A computational methodology for a micro launcher engine test bench using a combined linear static and dynamic in frequency response analysis

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Abstract: This article aims to provide a quick methodology to determine the critical values of the forces, displacements and stress function of frequency, under a combined linear static (101 Solution - Linear Static) and dynamic load in frequency response (108 Solution - Frequency Response, Direct Method), applied to a micro launcher engine test bench, using NASTRAN 400 Solution - Implicit Nonlinear. NASTRAN/PATRAN software is used. Practically in PATRAN the preprocessor has to define a linear or nonlinear static load at step 1 and a dynamic in frequency response load (time dependent) at step 2. In Analyze the following options are chosen: for Solution Type Implicit Nonlinear Solution (SOL 400) is selected, for Subcases Static Load and Transient Dynamic is chosen and for Subcase Select the two cases static and dynamic will be selected. NASTRAN solver will overlap results from static analysis with the dynamic analysis. The running time will be reduced three times if using Krylov solver. NASTRAN SYSTEM (387) = -1 instruction is used in order to activate Krylov option. Also, in Analysis the OP2 Output Format shall be selected, meaning that in bdf NASTRAN input file the PARAM POST 1 instruction shall be written. The structural damping can be defined in two different ways: either at the material card or using the PARAM, G, 0.05 instruction (in this example a damping coefficient by 5% was used). The SDAMPING instruction in pair with TABDMP1 work only for dynamic in frequency response, modal method, or in direct method with viscoelastic material, not for dynamic in frequency response, direct method (DFREQ), with linear elastic material. The Direct method – DFREQ used in this example is more accurate. A set in translation of boundary conditions was used and defined at the base of the test bench.

Key Works: Implicit Nonlinear, Frequency Response, Linear Static, NASTRAN, Krylov, PATRAN, PARAM, DFREQ, von Mises Stress, bdf file, OP2 file, combined static and dynamic analysis

1. INTRODUCTION

Over the past two decades, the space community focused its research efforts towards the reusable launch technologies, aiming to design an orbital launch system which can be reused more than 70% by relying on the vertical landing. In the framework of the National Nucleus Programme – AEROEXPERT 2016-2017, INCAS Research, Development and Innovation

Department is involved in the design and development of a test bench flying platform, as first step to a reusable launch system. The demonstrator platform consists in a Vertical Takeoff Vertical Landing (VTVL) vehicle based on turbojet engines, capable to perform an autonomous low speed, low altitude flight, but with similar main subsystems (avionics, telemetry, GNC, on-board computers) as the reusable orbital launcher. The ultimate goal is to have a demonstrator to experimentally qualify the GNC (Ground Navigation and Control) algorithms. In the qualification process, testing of the components at the subsystem level will be of primary importance. The National Nucleus Programme is dedicated to the design and manufacture of the test stands needed to perform the qualification procedures of the subsystems which are critical for the flight safety of the VTVL vehicle.

One of such test stands is designed for the engine testing as well as for the testing of the vehicle itself, in a tethered flight before the full autonomous flight – see Figure 1. The test stand is fixed on a concrete support (1) - see Figure 2 - and consists in two vertical beams (2) on which the horizontal beam (3) and the device under test (the VTVL vehicle) are fixed. Between the horizontal beam and the device to be tested, there is a force and moment transducer – see Figure 3. The vertical beam (4) will support the sensors for measurements of temperature and the speed for the intake air and for the exhaust gas, respectively.

Details on the mounting devices are shown in Figure 3: (1) is the mounting flange – attaching the vehicle on the stand, and (2) is the force transducer.
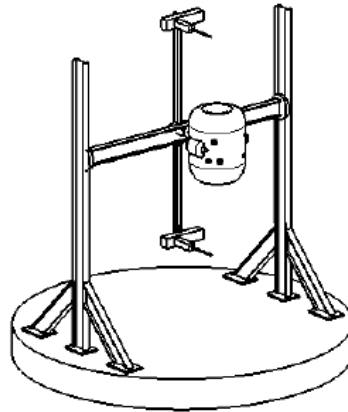

