MULTI-STAGE SUBORBITAL LAUNCHER MODAL AND DYNAMIC TEST PROGRAM

Mihai MIHAILA-ANDRES*, Flore LICA*, Paul-Virgil ROSU**
* Institute for Theoretical & Experimental Analysis of Aeronautical Structures,
**Military Technical Academy, Bucharest, Romania
DOI: 10.19062/1842-9238.2015.13.3.18

Abstract: *The launch phase of a suborbital rocket is always associated with severe structural stresses and they need to be cautiously accounted for during the design level. The structural testing and the numerical analysis of six degrees of freedom and variable mass multi-stage suborbital launcher at launch are reported here. The paper describes the results of free-free modal analysis followed by static and dynamic finite element model analyses of a three-stage rocket prototype subject to launch stresses. The numerical natural frequencies are compared with an experimental modal analysis conducted with the Impact Hammer Modal Testing method. The dynamic results obtained with a finite element model are also compared with dynamic tests in order to validate the numerical model. These results are part of the ROSA-STAR national project "Technologies for Testing and Validation of the Structure, and Modified Hybrid Rocket Motor for Suborbital Launcher- STRAC".*
Keywords: *suborbital launcher; modal analysis, dynamic test*

1. INTRODUCTION

The assemblies of a suborbital launcher are subject to various loads and environmental factors during space missions and they need to be carefully taken into account during the design and test phases to avoid mission failure or degradation of its subsystems.

Among all possible cases of mission failures, the structural vibration of the structure is a very important condition to be included since it may cause the overstress and/or the fatigue of materials. Mechanical vibrations are often most predominant during the launch and ascent phases of flight but, depending upon the structural configuration and mission details, they may also become critical during space flight and/or atmospheric reentry. Depending on the monitoring points and the structural and aerodynamic configuration of the launcher, the relative magnitude of the vibrations during space flight phases will vary considerably: locations near the rocket engine will undergo high vibrations during the launch phase and low vibrations during other phases while locations near the payload of a launcher will undergo high vibrations during transonic/supersonic periods of flight and low vibrations in all other phases [3,5].

Apart from the classic static and thermal requirements, the development programs of any launcher should therefore integrate these considerations by means of design and test requirements.

With all these requirements in mind, the purpose of this work is to present the vibration and dynamic tests performed on a three-stage suborbital launcher within the ROSA-STAR national project "Technologies for Testing and Validation of the Structure, and Modified Hybrid Rocket Motor for Suborbital Launcher-STRAC" [1,2].

In the light of the European Future Launchers Preparatory Programme, the project proposed a guided Suborbital Launcher (SLT) with a hybrid propulsion system used to launch small payloads (5-10kg) at heights of 100-150km. The prototype has three stages made of steel (Table 1): the first stage with a length of 1.145mm and a diameter of 0.120m is equipped with a hybrid rocket engine; the second stage with a length of 1.319m and a diameter of 0.120m is also equipped with a hybrid rocket engine; the third stage with a length of 1.890m (with a payload of 0.720m) and variable diameter (0120m-0.66m) has a solid propellant engine.

Table 1. Material Characteristics

Young's Modulus	Poisson's Ratio	Bulk Modulus	Shear Modulus	Tensile Yield Strength	Tensile Ultimate Strength
[Pa]		[Pa]	[Pa]	[Pa]	[Pa]
2.1e11	0.3	1.66e11	7.69e10	2.5e8	4.6e8

2. STRUCTURAL TESTS SETUP

The tests of the full-scale SLT structure had as the primary objective the acquisition of experimental data to validate the analytical models, which would then be used to simulate numerically the structural loads during the launch phase. An additional objective of the structural tests was to verify the finite element model and the accuracy of nonlinear capabilities implemented in the ANSYS structural analysis software.

In the framework of the project, two tests were performed: a modal test whereby the characteristic frequencies, modal masses and mode shapes of the SLT are determined and a dynamic test to determine the liftoff release loads caused by the rocket engine thrust during take-off phase. Extensive effort was dedicated in the design of both tests to closely approximate the boundary conditions and the launch loading conditions of the SLT.

For the experimental modal analysis, elastic straps were used to suspend the rocket (Figure 1). This type of support is designed to ensure that the rigid body's mode frequencies are isolated from the fundamental frequency of the structure by at least one order of magnitude.

