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ACOUSTIC CHARACTERIZATION OF VEGA LIFT-OFF ENVIRONMENT VIA RAY ACOUSTICS MODELLING AND DIRECT FIELD ACOUSTIC NOISE TESTING

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ABSTRACT

The lift-off phase during the space launch generates an extreme acoustic environment around the rocket fairing which must be considered for the qualification of large satellites. The sound waves, whose main source is the plume of gases coming from the rocket engine exhaust, travel through the fairing and impact the satellite, generating large vibrations in components with high surface to mass ratio. Dedicated models of the acoustic sources such as Distributed Source Method can be used to characterize the sound radiation from the jet of gasses. When it comes to modelling the spatial sound environments around the fairing, numerical approaches such as FEM or BEM are not well suited due to the large geometry of the problem and the need for extensive mesh refinements at high frequencies. In this context, geometrical acoustic methods such as ray acoustics provide a solution for full frequency simulations in very large geometries by assuming that the sound propagates along rays. Using this framework, this work focuses on the lift-off environment at the Vega launch pad and provides predictions of the sound pressure levels and directivity patterns around the payload fairing. Relevant considerations about how to replicate such conditions in laboratory tests are also discussed.

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1. INTRODUCTION

Satellites and spacecraft components experience extreme vibrations during the space launch. These excitations are due to mechanical and acoustic loads that travel through the rocket structure and fairing. Regarding the acoustic excitation, the most extreme environments are typically generated at the lift-off and transonic phases and are due to the sound generated by turbulent boundary layers, shock waves and the plume of gas deflected in the launch pad.

Characterizing these environments during the real launch entails a huge engineering challenge due to accessibility and cost issues. In this context, simulation models of various levels of fidelity are typically used to obtain approximations of the mechanical and acoustic loadings arising under such conditions [1]. However, simplifications and modelling assumptions always introduce a certain degree of uncertainty in the predictions made by these simulations, which explains why full-assembly dynamic environmental tests are always conducted in the space mission to validate the models and qualify the structures.

This paper proposes a combination of simulation and testing techniques to reproduce the acoustic loadings impinging the rocket during the space launch. Direct Field Acoustic Noise (DFAN) [2] is proposed as a testing method to simulate the non-diffuse sound fields at the lift-off in the laboratory using the predicted values as test reference. The findings of such research could be used to further understand the characteristics of the acoustic fields around the faring, as well as their interaction with the spacecraft structures. The Vega launcher is used as reference in the study.

2. LAUNCH ENVIRONMENT SIMULATION

The prediction of the actual acoustic environment at the lift-off phase of the launch is not an easy task. First, the modelling of the jet of exhaust gases from the launcher engines involves in all cases certain assumptions to characterize the noise sources and the sound propagation, including the various reflections and scatterings off the walls of the launch pad. Furthermore, the large size of the studied acoustic domain, which includes the launch pad structures as well as the rocket launcher, prevents the use of classical numerical methods based on FEM or BEM due to excessive computational costs.

2.1 Exhaust jet modelling

In the current research, the modelling of the acoustic sources during the lift-off is based on the Distributed Source Method (DSM) published by NASA [3]. This approach assumes that the noise source is confined in a small volume along the path of the exhaust plume. A user-defined number of point sources are introduced along this path, as it is shown in Figure 1, and the directivity of the sound is imposed typically via empirical indexes. Following the DSM, the radiation spectrum can be tuned to the specifications of the rocket engine and the launch pad.

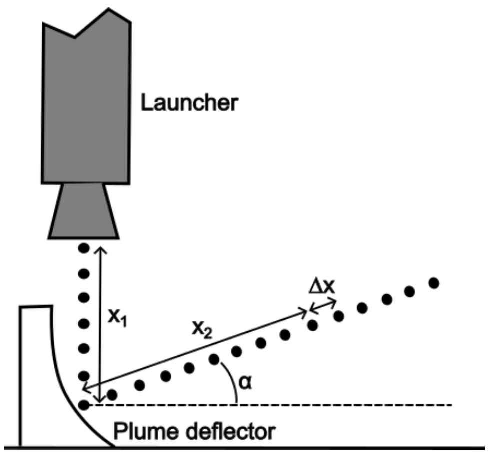

Figure 1. Representation of the gas plume according to the DSM method.

