LATVIAN JOURNAL OF PHYSICS
AND TECHNICAL SCIENCES
2024, N 5

DOI: 10.2478/lpts-2024-0036

MAIN STAGES AND RESULTS OF THE DEVELOPMENT OF MOBILE SPACE ENVIRONMENT SIMULATION FACILITY "METAMORPHOSIS"

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This article presents the main stages and results of the project "Mobile Space Environment Testing Equipment Development of "Metamorphosis" Prototype for Transportation Intermodal Traffic". For successful implementation of the project, the project has been divided into four stages: 1) Design calculations and design documentation for the design elements of the prototype; 2) Prototype software development; 3) Manufacturing of construction details and prototype assembly; 4) Industrial research and prototype testing. The goal of the project is, based on industrial research, to develop a prototype of the Mobile Space Environment Test Facility (MSTF) "Metamorphosis" transported in an intermodal environment, and to achieve the level of scientific and technical readiness of MSTF from TRL2 to TRL4 (by the scale of the European Space Agency (ESA)) for further development of the project. This project is unique and has no comparable analogues, as all existing test facilities are stationary. The project is implemented by Riga Technical University in cooperation with Cryogenic and Vacuum Systems Ltd.

Keywords: *Calculation, CubeSats, satellite technology, test requirements, test systems, vacuum pumping system, vacuum system.*

1. INTRODUCTION

A while ago, outer space was an exceptional territory where only governments of major powers and large corporations could implement their projects. The situation has changed radically over the past 20 years. New companies – start-ups – have begun to offer inexpensive access to space and, as a result, space has become more cost-effective. Technological trends, such as

- reducing the size of microprocessors,
- reducing launch costs,
- shorter development cycles,
- rapid technological improvement,
- new operational models,

are associated with miniaturisation of satellite technologies and have led to an exponential increase in the use of small satellites, creating new advantages for space projects.

All of these benefits will continue to drive the adoption of small satellites over the next decade and create new opportunities in education, commerce, government and science. The Union of Concerned Scientists estimated that there were 4,550 active satellites on the Earth's orbit in early 2023 [1]. The most common of these satellites were CubeSats, which made up to 70 % of all active satellites and were not state meteorological satellites or large communications satellites.

An increase in the number of small satellites can be explained not only by many unique advantages that they offer to science, business and society, but also by an increase in their lifespan, which is a huge benefit for the customer. The development of design technologies and the improvement of testing systems contribute to this benefit. While satellite is in operation, it is impossible to timely repair any of its elements; therefore, the testers are required to foresee all possible variants of the situations in which the spacecraft will be involved. That is why sets of tests are carried out and during these tests different extreme conditions, thermal behaviour of the satellite and its functionality are studied and analysed. As a result of the tests, the system's stability is evaluated. Thermal vacuum chambers are used to simulate space environment conditions as accurately as possible.

Such testing is carried out by special testing centres, which are stationary. The services of these centres are expensive and not always available to small companies, societies, educational institutions, etc. This problem can be solved by creating a mobile ground simulator of space conditions, with the help of which it would be possible to provide testing services at the request of the customers in a place and time acceptable to them [2]. Such type of project called Metamorphosis was developed at the Institute of Aeronautics of Riga Technical University ["Prototype Development of Transportable in Intermodal Traffic Mobile Space Testing Facility (MSTF) "Metamorphosis"" (Metamorphosis, project No. 1.1.1.1/18/A/133)] [3] in cooperation with Cryogenic and Vacuum Systems Ltd. This company specialises in the development and production of vacuum and cryogenic equipment. It has extensive experience in creating technologies used in space research and the development and operation of space environment simulators [4]. This cooperation project is unique and does not have any comparable analogues – all existing testing facilities are stationary. The main difference of the Prototype MSTF "Metamorphosis" from existing test facilities is the ability to maintain operational characteristics in conditions of intermodal transport, i.e., in conditions of vibration, shock, linear accelerations and angular displacements.

During the implementation of the project, the following 15 tasks have been consistently solved.

1. The analysis of existing technical solutions suitable for the development of prototype MSTF "Metamorphosis" has been carried out. In total, about 500 test facilities have been examined. The geometric and mechanical characteristics, composition and characteristics of the vacuum and cryogenic systems, alongside with operational characteristics of those facilities have been analysed. An analysis has also involved checking whether the requirements of ISO, ECSS and NASA standards have been met.
2. Based on the analysis, a generalised composition of the main systems, technical requirements for the Prototype, and the concept of its structure have been developed. The geometry characteristics of the test object (CubeSat sample) have been determined, and the geometric characteristics of the vacuum chamber of the Prototype have been calculated.
3. Based on the test object characteristics, the mean free path has been calculated for various test modes in molecular, viscous and transient modes, taking into account the Sutherland model and amendments for the Lennard-Jones potential. Based on the results obtained, the Knudsen number for different operation modes has been determined. The geometric characteristics of the vacuum chamber have been refined, taking into account the presence of cryogenic shrouds and minimising the parasitic heat inflow to the shrouds and the test object. Thus, by varying parameters and finding their mutually acceptable ranges, the geometric characteristics of the prototype vacuum chamber have been determined.
4. Various types of tests and modes of the Prototype operation have been analysed and their characteristics of the atmosphere (gas load, composition, etc.) have been determined. Based on the results obtained and in accordance with the requirements of the ISO, ECSS and NASA standards, the general requirements for allowable pressure have been determined for various types of the Prototype operating modes.
5. A pneumatic diagram and a preliminary layout of the vacuum system have been developed.
6. A mathematical model has been created, which includes a module for simulating of vacuum system gas load in various modes, a module for calculating the conductivity of elements of a vacuum system and a vacuum chamber, and a module for calculating the characteristics of vacuum pumps.
7. Based on the simulation results, technical requirements for vacuum pumps, valves, pipelines and gauges have been determined.
8. During the design and calculations, a systematic analysis of technical risks has been carried out, and the most vulnerable elements have been identified. It has been found that the greatest risks are exposed to: high-vacuum pumping system – vacuum valves, turbomolecular pumps, Stirling and Gifford-McMahon cryocoolers in cryogenic pumps; vacuum seals; thin-walled pipelines of cryogenic and vacuum systems with linear expansion joints, membrane bushings, cryogenic shrouds panels, vacuum chamber body; standard bellows, unloading and compensating spring elements of the cryogenic screen, fastening systems for the test object; a simulator of solar radiation, optical

feedthroughs; Van Allen belts simulator.

