Flight Dynamic Analysis of ITUpSAT1

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***Abstract-* In this paper, ITUpSAT1 is analyzed using computational methods to predict the response of its main structure to the launch environment. First, detailed Finite Element models are developed to observe its responses to the quasi-static accelerations. The India's PSLV launch vehicle's environment is used as reference. In PSLV, the most dominant loads are the accelerations caused by boosters which reach a value of 7g in vertical direction and dynamic accelerations 1.5g in horizontal direction. Both single and multiple deployment configurations are possible. Single deployment configuration with vertical and horizontal arrangements is considered. The Von Mises Stress values are calculated. Computed natural frequencies are found to compare well with the PSLV frequency tables. The results were satisfactory as the maximum stresses were quite below used material's limits. Harmonic dynamic response analysis is also carried out. The national capacities for building CubeSat main structures are also discussed.**

I. INTRODUCTION

CubeSats, educational and research picosatellite, have been built and launched since early 2000[1-5]. Recently, CubeSats have also received considerable attention and financial support by both European and US official organizations, such as ESA and NSF[6]. The first Turkish CubeSat ITUpSAT1 is being developed by İTÜ and is expected to be launched during the last quarter of 2008, by the Polar Satellite Launch Vehicle (PSLV) operated by Antrix Corporation, India.

The launch of any satellite is one of the major and costly steps in the way to the orbit or to outer space. When a launch vehicle is launched, strong vibrations are transmitted through the joining sections to the satellite on-board. CubeSats are ejected from a launch adapter named picosatellite orbit deployer (POD), specifically designed and built for CubeSats which use piggy-back launch opportunity. The adapter may be for a single satellite as well as three satellites in side by side configuration. During its launch, a satellite is subject to various external loads resulting from steady-state booster acceleration, vibro-acoustic noise, propulsion system engine vibrations, booster ignition and burn-out, stage separations, vehicle maneuvers, propellant slosh, payload fairing separation and ejection. A satellite must meet the requirements given by the launcher based on the launch vehicle specifications.

ITUpSAT1 is the first student built picosatellite of Space Systems Design and Test Laboratory at Istanbul Technical University. The laboratory which is part of Aeronautics and Astronautics Faculty of İTÜ has been founded in 2007 and the project which is also supported by TUBİTAK is the first work of the laboratory. ITUpSAT1 is based on the CubeSat program which is an international and educational project founded by Stanford and California Polytechnic Universities and aims to provide a standard low-cost platform to design a class of picosatellite [6]. The program consists of universities around the world building their own picosatellite that are 10 cm cubes with a mass less than 1 kilogram (1 unit CubeSat). Besides, despite being initialized as an educational project for university students, recently industry has taken interest in CubeSat and some companies began building their own picosatellite as well. Moreover, multiunit CubeSats is also successfully built and launched [7-8].

In this paper structural analysis of ITUpSAT1 during the launch is discussed. ITUpSAT1 is analyzed using computational methods to predict the response of its main structure to the launch environment. Preliminary studies for ITUpSAT1 were carried out in references [9] and [10]. First, detailed Finite Element models are developed to observe its responses to the quasi-static accelerations [11-12]. The India's PSLV launch vehicle's environment is used as reference [13]. In PSLV, the most dominant loads are the accelerations caused by boosters which reach a value of 7g in vertical direction and dynamic accelerations 1.5g in horizontal direction. Both single and multiple deployment configurations are possible. The Von Mises Stress values are calculated for single deployment configuration in vertical and horizontal arrangement. Computed natural frequencies are found to compare well with the PSLV frequency tables [13]. The results were satisfactory as the maximum stresses were quite below used material's limits. Harmonic dynamic response analysis is also carried out. The ITUpSAT1 will also be tested experimentally at İTÜ vibration and acoustics laboratory to meet the launchers requirements.

The national capacities for building CubeSat main structures are also discussed [10].