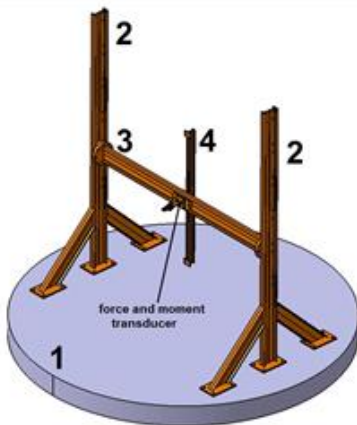
Figure 1. A micro launcher engine test bench
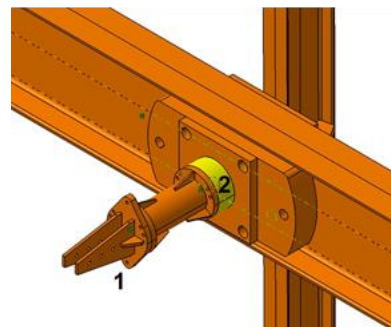

Figure 2. Test bench

Figure 3. Mounting devices of engine

The stand configuration from Figure 1 it is for the case when tests are performed to quantify the vane and engine dynamics, in other words, when the transfer functions of the turbojet engine and vane are experimentally identified.

The structure of the VTVL vehicle is mounted on the stand by means of a transducer which measures the force and moments variations as a result of the vane deflection and fuel flow command. From the recorded data, applying a system of identification algorithms, the transfer functions are available for the GNC engineers.

Also, the same stand was designed to be used in preliminary flight tests by minimal modifications. At first glance, designing of the test stand might look as an easy task for a mechanical engineer. However, the practice shows that a special care must be given to the structural rigidity of the entire assembly, which has to stand static and dynamical loads. For an accurate measurement of the vehicle characteristics, designing a test stand can be a very challenging work. The aim of the paper is to present the framework for the structural analysis of the test stand. In chapter 2 the load case and the boundary condition are presented, chapter 3 presents the calculation procedure, chapter 4 shows the simulation results and chapter 5 summarizes the main conclusions of paper.

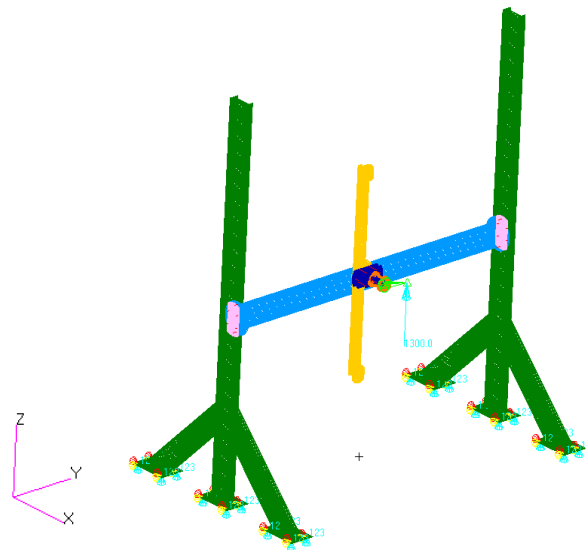## 2. THE LOAD CASE AND THE BOUNDARY CONDITION DEFINITION

Figure 4. Finite Element Model (FEM) of test bench

Two load cases were used:
1. Static load, defined by the gravitational acceleration in the z direction, -9.81 m/s², like an inertial load;
2. Dynamic in frequency response load, time dependent. For this load case a non-spatial tabular input field was created, with active independent variables – frequency [Hz] and the value of force equal to one. This field was associated with the dynamic in frequency response load, which has the force amplitude equal to maximum engine thrust. The frequency range of interest is defined in 0 up to 10 Hz and it was established using the modal analysis, 103 NASTRAN solution – Normal Modes, where the first four natural frequencies have the following values: 4.5, 5.8, 7.5 and 10.4 Hz.

The engine was modelled with CONM2 element, concentrated mass, where the mass in [kg], the mass moments of inertia [Kg*m^2] and the geometrical dimensions in [m] were defined. The dynamic load was applied in the node of the concentrated mass. A set in translation of boundary conditions was used and defined at the base of the test bench - see Figure 4.