All analysed components exposed to risks have been divided into two groups:

- components for which it is possible to purchase options in vibration-shock-proof performance;
- elements requiring special design and technological measures to prevent damage and/or destruction.

9. Since the vacuum system has been identified as the system subject to the greatest technical risks, it has been decided to apply continuous postoperative verification control. The most objective control method that allows for a comprehensive assessment of the presence or absence of the main risks to the system's operation is tightness control.
10. An analysis of existing methods of leakage control has been carried out and, as a control method for the Prototype tests during test drives, a leak control method using a helium leak detector has been determined by comparing the leakage of the test object with the readings of a control leak.
11. A thermodynamic model of the Prototype has been developed. As a result of the simulation, the geometry of the cryogenic shrouds, cryogenic pipelines and other parameters of the Prototype cryogenic system have been obtained, common vacuum-cryogenic diagram and layout have been designed.
12. Based on the analysis of the requirements of the ISO, ESA ECSS and NASA standards and the results of the analysis of the prototype operation during various types of tests and modes, the prototype operation algorithms have been developed.
13. Based on the developed technical requirements, technical specifications have been drawn up, an analysis of the materials and components market and their procurement for the manufacture of a vacuum system, a vacuum chamber, cryogenic shrouds, and elements of a control system have been carried out. As components are received, incoming control is carried out. Manufacturing, assembly, installation of structural elements of the Prototype systems and their testing have been carried out. In particular, the assembly and testing of the elements of the fore-vacuum and high-vacuum systems have been carried out.
14. On the basis of the simulation results, sketches of the system's design have been developed.
15. Based on the analysis of the measurement processes during the Prototype's test, vacuum and cryogenic diagram analyses, a list of the Prototype control system sensors with technical requirements and the sensor interfaces list have been determined.

This article describes the main stages of the development of the mobile thermal vacuum chamber to be used for testing CubeSats.

2. DESIGN CALCULATIONS AND DESIGN DOCUMENTATION FOR THE DESIGN ELEMENTS OF THE PROTOTYPE

The main task of the project is to create such a Prototype, the qualities of which are to be verified both from the point of view of compliance with the main characteristics of space environmental simulators [5]–[7] and from the point of view of maintaining performance after repeated transportation in intermodal transportation. The design of the vacuum pumping system and the Prototype leakage system must meet the above technical requirements. The purpose of vacuum calculation is to determine the design and technical requirement for the vacuum chamber, vacuum pumping system and associated facilities of the Prototype, as well as to create a specification and vacuum diagram of the Prototype.

We can single out the minimum requirements for the composition of the equipment of the test complex, which have allowed for the development and testing of space technology under conditions of imitation of outer space:

- the presence of a high-vacuum pumping system;
- availability of a system for simulating heat flows to simulate heat flows of the Sun and planetary surfaces;
- availability of a system of nitrogen cryogenic shrouds, simulating "black" space;
- availability of a control system for temperature and other parameters of the spacecraft;
- availability of a pressure control system in the vacuum chamber.

2.1. Determination of the Structural Appearance of the Prototype Vacuum Chamber

The vacuum chamber of a facility intended for testing space technology, while simulating the conditions of an operating environment, is a unique product of individual development and manufacture. The correct definition of the design of the vacuum chamber not only determines the ease of use of the test bench, but also has a significant impact on its operational capabilities and characteristics. On the basis of the analysis, it has been decided to adopt a cylindrical vacuum chamber for a horizontal structural type (Fig. 1) for equipping the Prototype [8].

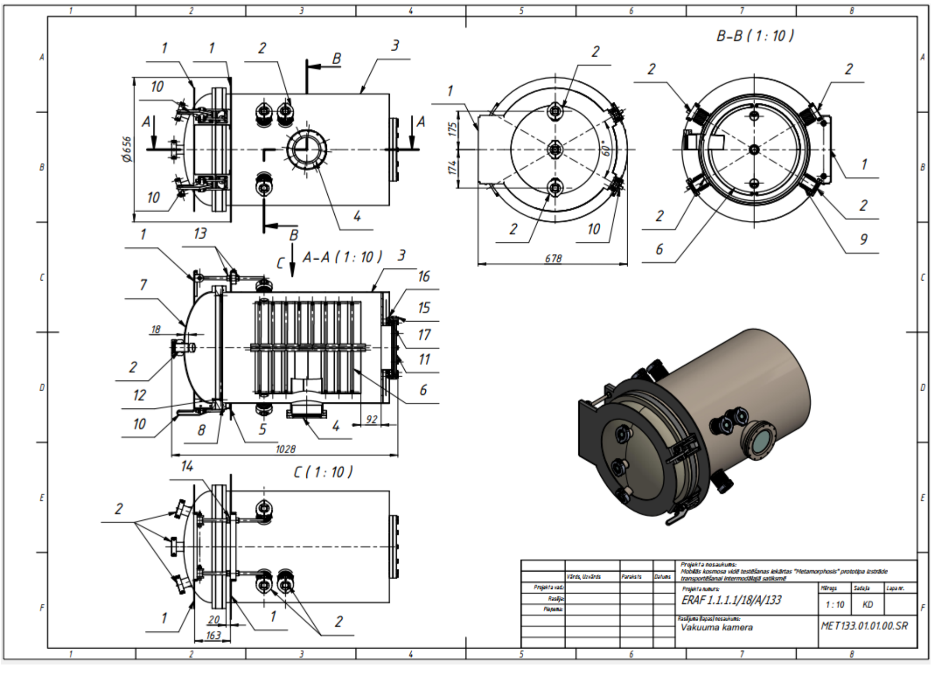

Fig. 1. Drawing of vacuum chamber.

2.2. Determination and Calculation of Geometric Characteristics of the Prototype Vacuum Chamber

The most probable test objects for the Metamorphosis mobile space testing facility are micro- (10–100 kg) and nano- (1–10kg) spacecraft, as well as parts and assemblies of such and larger spacecraft. The most common, and, therefore, probable type of such spacecraft is CubeSat. Based on the analysis of potential spacecraft to be tested, it has been decided to tentatively accept for the Prototype conditionally:

- minimum dimensions of the test object (LxWxH) 227x100x100 mm and mass 2.5 kg;
- nominal dimensions of the test object (LxWxH) 345x105x105 mm and mass 5 kg;
- maximum dimensions of the test object (LxWxH) 400x250x250 mm and mass 15 kg.