II. LAUNCH ENVIRONMENT and DESIGN CONSIDERATIONS

Predicting suitable loads is one of the hardest steps of designing a spacecraft. Because of the complexity and high variety of mission environments little inaccuracies in the finite element models are capable of causing large errors [9]. During its launch, a satellite is subject to various external loads resulting from steady-state booster acceleration, vibro-acoustic noise, air turbulence, gusts, propulsion system engine vibrations, booster ignition and burn-out, stage separations, vehicle maneuvers, propellant slosh, payload fairing separation and ejection. These sources' characteristic feature is being random and independent [14].

Every event generates structural loads in the life of a spacecraft from launch to put on orbit. Even though launch causes the highest value loads for most spacecraft structures; any other event can be critical and significant for some parts of the structure, such as manufacturing, ground handling- testing, pre-launch preparations, payload separation, on-orbit operations, landing.

Launch contains a sequence of actions, and these events have some independent source of load which is related to the launch vehicle and payload. Some of the loads are comparatively steady-state or constant over time, such as thrust while a rocket engine burns while some of them are transient, such as thrust when rocket ignites or shuts down. Acoustic loads are sound pressure waves. As the majority of the acoustics consist of waves with various frequencies, they cause the random vibration of the structures. Pyrotechnic shock is high-intensity, high-frequency vibration (>1000Hz) caused by the explosive commonly used to separate stages.

Lift-off is definitely the most visually remarkable part of launch. Furthermore, it causes complex and harsh dynamic atmosphere. After the main engines are ignited at lift-off, pressure grows quickly in the launch-pad's exhaust ducts. The air in the environment causes transient air pressure, or over-pressure forces, which in turn affect the vehicle. These forces are important since they are asymmetrical about the vehicle. Design of the launch pad significantly has an influence on these forces.

At the transonic speeds where the vehicle come close to the speed of sound and passes through it, a complex loading environment forms again. Shock waves develop, changing the aerodynamic pressures, which affect the vehicle. The energy and positions of the shock waves alter very quickly and arbitrarily, and the location of them depends significantly on the space vehicle's structural configuration. Effects of these loads are vital; they come together with static air pressure, steady winds, wind shears and gusts, and the forces used for the booster stabilization and maneuvering.

Satellites also are exposed to acceleration during stage separation and payload fairing separation. "Any time a rocket engine ignites or shuts down, the launch vehicle and payload experience a transient force. Axial acceleration during any stage builds as propellant is used up, because there is less mass to lift. For some boosters, the slowly increasing axial acceleration before shutdown becomes so high that it alone can be a design driver, even if the transient loading of shutdown is insignificant [14]."

After launch vehicle gains adequate altitude, the air becomes sparse enough, and as a result, aerodynamic forces and thermal effects no longer affect the payload, and the fairing of the payload becomes unnecessary baggage. While the high energy of this occasion brings forces in all directions at the fairing's interface to the launch vehicle, the radial forces are self-contained within the fairing segments [14].

The Single Picosatellite Launcher (SPL) [15] is a CubeSat deployment system with standards of California Polytechnic State University. It is an interface structure between the launch vehicle and the CubeSat. There are three neighbor satellites in their own cabins that all have spring mechanisms that separate the satellite from the launcher once it is in orbit and doors that keep the satellites within the SPL during the flight of the vehicle, as shown in Fig 1. We assume for analyses that the SPL is put in launch vehicle both horizontally and vertically.

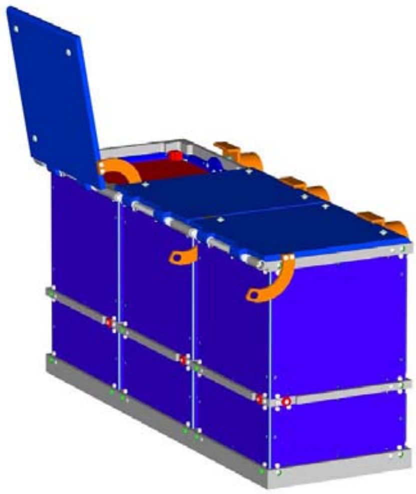

Fig. 1. The Single Picosatellite Launcher (SPL) along with other two at launch configuration.