3. DESCRIPTION OF THE CALCULATION PROCEDURE

NASTARN and PATRAN software were used [1], [2] and [4]. To prepare the NASTRAN bdf input file, the following steps should be performed:

- Geometry of the model is imported from CATIA in [m];
- The solid or shell elements can be used in the modelling;
- A linear or nonlinear static load is created;
- A dynamic in frequency response load - time dependent is created**;**
- The frequency range of interest is defined- [Hz], established using the modal analysis, 103 NASTRAN solution – Normal Modes;
- For the dynamic load case, a non-spatial tabular input field is created, with active independent variables – frequency [Hz] and the value of force equal to one. This field has to be associated with the dynamic load in frequency response, which has the force amplitude equal to the maximum engine thrust;
- The structural damping can be defined in two different ways: either at the material card or using the PARAM, G, 0.05 instruction. For this application a damping coefficient by 5% was used [9];
- In Analyze at Solution Type the Implicit Nonlinear Solution (SOL 400) is selected and at Results Output Format the OP2 format is checked;
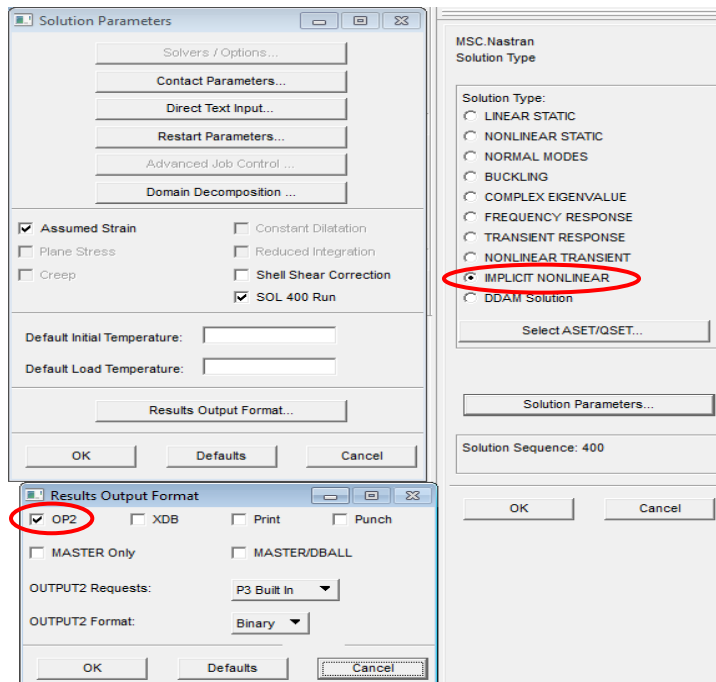
- In Analyze at Subcases Static for static load at Analysis Type and Transient Dynamic for dynamic load in frequency response are the chosen options;
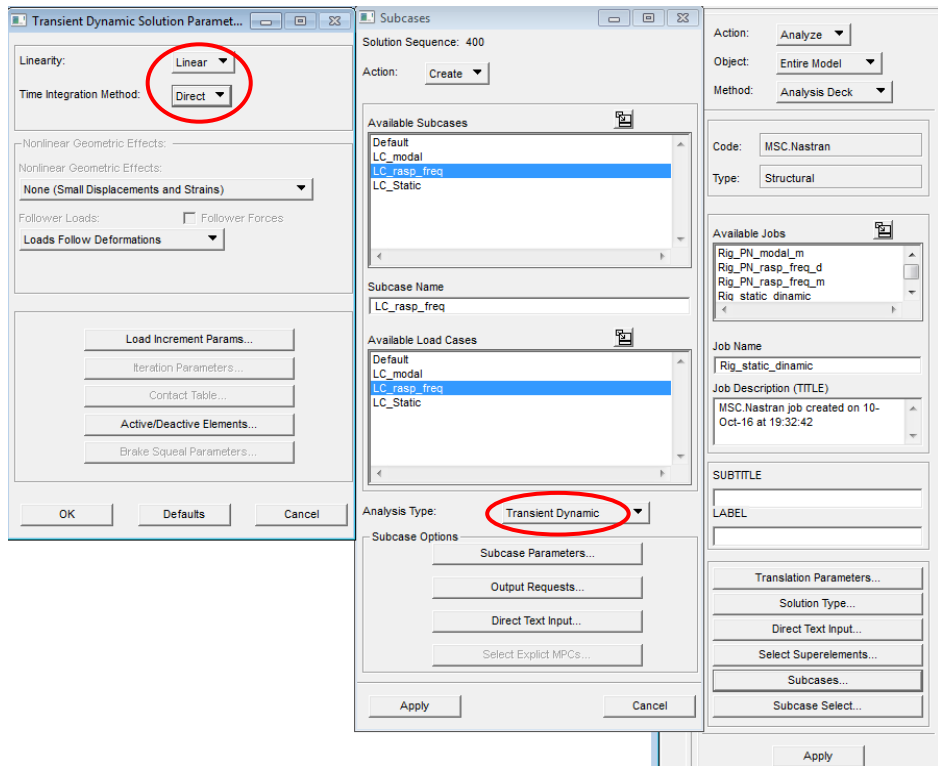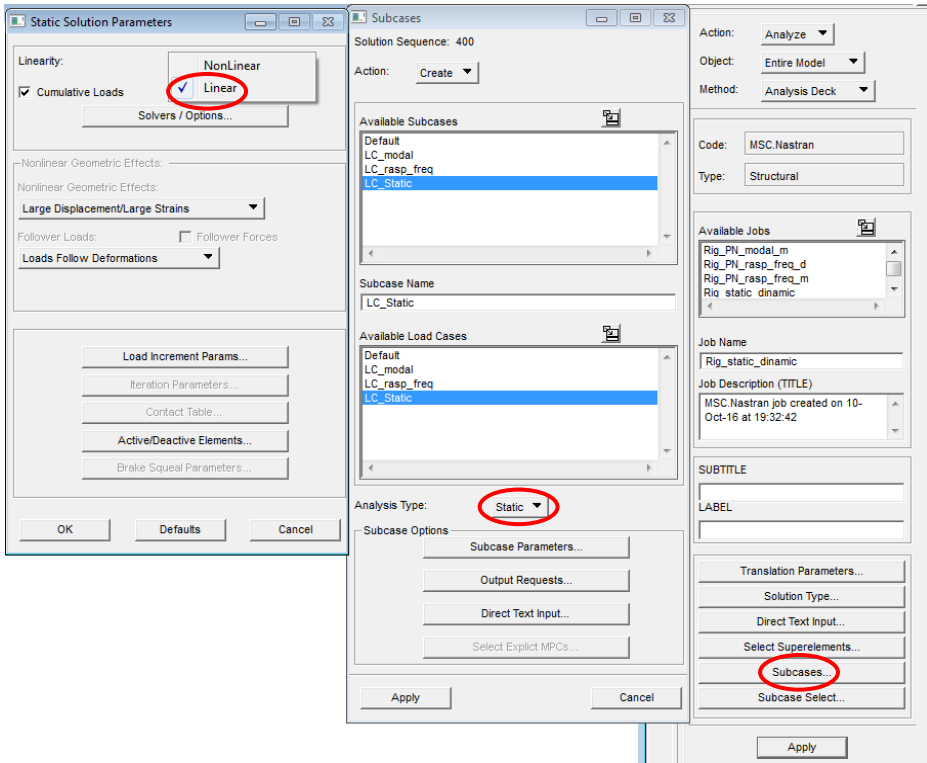
- In Analyze at Subcase Select the two cases, static and dynamic shall be selected
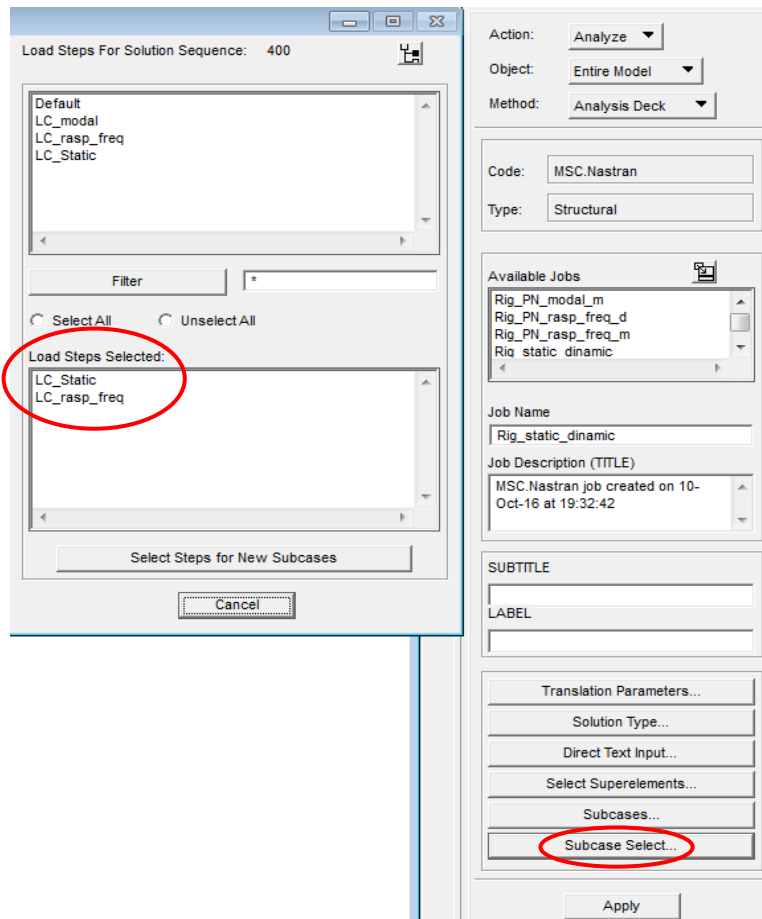
- In NASTRAN bdf input file some changes must be made:
  - o LOADSET = 1 is moved from the initial position (written above SUBCASE 1) inside of STEP 2. Label 1 of LOADSET command is set for identification number of at least one LSEQ Bulk Data entry;