Determination of the Diameter and Length of the Cylindrical Part of the Vacuum Chamber

The diameter of the vacuum chamber [7] can be determined as the sum of the characteristic diameters (Fig. 2):

$$D = D_s + 2L_{cs} + 2h_{cs} + 2h_m, \quad (1)$$

where
D – the diameter of the vacuum chamber, mm;
D_s – the characteristic diameter of the test object, mm. $D_{s\ min}$=141.4 mm; $D_{s\ nom}$=148 mm; $D_{s\ max}$=354 mm;
L_{cs} – the distance from the test object to the cryogenic shrouds, mm;
h_{cs} – the thickness of cryogenic shrouds, mm;
h_m – the distance from the cryogenic shrouds to the body of the vacuum chamber, mm.

The length of the cylindrical part of the vacuum chamber can be determined as the sum of the characteristic length:

$$L = L_s + 2L_{cs} + 2h_{cs} + 2h_m, \quad (2)$$

where
L – the length of the vacuum chamber, mm;
L_s – the characteristic length of the test object, mm. $L_{s\ min}$=248 mm; $L_{s\ nom}$=360 mm; $L_{s\ max}$=472 mm.

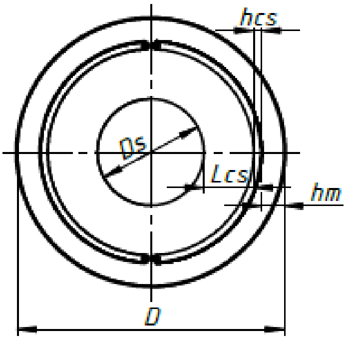

Fig. 2. Determination of vacuum chamber diameter size.

The main requirement of the standards [9], [10] for space environmental simulators is sufficient reliability of simulating real operating conditions, i.e., factors of outer space: 1) high vacuum; 2) zero reflection coefficient of electromagnetic radiation; 3) absence of convection and heat transfer through the thermal conductivity of the environment. High vacuum is understood as a state of gas in which collisions of gas molecules with the walls of the vessel prevail over the collision of gas molecules with each other. High vacuum is understood as a state of gas in which collisions of gas molecules with the walls of the vessel prevail over the collision of gas molecules with each other.

As prescribed in standards [9], [10], the pressure in the vacuum chamber should not exceed 10^{-5} Torr and in any case ensure the achievement of the molecular regime of a gas flow in the vacuum chamber, characteristic of the space environment.

The criterion for determining the nature of the movement and interaction of gas molecules is the Knudsen criterion:

$$K_n=L_m/D_s, \tag{3}$$

where
L_m – the mean free path of gas molecules;
D_s – the characteristic size of the vacuum vessel.

$$L_m = \frac{1}{\pi d^2 n\sqrt{2}}, \tag{4}$$

where
d – the effective diameter of gas molecule, m;
n – the number of molecules (concentration) per unit volume.

We can use the Botzmann equation:

$$p \cdot V = n \cdot k \cdot T, \tag{5}$$

where
P – the gas pressure, Pa. According to the standards, the minimum pressure in the vacuum chamber is 10^{-5}Torr and for air pressure it will be 1.33 10^{-3} Pa;
k – the Boltzmann constant, 1.38 10^{-23}J/K;
T – the gas temperature, K. The temperature of the atmosphere in the test bench chamber is 20 ^{0}C or 293 ^{0}K.

The expression for determination the mean free path of an ideal gas molecule (4) can be rewritten:

$$L_m = \frac{kT}{\pi d^2 P\sqrt{2}}. \tag{6}$$

Since the initial atmosphere in the vacuum chamber of the test complex is air – the largest effective molecular diameter of a diatomic structure (N_2 and O_2) is about 3.5 10^{-10}m.

At a result, the length of the average free path of an air molecule as an ideal gas (6) will be:

$$L_m = (1.38 \cdot 10^{-23} \cdot 293)/(3.14 \cdot (3.5 \cdot 10^{-10})^2 \cdot 1.33 \cdot 10^{-3} \cdot 1.414) = 5.6\, m. \tag{7}$$

The estimate of the free path for an ideal gas can be taken as the maximum. Turning to a real gas, it is necessary to introduce correction for the non-ideal nature of the gas. First, with increasing temperature, the vibrational motions of molecules increase, which is practically demonstrated as an increase in the free path and is expressed as Sutherland correction for mean free path:

$$L_m = \frac{kT}{\left(1+\frac{C}{T}\right)\pi d^2 P\sqrt{2}}, \tag{8}$$

where
C is the Sutherland constant. The Sutherland constant value for air is 120.

Then, taking into account the correction, the free path for air at a temperature of 293 K and a pressure of 10^{-5} Torr will be 4.74 m.

In a real gas, gas molecules do not behave like rigid spheres, but rather attract each other at large distances and repel each other at smaller distances, which can be described using the Lennard-Jones potential where the radius of the molecule is rm=21/6σ~1.122 σ . Then the value of the free path of an air molecule at a pressure of 10^{-5} Torr and a temperature of 293 K will be 0.93 m.

This estimate of the mean free path can be taken as the most probable in assessing the molecular regime of gas flow.

There is also a way to estimate the bridged path length from the assumption that the real gas is pseido-viscous. In this case, the mean free path of a molecule for a real gas is determined as follows:

$$L_m = \frac{\mu}{P}\sqrt{\frac{\pi RT}{2M}}, \quad (9)$$

where
μ – the viscosity, Pa s (μ=18.5 μPa s);
P – the pressure, Pa (1.33 10^{-3} Pa);
R – the universal gas constant, 8.31446261815324m^3PaK^1 mol^{-1};
T – the temperature, K (T=293K);
M – the molecular mass g/mol.

Then, when substituted in (9) we obtain L_m=0.27 m. This estimate can be discarded provided that a known molecular gas flow regime is ensured. Thus, it has been decided to accept for the vacuum calculation as the main estimate of the free path of a gas molecule in the vacuum chamber of the space environmental simulator at 0.93 m. From Eq. (8), taking into account the correction for the Lennard-Jones potential, we obtain a value of 0.186 m. Based on the obtained value of the mean free path and Eq. (3), let us determine the limitations of the overall dimensions of the vacuum chamber according to the Knudsen criterion to ensure the molecular regime of gas flow in the chamber for the main mode at maximum pressure (1 10^{-5} Torr):

$$D_s=L_m/K_n=0.93/10=0.093. \quad (10)$$

Thus, the characteristic size, i.e., the length of the shortest distance from the wall of the vacuum vessel to the test object should not exceed 0.093 m.