We have two design considerations for our design; one of them is the maximum static acceleration and the other one is its maximum mass. The static acceleration of the launch vehicle will be 7g in the longitudinal direction and 1.5g in the lateral direction according to the user's guide of Polar Satellite Launch Vehicle [13]. The ultimate load factor is stated as 1.25 again in the guide. In this case, the maximum static acceleration would be 8.75g's and the CubeSat will be exposed to a load of 85.8375 N, at most. Moreover, the satellite will be exposed to about 17.27 N on its top-feet because of the spring mechanism in SPL. The maximum weight of the satellite can be 1 kg.

Moreover, the boundary conditions of structure must be determined. The structure will be simply-supported in (z) direction at the bottom side of SPL where it has a contact with our picosatellite. Additionally, it will be simply supported in (x) direction while under loads along (y) direction, and (y) direction while under loads along (x) direction at all four hard-anodized rails of satellite structure, Fig. 2.

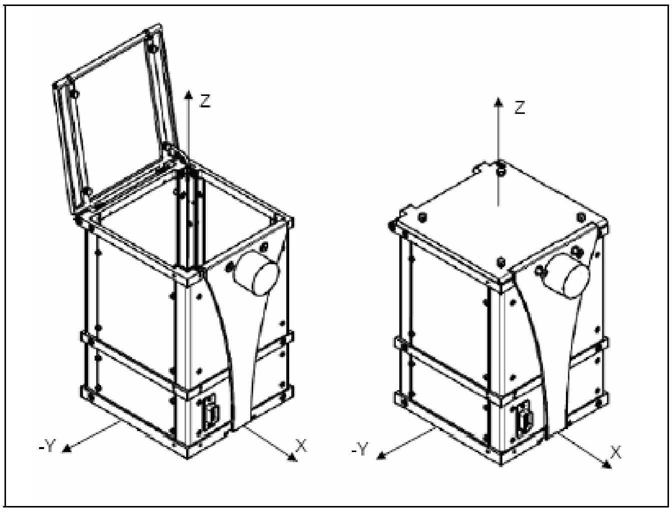

Fig. 2. Coordinate system of SPL.

III. MODELLING and ANALYSES

The CubeSat structure which is used and analyzed for ITUpSAT1 in this paper is purchased from Pumpkin Inc [16]. The image of the CubeSat structure, which is Revision D of Pumpkin Inc., including the computer board is shown in Fig. 3.

To simplify the analysis, some assumptions were made during the remodeling of the satellite structure. The structure is modeled using the CATIA software (www.catia.com).

Fig. 3. Pumpkin Inc. CubeSat structure, Rev D.

The Finite Element Model for the analysis, which can be seen in Fig. 4, consists of top and bottom faces, 4 side faces, 8 volumes as CubeSat feet, 4 beams which carry the boards such as payload board within the satellite and 4 additional volumes that connect the beams with the structure on side faces. The lateral faces' width are 100 mm and their height are 100 mm. Top and bottom face dimensions are 100mm x 100mm. Basically the satellite structure is a 10x10x10 cm cube. The screwing of the top-bottom faces to the side faces are omitted for the simplification of the modeling. Moreover, the side face on which remove before flight pin access area and data port access area lay is assumed to have no dissimilarities from other side faces. Additionally, all extra holes present on the structures' faces created after optimization of the satellite structure are neglected as they have very small dimensions. The beams are modeled as beams with lengths of 90 mm and radii of 1.5 mm.