  - o At STEP 1 ANALYSIS = NLTRAN command is replaced by ANALYSIS = DFREQ (that means a direct frequency response solution) and TSTEPNL = 2, which is correlated to TSTEPNL 2 from BEGIN BULK is replaced by NLSTEP = 2, which is correlated to NLSTEP 2 from BEGIN BULK;
  - o At STEP 2 is written FREQUENCY = 1 and at BEGIN BULK is written FREQ1- linear and FREQ - discrete. There are two ways of writing for FREQ1 and FREQ card either is written directly in NASTRAN bdf input file or with PATRAN by creating a new bdf file. From Analyze at Solution Type FREQUENCY RESPONSE, Direct Formulation (108 Solution) are selected. Then at Analyze from Subcases at Subcase Parameters in DEFINE FREQUENCY the FREQ1 and FREQ are defined. It must be considered that the values of discrete frequencies – FREQ are the values of natural frequencies obtained from the modal analysis (103 NASTRAN solution – Normal Modes);
  - o At the end of the bdf file TLOAD1 command is replaced by RLOAD1. Then there are three commands which work together RLOAD1, LSEQ and DLOAD.

```
$ NASTRAN input file created by the Patran 2012 64-Bit input file
$ Direct Text Input for Executive Control
$ Complex Eigenvalue Analysis, Direct Formulation, Database
NASTRAN SYSTEM(316)=19
SOL 400
CEND
$ Direct Text Input for Global Case Control Data
TITLE = MSC.Nastran job created on 10-Oct-16 at 19:32:42
ECHO = NONE
$SDAMPING = 1
SUBCASE 1
 STEP 1
    SUBTITLE=LC_Static
    ANALYSIS = LNSTATICS
$   NLPARM = 1
    SPC = 2
    LOAD = 3
    DISPLACEMENT(PLOT,SORT1,REAL)=ALL
    SPCFORCES(PLOT,SORT1,REAL)=ALL
    STRESS(PLOT,SORT1,REAL,VONMISES,BILIN)=ALL
$ Direct Text Input for this Subcase
 STEP 2
    LOADSET = 1
    SUBTITLE=LC_rasp_freq
$    ANALYSIS = NLTRAN
    ANALYSIS = DFREQ
$   TSTEPNL = 2
    NLSTEP = 2
    FREQUENCY = 1
    SPC = 2
    DLOAD = 4
    DISPLACEMENT(PLOT,SORT1,REAL)=ALL
    SPCFORCES(PLOT,SORT1,REAL)=ALL
    STRESS(PLOT,SORT1,REAL,VONMISES,BILIN)=ALL
$ Direct Text Input for this Subcase
BEGIN BULK
$ Direct Text Input for Bulk Data