According to experimental data, during thermal cycling with imitation of the shadow side of a spacecraft in a space environmental simulation facility with liquid nitrogen cryogenic shrouds with a temperature of 90–95 ^{0}K, the temperature in the region close to the surface of the space of the spacecraft is close to 150 ^{0}K.

A verification calculation should be made to account for the effect of viscosity at low temperatures. For example, when the temperature of the atmosphere in the local volume of the vacuum chamber decreases from 293 ^{0}K to 150 ^{0}K, taking into account the value of the Sutherland coefficient (for air 120) and initial viscosity μ_0=18.5 μPa s, the viscosity of air at a temperature of 150 ^{0}K will be 14.1 μPa s, and, the free path of a molecule in accordance with (9) will be 0.08715 m.

Since the effect of a decrease in temperature on the mean free path of a molecule in viscosity is very significant, we will take this limitation into account. Then the characteristic size of the vacuum chamber should not exceed 0.0872- m.

Substituting into (1) the obtained values of the characteristic diameter of the test object and the double distance from the test object to the cryogenic shroud (7–9), taking the thickness of the cryogenic shields as 10 mm and the distance from the cryogenic shroud to the body of the vacuum chamber as 40 mm, we obtain the calculated diameters of the vacuum chamber:

$$D_{min} = 141.4 + 2 \cdot 87.2 + 2 \cdot 10 + 2 \cdot 40 = 415.8;$$
$$D_{nom} = 148 + 2 \cdot 87.2 + 2 \cdot 10 + 2 \cdot 40 = 422.4;$$
$$D_{max} = 354 + 2 \cdot 87.2 + 2 \cdot 10 + 2 \cdot 40 = 628.4.$$

Taking into account the technological tolerances, we initially take the calculated inner diameter of the prototype vacuum chamber: $D_{min} = 400^{+10}$ mm; $D_{nom} = 500^{+10}$ mm; $D_{max} = 800^{+10}$ mm.

Substituting into (2) the obtained values of the characteristic length, we obtain the total length of the cylindrical part of the vacuum chamber:

- for a diameter of 400 mm, the length of the cylindrical part is taken as 650 mm;
- for a diameter of 500 mm, the length of the cylindrical part is taken as 780 mm;
- for a diameter of 800 mm, the length of the cylindrical part is taken as 1300 mm.

Tests that can be done with the Prototype and its Operation Mode:

1. Thermal vacuum tests are the final certification, qualification or acceptance tests both in relation to individual parts, assemblies, assemblies and systems, and in relation to spacecraft as a whole. There are the following types of heat and vacuum tests:
   - thermostating;
   - thermal cycling;
   - thermobalance tests;
   - no-load vacuum tests – checking the performance of the thermal control system;
   - vacuum tests with partial load – with the inclusion of the thermal control system and partial activation of the on-board equipment for testing individual systems, assemblies and assemblies of the spacecraft;
   - vacuum tests with full load – with the inclusion of all systems of the spacecraft in the normal mode and full imitation of the payload operation program.

When carrying out thermal vacuum tests, it is necessary to ensure that the pressure in the vacuum chamber does not exceed $1x10^{-5}$ Torr (1.33 $x10^{-3}$ Pa).

2. Pneumatic tests are acceptance tests for pneumatic and hydraulic systems of spacecraft and are preliminary tests in the test program for assemblies, assembly systems and spacecraft, in general. The following types of pneumatic tests are distinguished:
   - control of the tightness of the product by the mass spectrometric method;
   - analysis of the residual gases of the atmosphere of the vacuum chamber.

To carry out pneumatic tests, the accepted maximum pressure of $5x10^{-5}$ Torr ($7x10^{-3}$ Pa) is sufficient.

3. Electrical tests are acceptance tests for electrical systems of spacecraft and are preliminary tests in the testing program for assemblies, assembly systems and spacecraft, in general. There are the following types of electrical tests:
   - electrical tests with partial activation of on-board equipment for testing individual systems, assemblies and assemblies of the spacecraft;
   - electrical tests with the inclusion of all systems of the spacecraft in the normal mode and full simulation of the payload operation program.

Since voltages up to 400 V are usually used in on-board spacecraft equipment, the product of the distance between the conductors and the pressure should be less than 0.2. Spacecraft are characterised by a high packing density, and the distance between conductors can be up to 0.5 mm. In this case, to prevent ignition of the charge, the pressure in the vacuum chamber, the pressure should be less than $1x10^{-2}$ Torr (1.33 Pa). This condition is also satisfied by the maximum pressure in the vacuum chamber $5x10^{-5}$ Torr ($7x10^{-3}$ Pa).

4. Broad spectrum solar radiation tests. To carry out such a test, it is required to equip the simulator with a solar radiation simulator.
5. Test for the effects of ultraviolet radiation and radiation, which are part of the solar radiation spectrum. Test requires equipping the simulator with UV and X-ray solar radiation simulators.

6. Radiation tests under conditions of imitation of the impact of Van Allen radiation belts. To carry out such tests, it is required retrofitting of the test complex with sources of electrons, protons and helium nuclei (alpha particles) of the corresponding energy.
7. Degassing mode. In the degassing mode, parasitic gases and volatiles are removed from the surface and from the unpressurized volumes of the spacecraft.
8. Process thermostating mode. The pressure requirements for this type of test are similar to the requirements for thermal vacuum testing.

Estimated Gas Load and Vacuum Chamber Atmosphere Composition in Various Operating Modes

To analyse the gas load in different operating modes, it is necessary to assess the influence of various components on the overall picture of the gas load. The computational layout diagram of the test facility vacuum chamber is shown in Fig. 3.