The analysis of the structure is carried out using ANSYS 11 software [17]. The input thickness values of the top-bottom faces and side faces are 1.524 mm and 1.27 mm, respectively. These values are the exact values measured from the structure itself. The dimensions of each foot are 7.5x7.5x7 mm and as stated earlier; they are modeled as solids. The material for the 6 faces is aluminum alloy 5052-H32 and for the feet and beam connection solids is aluminum alloy 6061. The densities of these alloys are 2.68×10^{-9} and 2.70×10^{-9} tonnes/mm^3 respectively. The Poisson ratio for both alloys is 0.33 and moduli of elasticity of these alloys are 70.3 GPa and 68.9 GPa, respectively. The material of the beams is stainless steel while its density is 9.1×10^{-9}tonnes/ mm^3, Poisson ratio is 0.22 and modulus of elasticity is 68.9 GPa.

For the FEM analysis, the plates are modeled as shell structures while feet volumes are solids with beams modeled as beams. SHELL181 element is chosen for shell elements of faces as it is a suitable element type for analyzing thin shell structures. SOLID185 is chosen for solid elements of the feet because this element has plasticity, hyper elasticity, stress stiffening, creep, large deflection, and large strain capabilities. Beam elements are chosen as BEAM189 for its suitability for analyzing slender to moderately thick beam structures [17]. During the meshing of the structure, the shapes of the elements are chosen as quadrilaterals for shells and hexahedral for volumes. The shape of elements for beam is not selectional as the process is in fact creating a mesh for a line. The meshed structure is seen in Fig. 4.

In this study static, modal and harmonic analyses of the satellite structure is performed. In order to estimate the strength of the satellite structure, static analysis is crucial. Tensile and compressive stress values are calculated using static analysis and compared with the yield strength of the materials used in construction of the structure. Moreover, in order to discover the natural frequencies and mode shapes of a structure, modal analysis is required for dynamic loading conditions. It is also the first step for harmonic response analysis, which is carried out to determine possible maximum stress on structure.

IV. RESULTS and DISCUSSION

Static analysis, modal analysis and harmonic analysis results of ITUpSAT1 structure are presented. Stress and displacement values for vertical arrangement evaluated in static analysis of the structure are plotted in Figs. 5 and 6, respectively.

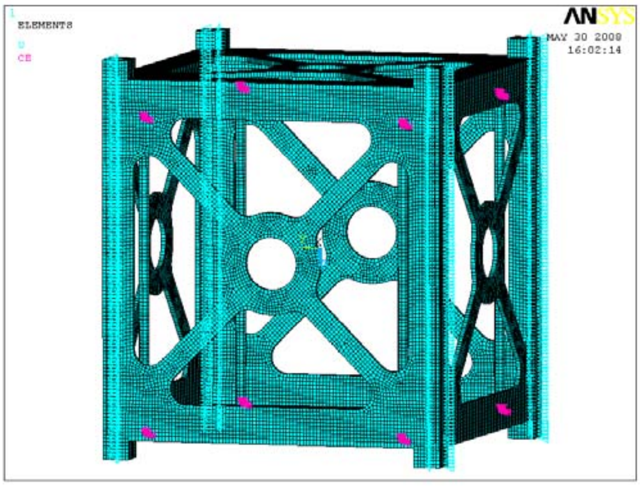

Fig. 4. Meshed CubeSat structure.

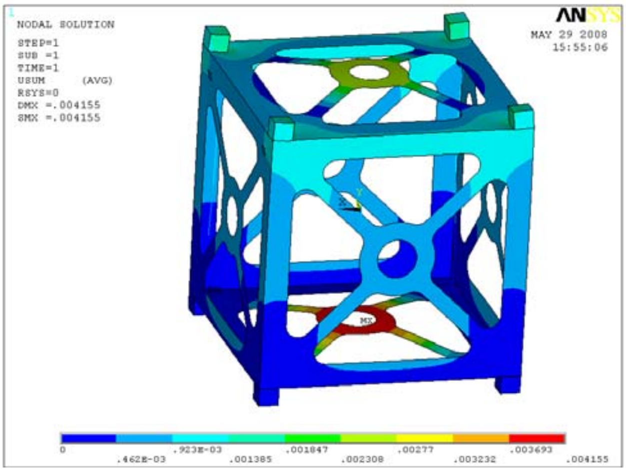

Fig. 6. Displacement values of the ITUpSAT1 structure in vertical arrangement.