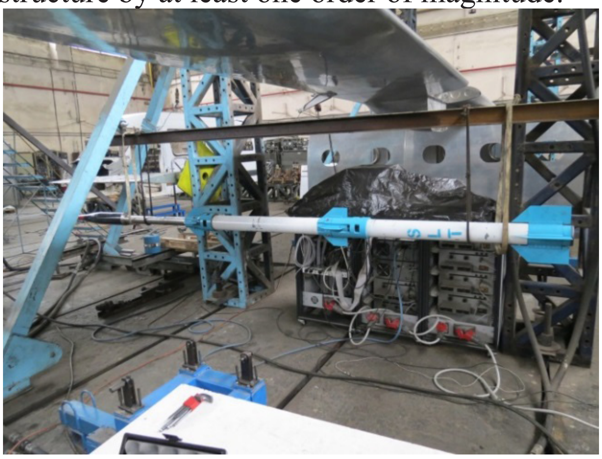

Fig. 1 Modal test support system

Mode testing has taken advantage considerably from the many advances in digital acquisition and processing systems, transducers, testing accuracy, and mode extraction algorithms but shaker (vibration tester) testing and impact hammer testing are still commonplace today. For the impact hammer test used in the project, the instrumentation of the structure consisted in a load cell attached to the end of the hammer to record the force and an accelerometer moved in different positions on the structure during multiple tests.

A single accelerometer was fixed in several positions and the structure was excited with different hammer tips in different positions. This is a combination of "roving hammer" test and "roving accelerometer" test allowing to use the least resources at the expense of time needed to take several measurements and to move the accelerometer.

Fig. 2 Dynamic test bench

For the dynamic test the structure was mounted on a custom made test bench. The set-up was arranged to test the SLT under a variable load applied directly through an Electro-Servo-Hydraulic Schenk Hydropulse System (Figure 2). The hybrid rocket engine thrust diagram presented in Figure 3 shows a maximum thrust of 300daN at 0.1 seconds from ignition followed by a constant thrust of 205-215daN between 0.6 and 1.9 seconds from ignition. On the last interval, between 1.8 and 2 seconds, the thrust decays abruptly to 0.

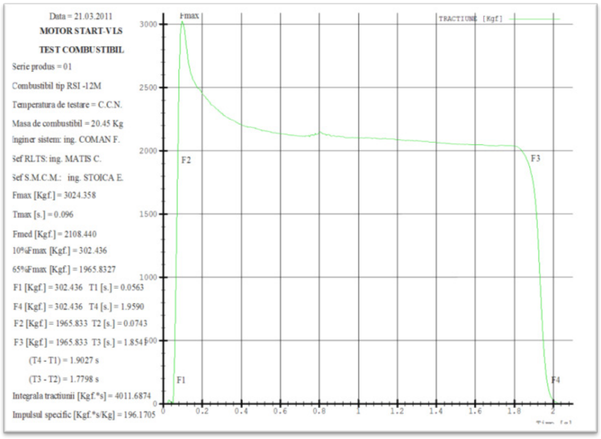

Fig. 3 Hybrid rocket engine thrust diagram

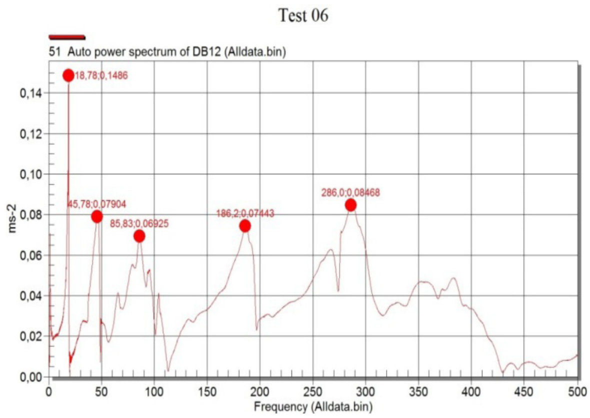

Fig. 4 Impact hammer test no.6

Due to the particular shape of the exhaust system, the axial force of the hydraulic cylinder was applied on the back of the first stage through a cylindrical interface device which ensured perfect contact between them. Strain gages were used to measure the local strain of the structure and compensation gages were used to reduce the thermal sensitivity.

The data acquisition and post-processing system included the HBM MGCPlus Measuring Amplifier System Multi − channel I/O module, the Spider 8 Measuring System and the Catman Professional 5.0 Data Acquisition Software.

3. TEST RESULTS

With the structure suspended on the elastic straps and instrumented as described before, 19 modal tests were prepared for different structural configurations during flight (all three stages - the launch configuration; two stages - after the jettison of first stage; stage three with payload – the end of ascent phase), different hammer tip types (rubber, plastic, metal) for a wide range of impact times, different directions of excitation (horizontal, vertical, torsion) and different positions of the accelerometer (Figure 4).