PARAM    POST     1
PARAM    G        .05
PARAM    PRIMAXIM YES
$PARAM    MRNOECHO 123
PARAM    LGDISP   1
$TSTEPNL  2        100      .01               AUTO              UPW
NLSTEP   2
FREQ1    1        1.       .09      100
FREQ     1        1.       4.17     5.82     7.56     10.
$TABDMP1  1        G
$        0.       .05      10.      .05      ENDT
$ Elements and Element Properties for region : masa_concent
CONM2    90892    94105    1        70.834
         4.165    -.298    4.206    -.034    .018     2.85
$ Elements and Element Properties for region : t_20
PSHELL   1        1        .02      1                 1
$ Pset: "t 20" will be imported as: "pshell.1"


GRID     94105             .52342   0.       1.8481
$ Loads for Load Case : LC_Static
SPCADD   2        3
LOAD     3        1.       1.       2
$ Displacement Constraints of Load Set : fixare
SPC1     3        123      127      257      667      797      18363    18416
         18487    18528    18678    18968    19015    19108    31366    31496
         31906    32036    49602    49655    49726    49767    49917    50207
         50254    50347
$ Loads for Load Case : LC_rasp_freq
$TLOAD1   6        7                          1
RLOAD1   6        7                          1
LSEQ     1        7        5
DLOAD    4        1.       1.       6
$ Nodal Forces of Load Set : dyna_force
FORCE    5        94105    0        650.     0.       0.       1.
$ Gravity Loading of Load Set : acc_g
GRAV     2        0        9.81     0.       0.       -1.
$ Referenced Dynamic Load Tables
$ Dynamic Load Table : freq_depend_loads
TABLED1  1
         0.       1.       10.      1.       ENDT
$ Referenced Coordinate Frames
CORD2R   1                 .523419  0.       1.8481   .523419  0.       3.76889
         2.44421  0.       1.8481
ENDDATA bda36597
```
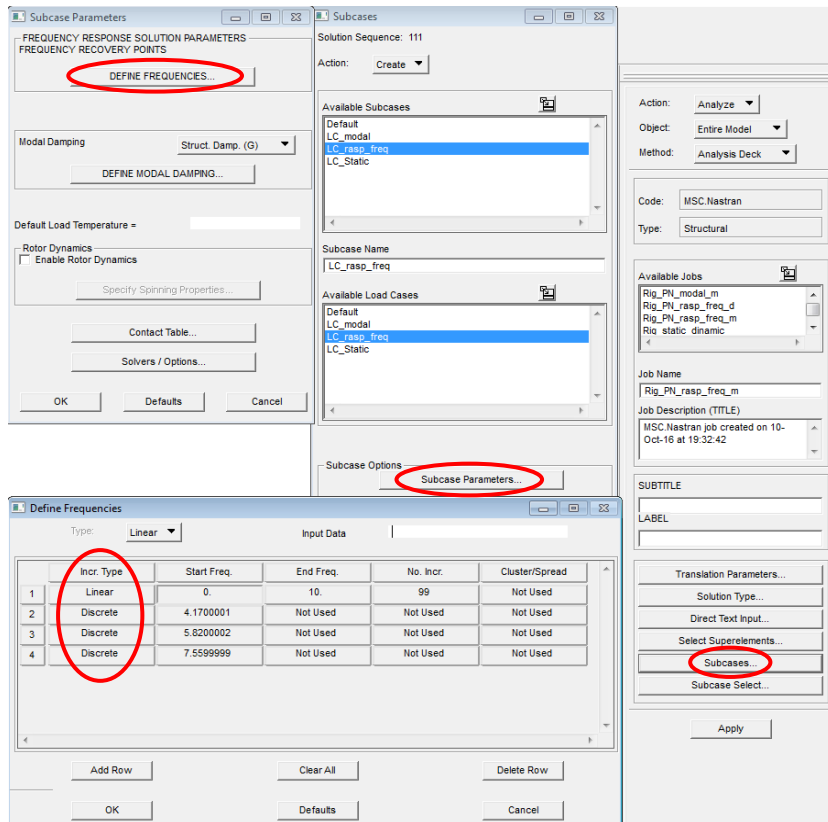
4. ANALYSIS OF TEST BENCH RESULTS