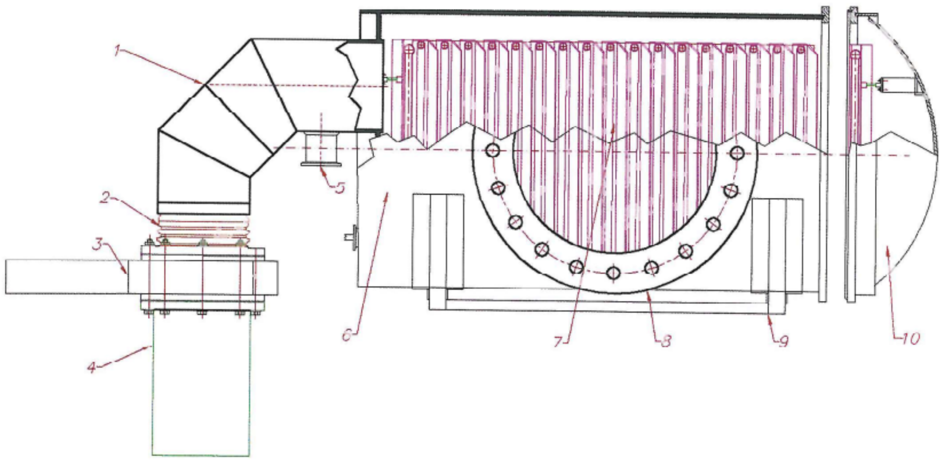

Fig. 3. Computational layout diagram of the Prototype vacuum chamber: (1) high-vacuum outlet; (2) vibration decoupling; (3) vacuum seal; (4) high-vacuum pump; (5) fitting for connecting the shutter of the fore line pump; (6) body of vacuum chamber; (7) cryogenic shroud; (8) optical feedthrough for inputting radiation from the Solar simulator; (9) lodgements and connections for camera mounting; (10) removable front cover.

During this step, operational pressure (10^{-5} mbar) and maximal gas load have been calculated. Then, the required pumping speed of fore vacuum pump (≥20 m^3/h) and turbomolecular pump (≥900 l/s) have been calculated. The required through diameter of the entire high-vacuum path of the vacuum pumping system has also been calculated (≥200 mm).

2.3. Thermophysical Calculation

One of the tasks to solve in the creation of facilities for simulating the conditions of outer space is a reliable imitation of the properties of outer space in terms of energy dissipation. A high vacuum also belongs to the properties of outer space; therefore, such heat transfer mechanisms as convection and heat transfer cannot be used. The imitation of the process taking place in outer space will be reliable if only the radiation mechanisms of energy transfer are used. The problem of ensuring the reliability of simulating the dissipative capacity of outer space becomes especially important when testing modern leaky satellites with a passive thermal control system, which also include CubeSat.

This problem can be solved if the test object, placed inside the vacuum chamber of the space simulator, at a sufficient distance, is surrounded by surfaces absorbing thermal energy, having a temperature significantly closer to absolute zero than the temperature of the test object.

The basis of the project of the cryogenic system of the space simulator is its calculation. This calculation consists of a thermophysical part and a hydraulic part. The purpose of the thermophysical calculation is to prepare technical requirements for the elements of the Prototype cryogenic system.

Thermophysical calculation has been carried out using many results of vacuum calculation: information about the types of tests and operating modes of the Prototype, the nature of the gas load and pressure in the vacuum chamber, geometric characteristics of the vacuum chamber and the test object, dimensional characteristics of cryogenic screens, etc.

3. VIBRATION LOAD ANALYSES

According to posed requirements, the vacuum chamber system should be rigid enough to stand multiple transportation type loads. During transportation, mechanical systems are subjected to vibration loads caused and coming from different sources like engine, gearboxes, axels and other more unpredictable from road bumps and uneven parts of them. Most common transportation system to use for the vacuum chamber transportation has been taken to be road by truck or by railway.

In the beginning, the research on the mentioned subject has been conducted to obtain information about vibration levels, which appear during transportation on truck and train platforms. The designed system is intended to be transportable in intermodal environment. In intermodal environment, the transportation system can be subjected to vibration loads from transportation systems, which, in turn, come from rotating equipment, engines and uneven road bumps. According to research truck and railroad transportation, frequencies compose the range from 1 to about 120 Hz.

In this research, a system natural frequency range has been determined and analysed in comparison with frequencies caused by transportation, its impact on the system has been determined and solutions have been searched to reduce negative influence on the system for safe transportation.

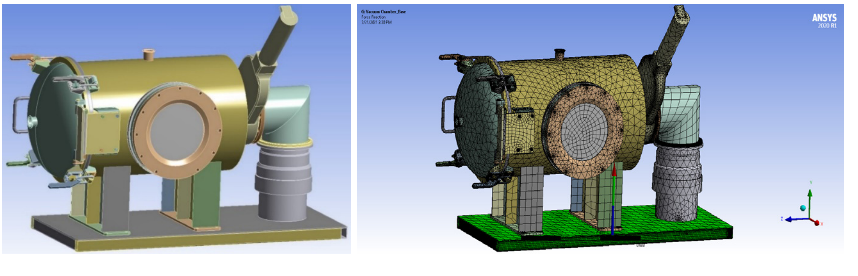

Fig. 4. Redesigned *Vacuum Chamber* construction.

From previous design steps and vibration load analyses, the construction has already been redesigned (integral base support part, chamber outtake part), providing positive results. Figure 4 illustrates the redesigned construction that will be subjected to vibration load analyses in the current design step. To determine construction load from the system inertial response forces and preload conditions for modal analyses, the Static Structural Analyses have been completed applying Standard Earth Gravity to the system. The system natural frequencies have been determined by modal analyses.

The vibration load influence from transportation is determined by Random Vibration Analyses. The system *CAD* model has been tested in *ANSYS* software environment. To check system on vibrational loads, it is necessary to complete simulation on loads in the following *ANSYS* modules [11]:

- *Static Structural Analyses* – during which it is prepared for a pre-stressed modal analysis [12]–[14];
- *Modal Analyses* – during which system natural frequencies are determined [15];
- *Random Vibration Analyses* – during which the structure response is determined under random loading [16]–[18].

The Vacuum Chamber weight is 349.35 kg, material is stainless steel, Young's Modulus of Elasticity – 1.93e+11 Pa, Poisson's Ratio – 0.31, density – 7750 kg/m^3, Tensile Yield Strength – 2.07e+08 Pa, Tensile Ultimate Strength – 5.86e+08 Pa.

The vibration loads are cyclic and repetitive, as well as vessels for use under pressure (in this case negative pressure), so for the current design the Vacuum Chamber structure is considered to be subjected to metal fatigue. Also, considering the aforementioned factor of safety for pressure vessels, the factor of safety value of 3.5 is taken for the current design.

3.1. The Static Structural Analyses

The system inertial response forces have been identified in Static Structural Analyses applying Standard Earth Gravity to the system. The results of Static Structural Analyses show the biggest directional deformation from structure inertial load at tank upper part, but values are not critical. Also strain energy concentrates in tube part with right angle; values are also not critical. Total deformation shows its concentration in part of structure where vacuum pump and shatter are mounted. Though the values are not critical, they can point to problems on those parts caused by vibration loads (Fig. 5).