2.2 Ray Acoustics simulation

The simulation of the sound propagation in the launch pad and around the rocket faring requires the solution of a large acoustic domain that involves the acoustic sources, the launchpad and the full rocket launcher. Solving the computational problem using numerical approaches such as FEM or BEM is unfeasible due to the large number of elements that would be needed to capture the high frequency responses. In this work, a ray acoustics solver available in Simcenter 3D [4] was employed to predict the acoustic responses around the fairing generated by the noise sources. Ray acoustics modelling is a geometrical acoustic solution which assumes that the sound propagates along rays which are normal to the wave fronts. Accordingly, the mesh must only capture the surface geometries irrespective of the maximum frequency analyzed, and the accuracy is not dependent on the volume discretization. Figure 2 shows the geometrical model of the launch pad and rocket, including the plume deflectors and ducts. The sound sources (red dots) were defined in the 3D model based on the DSM approach. The generated ray acoustics model accounted for the wave reflections off the closer surfaces of the launch pad, as well as for the diffraction around selected edges.

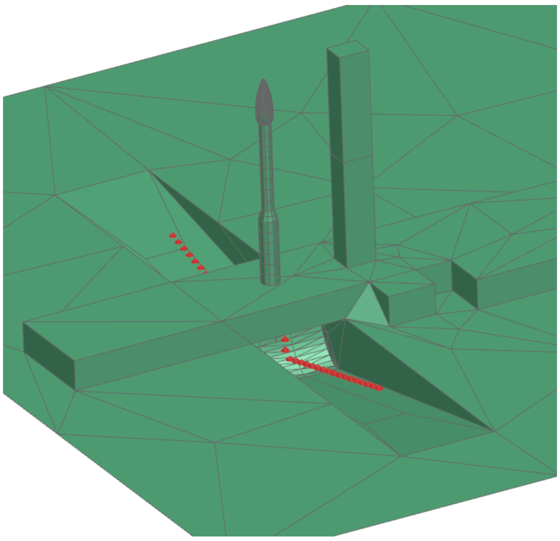

Figure 2. Model geometry of the Vega launch pad used for the ray acoustics simulation.

3. LAUNCH ENVIRONMENT ANALYSIS VIA DFAN

The acoustic tests for space applications aim at subjecting the spacecraft to the sound environment of the launch in a controlled facility. Typically, these tests have been conducted in large reverberant chambers, although in the past years a new testing approach known as DFAN is becoming popular. DFAN is based on the use of a portable electro-acoustic systems, like those installed in music concerts, to simulate the diffuse acoustic conditions that are assumed inside the fairing. Early works on the fundamental aspects of this technology can be found in [5] [6]. The loudspeaker cabinets are typically arranged in a cylindrical configuration with the spacecraft in the center and are driven by several independent signals generated by a Multiple-Input Multiple-Output (MIMO) controller. This exploratory research proposes the use of DFAN to experimentally reproduce the non-diffuse acoustic fields around the launcher fairing using a set of control points to feedback the MIMO controller.

3.1 Acoustic target synthesis for MIMO testing

The role of the MIMO controller is to compute the voltage signals that better reproduce the desired acoustic pressures at the control points. In the present research, the pressure targets are obtained from the simulation model depicted in Section 2, which provides the pressure responses in the volume surrounding the rocket for the frequency range of interest (16 Hz to 8000 Hz). Figure 3 shows the acoustic fields at 50Hz in a horizontal plane intersecting the fairing. The matrix of acoustic targets for the MIMO controller is then obtained from these pressure levels and the spatial correlation between the selected control points. Concerns about the realizability of the acoustic environments and the selection of optimal test parameters must be considered [7].

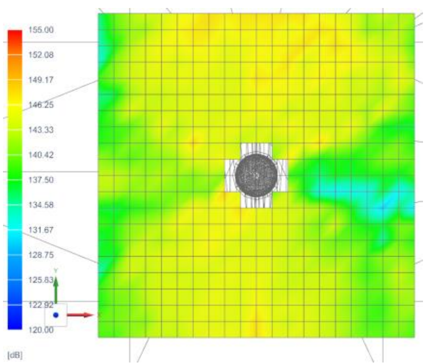

Figure 3. Simulated sound field at 50Hz.