From the analysis of the results, we find that the critical area is between the engine mounting device and the horizontal beam. The structural analysis was made both with and without structural damping. Without structural damping the values of stress are eleven times greater than the stress values with structural damping, as it can be seen in the diagrams below. The stress values is given in [Pa] and the frequency in [Hz]. For the sizing of the test bench von Mises criteria were used [3], [6], [7] and [5].
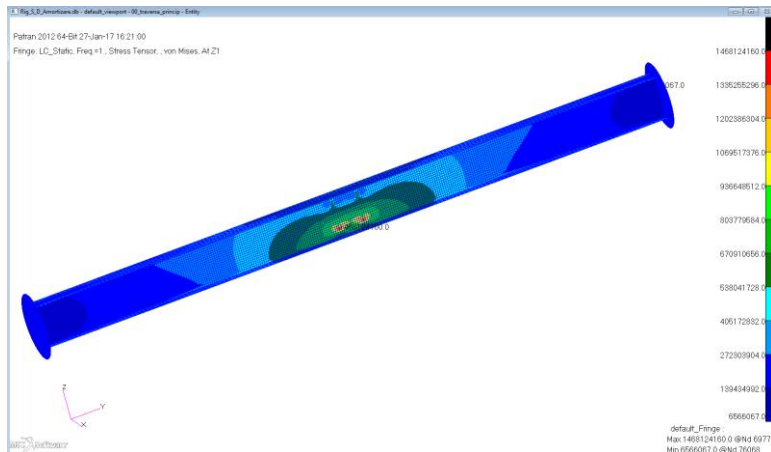