As seen in Fig. 5, the greatest Von Mises stress values are observed to be 5.059 MPa at intersection points of feet and top-bottom faces as well as side faces. This result is well below 193 MPa and 276 MPa which are the yield strengths of aluminum alloys 5052-H32 and 6061 that are the materials used in the construction of these areas. The greatest displacement values are observed on the top face and are found to be about 0.004 mm, Fig. 6. This result can be accounted for the thickness of top-bottom faces which is about 0.25mm thicker than side faces. The difference between stress values of top and bottom halves of the side faces is thought to be a result of pressure generated by the spring. Figures 7 and 8 shows stress distribution and displacement values for horizontal arrangement, respectively. The maximum stress value found in this analysis is similar to the one found in vertical arrangement analysis. However there is a significant difference between the two arrangements in displacement values. In case of vertical arrangement the top and bottom faces are exposed to the gravitational acceleration, Fig. 6, while in the horizontal case, side faces are most affected, Fig. 8.

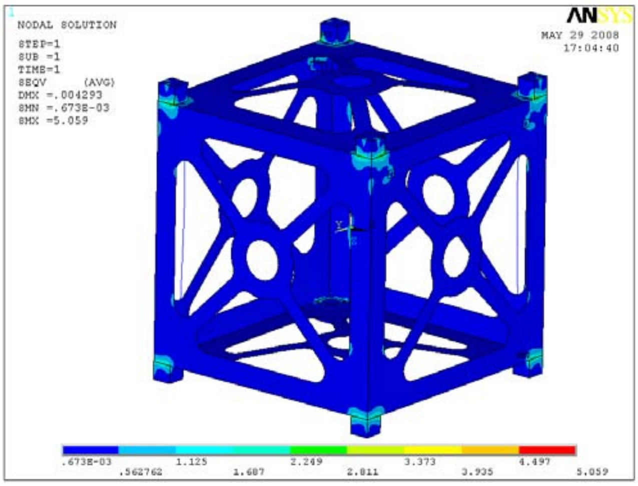

Fig. 5. Stress distribution of the ITUpSAT1 structure in vertical arrangement

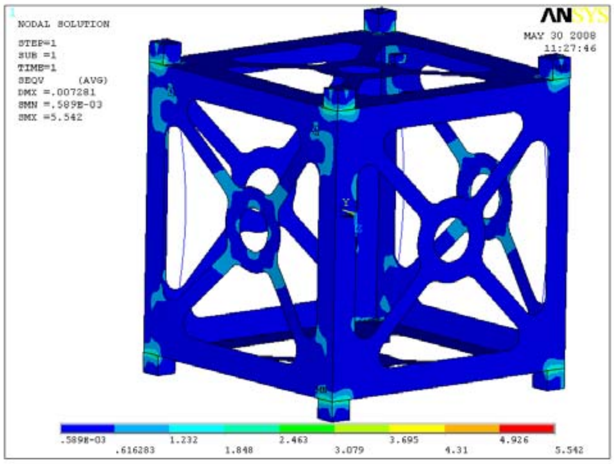

Fig. 7. Stress distribution of the ITUpSAT1 structure in horizontal arrangement.