The modal test configurations are presented in Table 2 and the natural frequencies extracted are presented Table 3.

Table 2. Modal test configurations

Test	Hammer Tip	Direction	Excitation	Accelerometer position
3 stages				
01	Rubber	Horizontal	Stage 1	Payload tip
02	Plastic	Horizontal	Stage 1	Payload tip
03	Metal	Horizontal	Stage 1	Payload tip
04+05	Plastic	Horizontal	Stage 1	Payload tip
06+07	Plastic	Vertical	Stage 1	Payload tip
08	Plastic	Torsion	Stage 1 wing	Payload side
09	Plastic	Torsion	Stage 2 wing	Payload side
10	Rubber	Torsion	Stage 1 wing	Stage 1 side
11	Rubber	Torsion	Stage 1 wing	Stage 2 side
12	Plastic	Vertical	Stage 1	Stage 2 tip
13	Plastic	Vertical	Payload tip	Stage 2 tip
14	Plastic	Vertical	Payload tip	Stage 2 side
2 stages				
15	Plastic	Horizontal	Stage 2	Payload tip
16	Plastic	Vertical	Stage 2	Payload tip
17	Plastic	Torsion	Stage 2 wing	Payload side
18	Plastic	Torsion	Stage 2 wing	Payload side
1 stage				
19	Plastic	Horizontal	Stage 3	Payload tip

Table 3. Modal test results

Natural Frequency [Hz]	Three stages	Two stages	One stage
Frequency 1	18.27-18.93	26.70-28.90	267.50
Frequency 2	43.72-44.02	74.97	-
Frequency 3	83.19-85.83	87.88	-
Frequency 4	185.20-187.80	224.00	-
Frequency 2	200.90	233.60-235.30	-

For the dynamic test the structure was mounted on the custom made test bench and two strain gages were mounted (Figure 5).

Based on the thrust diagram of the hybrid rocket engine, the RIGOL DG1022 Arbitrary Waveform Generator was used to simulate the thrust force during the launch phase. The generated force was axially applied with the Electro-Servo-Hydraulic Schenk Hydropulse System to the rear of the launcher (Figure 6).

Fig. 5 Strain gages position

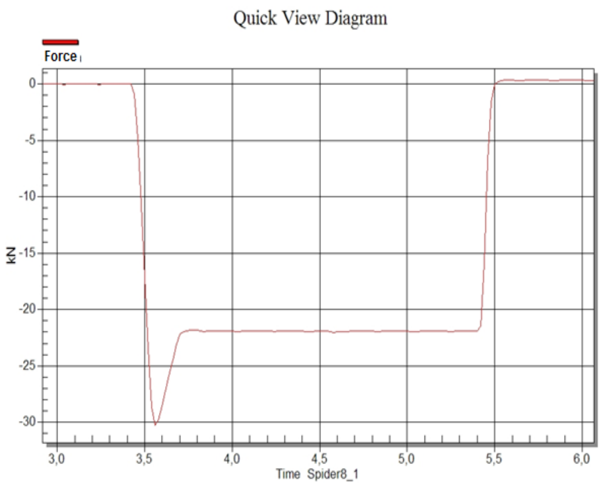

Fig. 6 Generated thrust diagram

The signal from the strain gages is presented in Figure 7.

The interpretation of all test results should be made in compliance with existent standards [4,6,7,8,9,10].

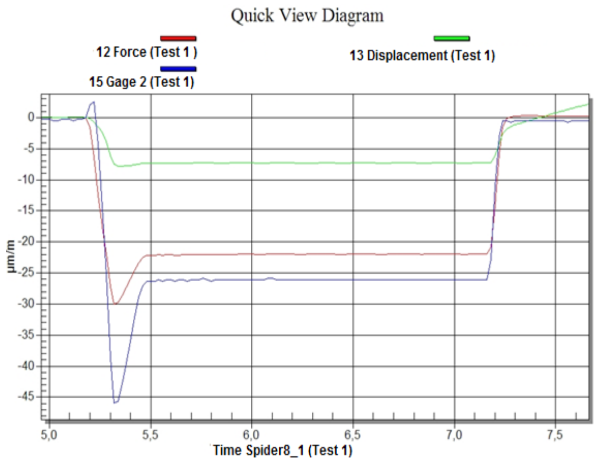

Fig. 7 Quick-view diagram of strain gage reading

According to NASA-STD-5001B and ECSS-E-ST-32-10C standards, depending on the type of test (qualification tests, acceptance tests, protoflight tests) different structural factors of safety should be applied. Since the structure of the launcher is a complex one, with junctions between stages, one should use a yield design factor of safety (FOSY) of 1.1 and an ultimate design factor of safety (FOSU) of 1.25. With these factors, based on the strain gage readings (Figure 7) the axial compression on the structure at launch is 10MPa which gives a yield safety factor of 25 at the gage position compared to minimum accepted 1.1 for FOSY.