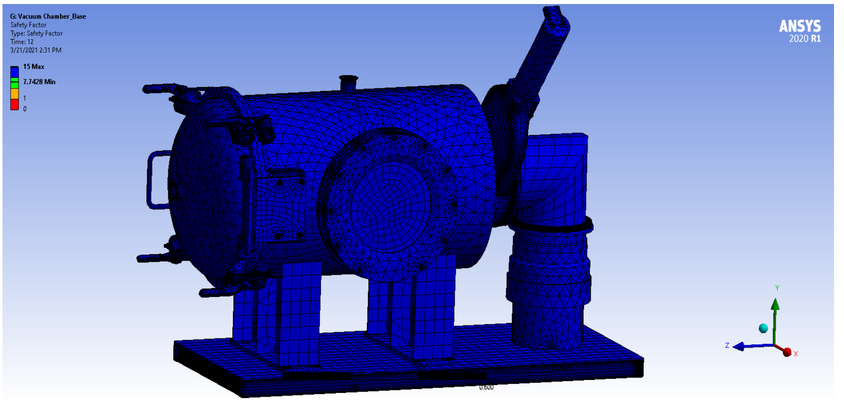

Fig. 5. The Vacuum Chamber analysed in *Static Structural* module.

Table 1. Summary of Static Structural Analysis Results

No.	Results	Minimum	Maximum	Units
1.	Normal Stress	-5.89E+06	2.05E+07	Pa
2.	Directional Deformation	-4.04E-05	1.05E-04	m
3.	Total Deformation	0	1.48E-03	m
4.	Equivalent Stress	0	2.67E+07	Pa
5.	Safety Factor	7.7428	7.7428	-

In the construction model for the *Static Structural Analyses*, the probe input has been made that shows the following reaction forces of -2.2042e-004 N, 3414.6 N, 3.0342e-004 N and 3414.6 N for X, Y and Z axis and total, respectively.

In Table 1, we can see the simulation results where the maximum stress is 20.5 MPa and maximum deformation is 0.105 mm in Z-axis direction and total deformation of 1.48 mm. In Table 2, we can see that the reaction force is 3414.6 N.

3.2. The Modal Analysis

Modal Analyses on twenty modes of natural frequencies have been determined, ranging from 6.6923 Hz to 286.41 Hz (Table 2). The most dangerous frequencies for the system that can lead to its disintegration are 126.22 Hz, 142.15 Hz, 200.52 Hz, and 247.48 Hz. Those dangerous frequency modes show strong shutter response that also affects the structure part with connection to chamber. Example of analysis results are depicted in Figs. 6 and 7.

Table 2. Summary of Modal Analysis Results

Mode	Frequency, Hz	Mode	Frequency, Hz
1.	6.6923	11.	142.15
2.	13.418	12.	169.59
3.	16.602	13.	185.24
4.	33.225	14.	186.6
5.	38.435	15.	200.52
6.	61.888	16.	210.37
7.	66.526	17.	217.88
8.	112.69	18.	233.17
9.	120.6	19.	247.48
10.	126.22	20.	286.41

If the applied force frequency is close to the construction system natural frequency, it dramatically affects the amplitude of oscillation which becomes very large and can lead to destruction of the construction system.

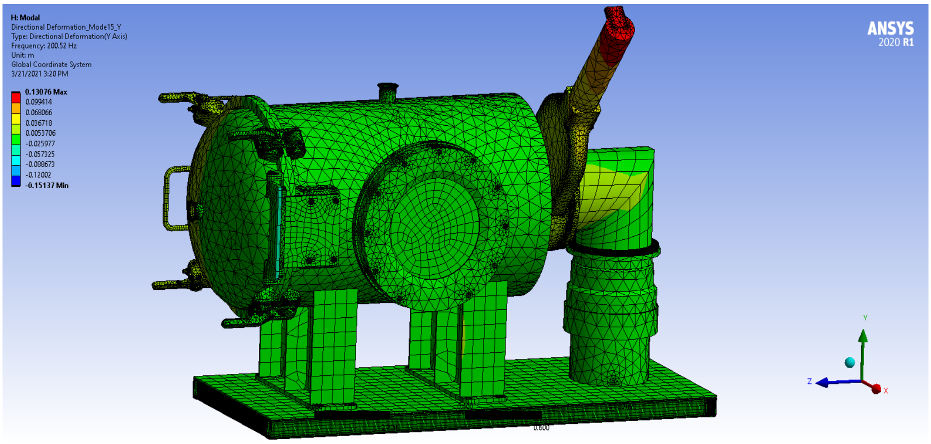

Fig. 6. Example of the Modal Analysis results.

The current study has determined twenty natural frequencies (Table 2) corresponding to the twenty normal frequencies. From the theoretical point of view, to determine system durability, it is necessary to take a wider range of frequencies that system will be subjected in real life with 1.5 probability that is to about 180 Hz. Thus, from Table 2, we can assume that the construction will show large amplitude oscillations when the exciting frequency is close to either of fourteen natural frequencies.

Results show that there is strong response in the X and Z axis directions. If it were on the support under chamber structure, it could be considered acceptable due to the material strength, but in this case the load direction could influence proper functioning of the vacuum pump and the gate valve. The system itself is strong enough to withstand those loads but as it refers to technically sophisticated assemblies that can influence their proper functioning, careful considerations should be taken, and it is very desirable to redesign that part of the system.

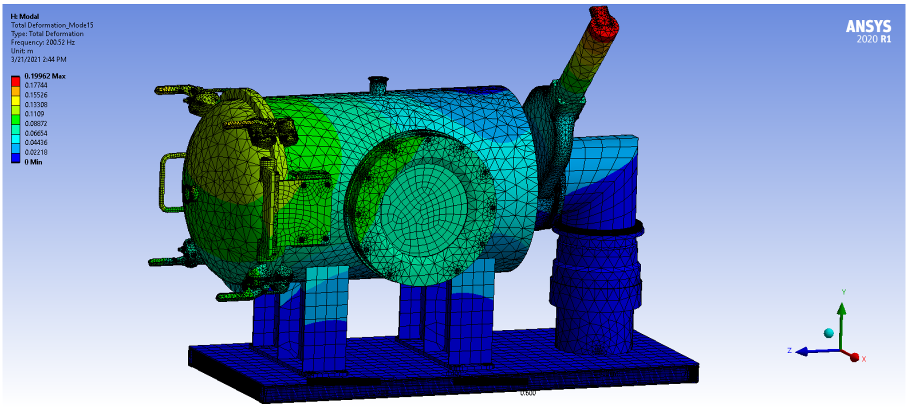

Fig. 7. Example of the Modal Analysis results.