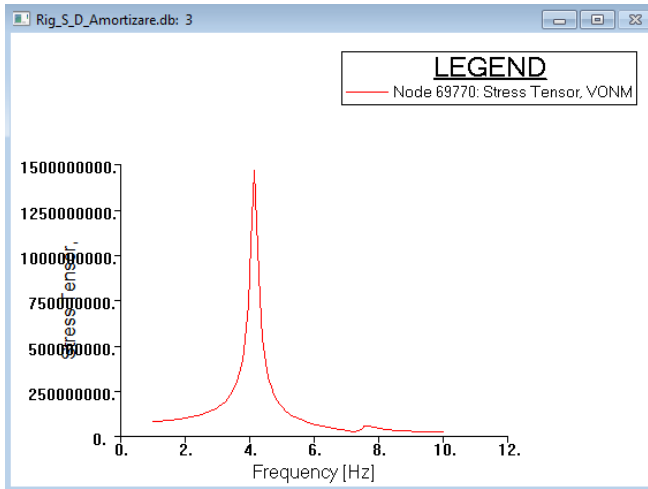Figure 5. Von Mises stress plots of horizontal beam, with structural damping

Figure 6. Critical Von Mises stress of horizontal beam, with structural damping
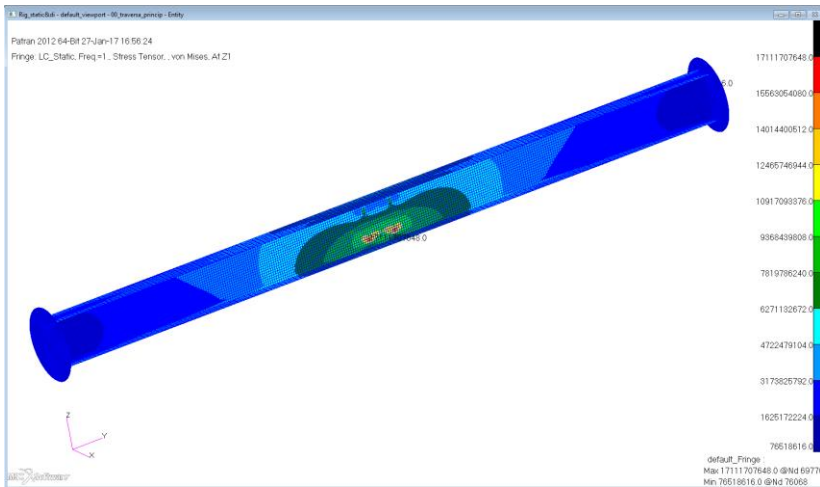