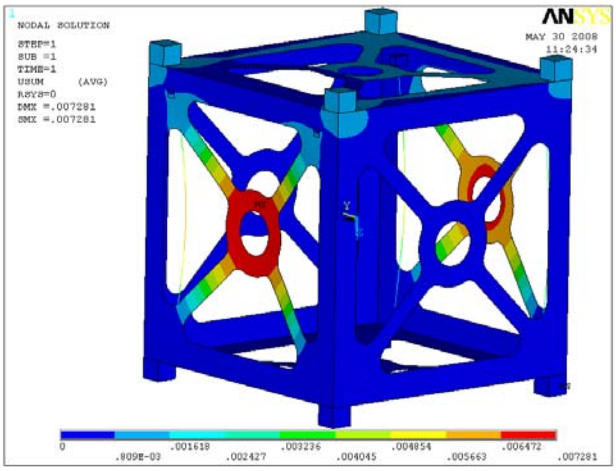

Fig. 8. Displacement values of the ITUpSAT1 structure in horizontal arrangement.

The natural frequencies in the range of 0 to 2000Hz are found as a result of modal analysis and all 26 modes are shown in the Table I. There are some similarities in the different modes of vibration due to the almost full symmetry in the geometry of the structure. The modes of vibration for first and last modes are shown in Fig. 9 and 10. According to the user's guide of Polar Satellite Launch Vehicle, the payload of launch vehicle has to be designed with a structural stiffness which guarantees that the values of fundamental frequencies of the auxiliary satellite at the launch vehicle interface are not less than 90 Hz in the longitudinal axis and 45 Hz in the lateral axis. In order to prevent a resonance, the natural frequencies calculated by the analysis must be above these constraint values. The first natural frequency of ITUpSAT1 structure is found to be 633.25 Hz which is well above the minimum fundamental frequency constraint of the launch vehicle and the last one is 1948.3 Hz.

TABLE I

Natural Frequencies of the ITUpSAT1 Structure in ANSYS

Mode	Natural Frequencies(Hz)	Mode	Natural Frequencies(Hz)
1	633.25	14	821.84
2	639.74	15	1605.1
3	639.81	16	1607.8
4	639.89	17	1616.0
5	726.44	18	1628.1
6	727.07	19	1660.0
7	727.72	20	1662.2
8	729.50	21	1662.3
9	750.30	22	1667.4
10	751.16	23	1930.0
11	751.82	24	1940.6
12	752.42	25	1944.8
13	810.13	26	1948.3

In first mode, bending occurs dominantly toward two directions, as tensile in both of X and Y axes. Bending occurs similarly for 2nd, 3rd and 4th modes that are dominant just for one direction because of the symmetry of the model in four side faces. The bending that occurs in shells, is in X and Z directions and there is not any bending in Y direction and it occurs dominantly in all beams, in 5th mode. In modes from 6th to12th, natural frequency values are very close to each other and bending happen in beam parts of the satellite. The bending in 13th mode occurs just in Z direction of CubeSat, also bending in top is bigger than the bottom. However, in the same case for 14th mode, bending in bottom is bigger than the top. There are two bendings (one tensile and one compression) occurred in side faces in modes from 14th to 26th. The natural frequencies increase suddenly in these modes. For example in the 26th mode, two bendings occur as a tensile and compression in Z direction dominantly and in addition in Y direction slightly, as shown in Fig. 10.

After modal analysis, harmonic analysis of the satellite structure was carried out for the vertical alignment of the satellite. Seven natural frequency modes are selected for the harmonic analysis and damping ratios for each natural frequency is calculated using the following formula [11]:

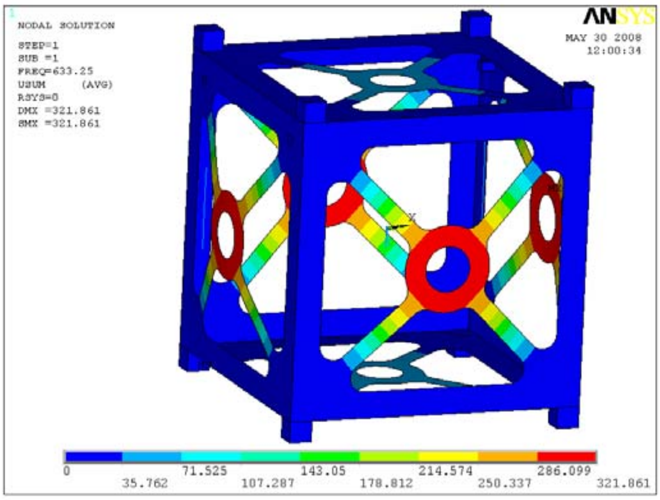

Fig. 9. First mode of ITUpSAT1 structure.