4. NUMERICAL ANALYSIS/TESTS CORRELATION

A detailed finite element model was developed using ANSYS 14.0 structural software to simulate the loading of test configurations. All components of the launcher were modeled, including the junctions to properly distribute loads between the stages (Figure 8). The stages were modeled as thin walls cylinders and they were meshed with SHELL181 elements and the propellant and the payload were modeled as concentrated masses and represented as MASS21 elements. The contact between stages and junctions and between stages and stabilizing wings was represented by contact elements CONTA174 and TARGE170.

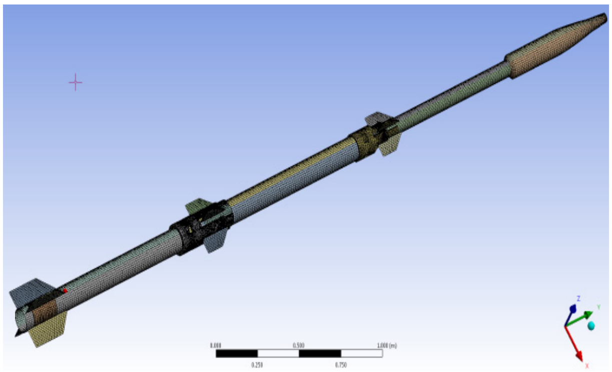

Fig. 8 Launcher's finite element model

The finite element model has been verified and calibrated through extensive simulations of the structural response to unit accelerations and through mesh density convergence analysis.

For the free-free modal analysis the contacts were declared BONDED because only linear elements are allowed. The solution confirmed the expected rigid modes (the first six natural frequencies are zero or at least one order of magnitude smaller than the first characteristic frequency). The value of the first natural frequency obtained has an 8% error compared to the modal test results (Table 4).

Table 4. FEM modal results

Natural Frequency [Hz]	Three stages	Error
Frequency 1	20.56	8%
Frequency 2	51.23	14%
Frequency 3	113.07	33%

A nonlinear static analysis of the launch phase was computed on the same free-free configuration (no constraints).

Using inertia forces calculated in a static linear analysis where the maximum thrust force of 300daN was applied with a multiplication factor of 2 to account for the dynamic nature of the thrust force. Reading the equivalent (Von-Misses) stress presented in Figure 9, the minimum yield factor of safety is 10.8 and is located on the junction between stages 2 and 3.

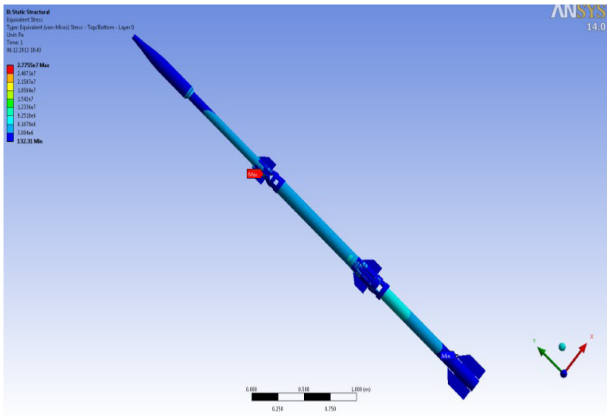

Fig. 9 Von-misses stress in nonlinear static analysis

CONCLUSIONS

The development of the proposed suborbital launcher cannot be completed without a thorough analysis of structural vibrations under various loads and environmental factors. This analysis should be performed as early as in the design phase of the project through experimental tests and numerical simulations.

The structural testing and the finite element model analysis of a multi-stage suborbital launcher were reported here. The paper described the results of free-free modal tests and dynamic tests followed by modal and dynamic FEM analyses of a three-stage rocket prototype subject to launch stresses. The numerical natural frequencies of vibration were compared with the experimental modal analysis conducted with the Impact Hammer Modal Testing method. The dynamic results obtained with FEM were also compared with dynamic tests in order to validate the numerical model.

Several considerations can be emphasized as a result of the experimental tests and the numerical analysis. It is critical to adequately represent the boundary conditions and to properly load the model in both tests and simulations. The mesh resolution can limit the accuracy of numerical simulations and poor representation of structure's interfaces can negatively influence the numerical results. Residuals convergence and solution controls must be tuned and verified by experimental data and care must be taken to monitor and evaluate the tests or the simulations as they are running to confirm proper model behavior.

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