From Table 3 we can see that modes that influence the Vacuum Chamber structure in the most severe way are 126.22 and 142.15 Hz, respectively.

Table 3. Summary of Modal Analysis Results

Results	Minimum	Maximum	Units	Reported Frequency (Hz)
Maximum Shear Elastic Strain	0	0.18285	m/m	6.6923
Normal Elastic Strain	-5.63E-02	7.56E-02	m/m	6.6923
Shear Elastic Strain	-5.80E-02	8.54E-02	m/m	6.6923
Maximum Shear Stress	0	1.35E+10	Pa	6.6923
Normal Stress	-1.85E+10	1.31E+10	Pa	6.6923
Shear Stress 2	-4.28E+09	6.29E+09	Pa	6.6923
Directional Deformation_Mode1	-5.30E-02	6.40E-03	m	6.6923
Directional Deformation_Mode3	-0.31106	4.59E-02	m	16.602
Directional Deformation_Mode10	-0.10989	7.74E-02	m	126.22
Directional Deformation_Mode11	-0.14774	9.94E-02	m	142.15
Directional Deformation_Mode14	-2.38E-02	2.60E-02	m	186.6
Directional Deformation_Mode17	-1.00E-02	1.07E-02	m	217.88

3.3. The Random Vibration Analysis

In Random Vibration Analyses, the system has been checked on possible damage types caused from vibration loads during transportation in the fourteen frequency modes that have been determined during Modal Analyses and correspond to a range of frequencies that can generate during transportation.

The construction has been tested on Sigma I stress level. The Sigma stress levels mean that these stress levels will occur 68.27 %, 95.45% and 99.73% of the time, respectively. 1-sigma, 2-sigma and 3-sigma levels are usually used, but these can be more, if necessary. For fatigue evaluation, 3-sigma stress level is essential. The stress levels from the Random Vibration are real, vary with time and have meaning. Similarly, the Von Mises stress is an indication of stress level severity at a point and its closeness to failure levels.

Analysis results also show strong structure response in Z axis and YZ component directions when vibration frequency is close to structure natural frequency. Result values do not exceed material (Stainless Steel) Yield Strength. The Factor of Safety should be considered (Figs. 8 and 9).

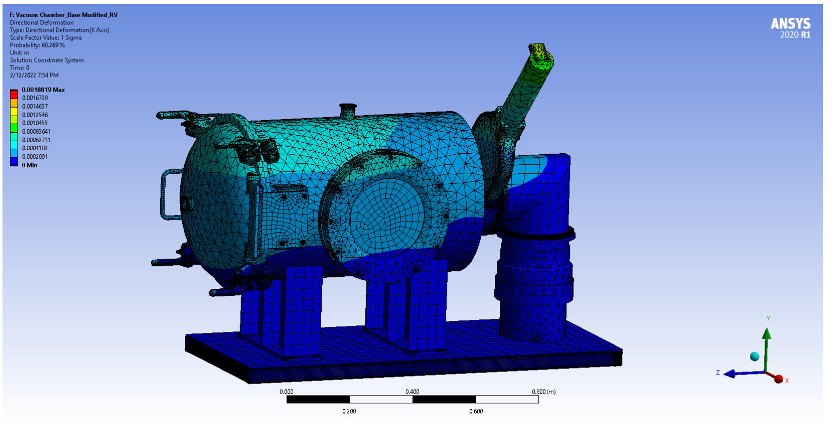

Fig. 8. Example of the Modal Analysis results.

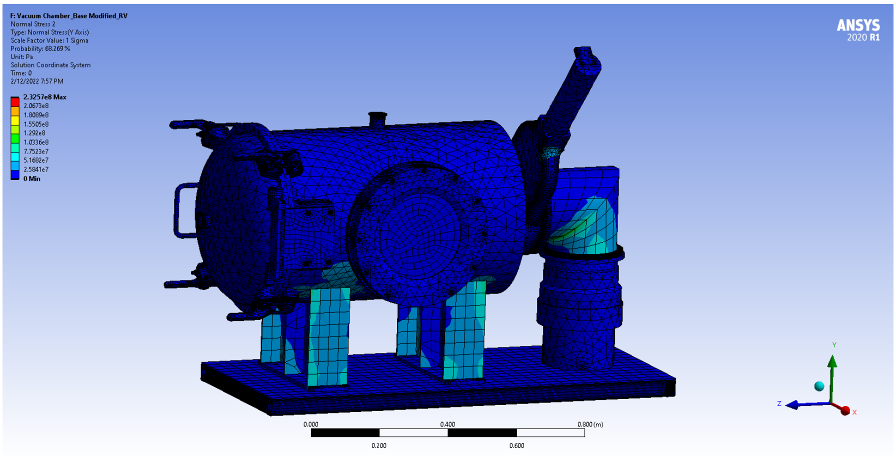

Fig. 9. Example of the Modal Analysis results.

Table 4. Summary of Random Vibration Analysis Results

Results	Minimum	Maximum	Units
Directional Deformation	0	6.85E-03	m
Normal Elastic Strain	0	1.30E-03	m/m
Shear Elastic Strain	0	8.89E-04	m/m
Normal Stress	0	3.44E+08	Pa
Shear Stress	0	6.55E+07	Pa
Equivalent Stress	0	2.026E+08	Pa
Directional Velocity	6.19E-02	0.94465	m/s
Directional Acceleration	39.392	711.16	m/s²

In Table 4, we can see the simulation results where the maximum stress is 344 MPa and maximum deformation is 6.85 mm in Z-axis direction.

By completing the Vacuum Chamber analyses in ANSYS, it has been possible to identify deficiencies in the construction. The Static Structural Analyses have revealed that the safety factor is too high, it is equal to 7.74, which is more than twice of the necessary value defined in the beginning – 3.5. That can also be identified by Equivalent von-Mises Stress value (see Table 1) of 2.67e+07 Pa, which is only about 13 % of the allowable load. The system is too bulky. The changes can be made in support construction that will save same material and make construction lighter.

From the Modal Analyses and the Random Vibration Analyses, it can be seen that there is rather big vibration influence on the gate valve. As it is a sophisticated device and it can influence its proper functioning, consideration should be taken to change it for the other type of valve that is more appropriate to design situation (e.g., an electro-pneumatic angle valve).