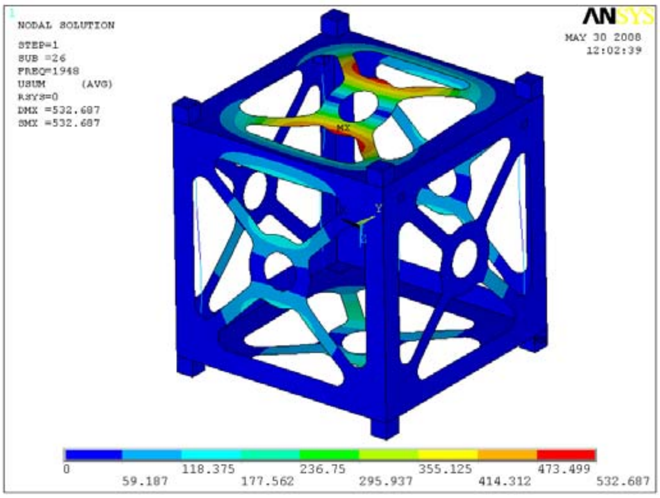

Fig. 10. The 26th mode of ITUpSAT1 structure.

$$\xi = \frac{1}{10 + 0.05 f_n}$$

where ξ is the damping ratio and f_n is the natural frequency in Hertz. Table II shows the results of harmonic analysis. Maximum stress values and maximum displacement values are shown with damping ratios for natural frequencies.

TABLE II

Harmonic Analysis Results

Natural Frequency (Hz)	Damping Ratio	Maximum Harmonic Stress (MPa)	Maximum Displacement (mm)
639.81	0.0240	4.833	0.0111
727.72	0.0215	4.921	0.0213
751.16	0.0210	5.785	0.0280
821.84	0.0195	7.206	0.0567
1616.0	0.0110	5.310	0.0016
1662.2	0.0107	5.390	0.0027
1944.8	0.0090	5.441	0.0038

As seen in TABLE II, maximum harmonic stress for the satellite structure is found to be 7.206 MPa. If it is assumed that the maximum stress evaluated by static analysis, which is 5.059 MPa, and the maximum stress evaluated by the harmonic analysis are positioned at the same node, then total maximum stress the structure will be exposed to would be 12.265 MPa. Again we can easily state that the materials' yield strengths are strong enough to handle the loads satellite will encounter.

V. NATIONAL RESOURCES for MANUFACTURING

As the local manufacturing of CubeSat structure is planned, the national capabilities towards it are examined. Sheet metal processing is commonly handled in Turkey. Automotive industry, appliances' industry are some of those who make extensive use of sheet metal based production. A quick survey conducted in Istanbul region has shown that the technological infrastructure is present to manufacture a CubeSat main structure that is similar to that of Pumpkin Inc. Rev C or D. These capabilities include:

- Sheet metal bending and folding in high temperatures
- Hard metal bonding or punching into sheet metal
- Laser cutting
- Wire EDM Machining
- High resolution water jet cutting
- Various CNC machining
- Aluminum dying and anodize

An important shortcoming is purchasing of locally manufactured material for space applications. However, a number of high technology companies of various sizes are able to import such material. Moreover, composite manufacturing and processing techniques are being increasingly developed, as well.

Nonexistence of national companies with space heritage is another serious drawback.

ACKNOWLEDGMENT

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