (baseline and full with the noise dampers) leads to a reduction of the SPL ranging from:
- 1.5dB to 4dB in the low frequency and high frequency regions, respectively, at 0m;
- 1.5dB to 2.5dB (average value) in the low frequency and high frequency regions, respectively, at 10m and 25m.

### 7 Conclusions

The acoustic characterization of the Vega launcher environment at lift-off has been performed in two different test campaigns. The first (performed at MARTEL facility, CEAT Poitiers) has led to the qualitative assessment of the variations in terms of SPL induced by all the possible modifications of the launch pad configuration. The second (performed at the BEAT test bench, AVIO Colleferro) has allowed the determination of the acoustic field induced on the launcher by the Vega 1st stage engine at lift-off, reproducing the environment generated during the first four seconds after the P80 engine ignition (when the launcher performs an ascent trajectory from 0m to 75 m above ground). The results of this test activity is the evaluation of the critical configuration of the launch pad and the critical altitude of the launcher above ground where the maximum acoustic loads on the launcher fairing are registered.

An additional short test campaign will be performed within 2005 in order to check the effect on the SPL induced by further modifications on the launch pad configuration, which have the aim to enhance the efficacy of the noise dampers already considered (covering of the flues and water injection on the plume).

### References

* European Launch Vehicle, Frascati, Italy
** AVIO, Colleferro, Italy
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