Also, from the Random Vibration results, we can conclude that the Vacuum Chamber system is safe for transportation; however, originally the system has been designed as a transportable unit. If this is taken into account, then the safety factor of 3.5 should be also addressed to analysis results from the Random Vibration that show Equivalent von-Mises Stress value of 2.026e+08 Pa (Table 4), which is about 98 % of the allowable load. If it is a safety factor, but as a design safety factor is determined to be 3.5, this points to the weakness of the construction. This indicates a too week design safety factor in case the system is subjected to transportation vibration. Thus, we need to assess the opportunity to redesign the Vacuum Chamber base construction, including some damping mechanisms. Since the Vacuum Chamber transportation state is not in its working state, but just only transfers to the point where actual work is to be completed, and that it will take very small part of its lifetime use, the damping system or mechanism should not be very complicated and raise overall price of the construction. It is suggested to use material at mounting place between the Vacuum Chamber and the transportation vehicle floor, with good damping properties.

Redesigned construction is depicted in Fig. 10.

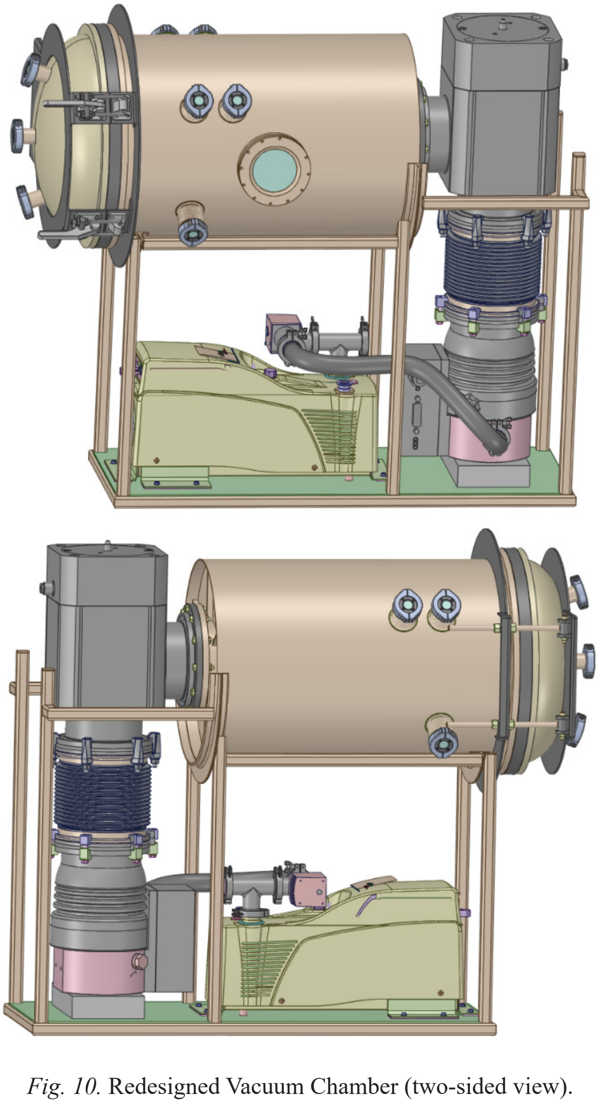

Fig. 10. Redesigned Vacuum Chamber (two-sided view).

According to the requirements, the Vacuum Chamber should be mounted on a vehicle and used as a mobile lab, it is also depicted in the mounted state that can be seen in Fig. 11. The Vacuum Chamber has been redesigned according to the obtained results. The initial design can be viewed in Fig. 4 (and also other from vibration simulation), the redesigned construction is depicted in Fig. 10.

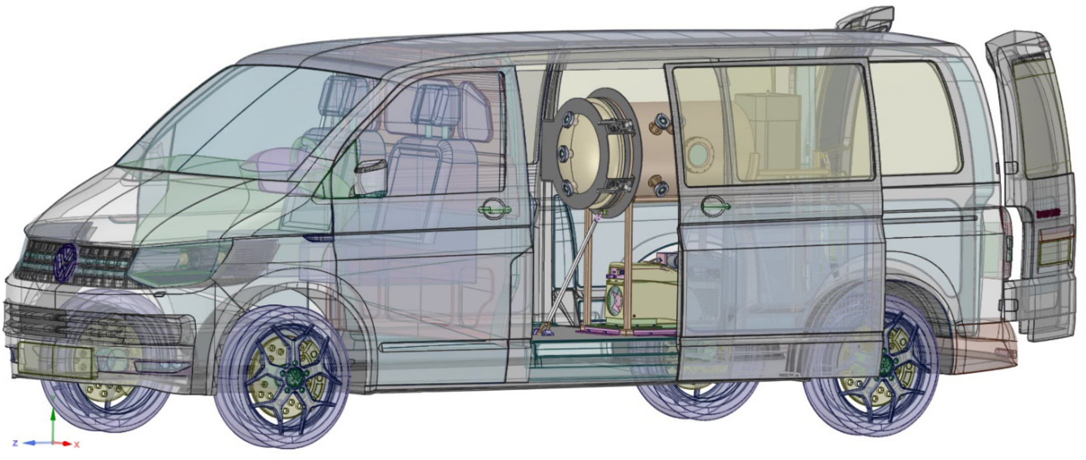

Fig. 11. Redesigned Vacuum Chamber mounted on a vehicle.

Completing the Modal Analyses and the Random Vibration Analyses, it has been observed that there is a rather big vibration influence on the gate valve (Figs. 6–8). As it is a sophisticated device and it can influence its proper functioning, consideration should be taken to change it for another type of valve more appropriate to the design situation. The gate valve has been changed to the electro-pneumatic angle valve.

4. CONCLUSIONS

The main stages of development of mobile thermal vacuum chamber to be used for testing CubeSats have been described in this article. The project for creating mobile testing facility for simulating the outer space environment has been implemented by Riga Technical University in cooperation with Cryogenic and Vacuum Systems Ltd.

Based on the developed technical requirements and the results of the Vacuum, Thermophysical calculation and Vibration Load Analyses and design documentation, technical specifications have been drawn up; the analysis of the market for materials and components has been performed; procurements of materials and components for vacuum and control systems manufacture have been provided, the supplied components incoming quality control has been performed; the prototype structural elements have been produced and/or purchased. During the further project implementation, all these elements have been sent to the assembly of the prototype, which has been then tested.

ACKNOWLEDGEMENTS

The research has been financed by the Aeronautics Institute of Riga Technical University project “Prototype Development of Transportable in Intermodal Traffic Mobile Space Testing Facility “Metamorphosis”” (Metamorphosis, project No. 1.1.1.1/18/A/133) budget.

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