3.2 Small-scale setup

The validation of the proposed experimental acoustic framework on an actual space launcher is out of the scope (and budget) of the current research. Consequently, a small-scale setup was built instead in the facilities of Siemens in Leuven, Belgium, which is shown in Figure 4. The electro-acoustic test plant includes 9 columns of loudspeakers of the model JBL Control 1 Pro, signal processing and amplification units from Auvitran, 24 free-field microphones and a Simcenter SCADAS acquisition system and signal generator. A large aluminum tube was introduced in the center of the loudspeaker setup to simulate the presence of the rocket fairing in the test. The acoustic MIMO control was performed using the software Simcenter Testlab MIMO Random Control [8].

A Digital Twin of the small-scale DFAN setup was created to support the design of the experimental test. This multidisciplinary analysis simulates all the components of the electro-acoustic system, including the electric, mechanical, and acoustic parts. The simulation framework proposed in [9] for DFAN analysis was employed. According to it, the loudspeakers were modelled using lumped-parameter models and the sound propagation was captured using an adaptive order FEM solver [10]. Such high-fidelity model enabled the computation of the transfer functions of the system, and thus the simulation of the closed-loop MIMO control test. Various combinations of test parameters were tested in the virtual environment to optimize the test layout.

Figure 4. Small-scale DFAN setup for laboratory tests.

4. PRELIMINARY STUDY

The Digital Twin of the DFAN test setup was used to predict the achievable acoustic fields around the launcher mockup. Several simulations were conducted considering different test configurations to search for optimal sets of control parameters. In this context, the design space included random selections of loading configurations, i.e. sets of loudspeakers driven by the same signal, as well as control sensors. An example of the predicted sound fields in a cylindrical grid of sensors around the specimen obtained from the simulation of the MIMO control test is shown in Figure 6. The outcome of this pre-test analysis was compared to the experimental results obtained using the physical DFAN setup. The synthesis of optimal test references based on the simulation predictions and the selection of optimal test parameters was investigated.

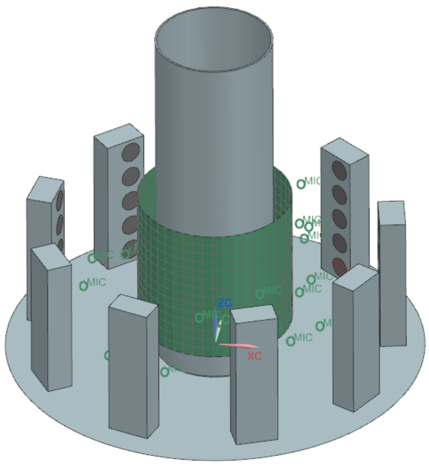

Figure 5. Digital Twin of the DFAN test.

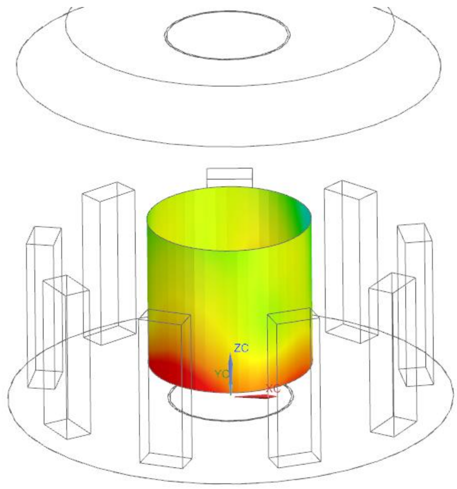

Figure 6. Predicted acoustic fields in a closed-loop control test simulation at 315 Hz.

5. CONCLUSIONS

This paper presents an innovative framework to reproduce the acoustic environments of the space launch in a laboratory. It is based on a combination of acoustic simulations of the sound pressures at the lift-off phase of the space launch with a Direct Field Acoustic Noise testing (DFAN) methodology to reproduce in the laboratory the non-diffuse acoustic fields at the surroundings of the fairing. A Digital Twin model of the test platform was also generated to optimize the layout of this non-standard acoustic test. The preliminary results show that the processing of the acoustic targets as well as the drive routing must be carefully studied to be able to reproduce accurately the operational acoustic fields.

6. ACKNOWLEDGMENTS

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