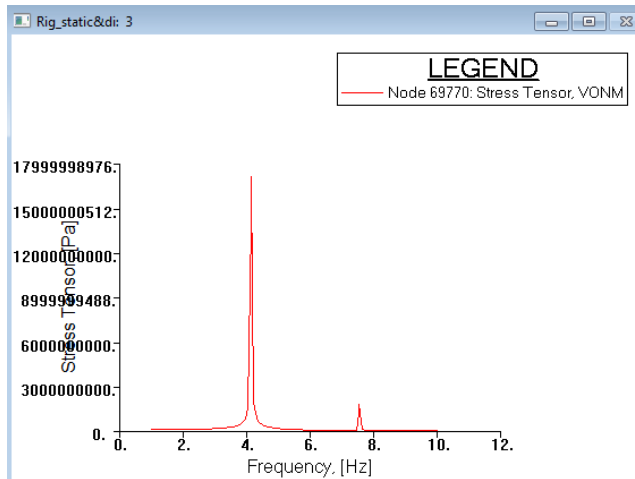Figure 7. Von Mises stress plots of horizontal beam, without structural damping

Figure 8. Critical Von Mises stress of horizontal beam, without structural damping

5. CONCLUSIONS

This article establishes a quick methodology to determine the critical values of the forces, displacements and stress function of frequency, under a combined linear static - 101 Solution, Linear Static and dynamic load in frequency response - 108 Solution, Frequency Response, Direct Method, applied to a micro launcher engine test bench, using NASTRAN 400 Solution - Implicit Nonlinear. NASTRAN/PATRAN software is used [1], [2] and [4].

Chapter 1 describes the VTVL engine test bench, which was developed in the framework of the National Nucleus Programme – AEROEXPERT 2016-2017.

In chapter 2 the load case and the boundary conditions definition are presented.

Chapter 3 develops the computational methodology using a combined linear static – 101 Linear Static Solution and dynamic load in frequency response – 108 Frequency Response, Direct Method analysis.

In chapter 4 this calculation procedure is applied on a test bench, where a comparison between Von Mises stress in the critical area with and without structural damping [3], [5] [6] is made.

The values of the structural damping generally ranges between $(2 \div 5)\%$. In this application the value of 5% was adopted [9].

In the table below the results of the calculation for Von Mises stress in the critical area of the test bench with and without structural damping are shown comparatively.

Table 1 – Critical Von Mises stress

Method of calculation	Von Mises effective stress [N/mm²]	Natural frequency [Hz]	Remarks
This methodology	1468	4.5 1st frequency	With structural damping
	17112	4.5 1st frequency	Without structural damping

Remarks:
- the Von Mises effective stress without structural damping is around 11 times greater than the Von Mises effective stress with structural damping;
- the peak of the Von Mises effective stress appears on the first resonance frequency [8];
- the Krylov solver can be used to shorten the running time. In this example, the running time is reduced by three times, for around 91.000 total elements, used in modelling.

The original contributions of the author are:
- a) Establishment of a calculation procedure for a combined static and dynamic application;
- b) Establishment of a NASTRAN bdf input file for NASTRAN solver.

This article also is intended to be a calculus guide for students and design and stress engineers, adapted to INCAS needs and enabling a correct understanding of the combined static and dynamic calculation.

The dynamic loads act and run on the pre-tensioned and pre-deformed structure from the linear static loads.

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