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FEM STUDIES ON INCREMENTAL FORMED AND MACHINED SATELLITE STRUCTURES

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ABSTRACT

The satellite structure should have high strength to withstand the harsh conditions resulting from the transient dynamic loads of low frequency, during the initial period in the launch phase. Satellite structures of similar shapes, manufactured by similar manufacturing processes, but made of different class of aluminum, have similar vibration behavior. However, for satellite structures manufactured by different manufacturing processes, it becomes necessary to study and analyze the structures to determine their vibration behavior. In this paper, the dynamic behavior of three identical satellite structures (two formed and one machined), has been analyzed and compared using the Finite Element Method. Incremental forming and machining have been selected as manufacturing methods. We have used the analysis results for qualification of design and the manufacturing methods, without performing the costly vibration tests. The results show the superiority of the formed structures from the vibration behavior point of view. The results also demonstrate the viability of forming as possible replacements for the machining process, with potential for cost reduction.

Keywords: Mode shape, Natural frequency, Incremental forming, Satellite structure.

1. INTRODUCTION

Satellite structure must be designed to support the internal and external components of satellite and bear their weight [1]. In addition, it must withstand the static and dynamic structural loads during the satellite launch and separation from the launcher [2, 3]. The two primary requirements of any satellite structure are; a minimum possible weight, and an ability to bear the structural vibration loads. In addition to these primary requirements, the satellite structure must fulfill two basic requirements in accordance with the launcher Interface Control Document (ICD) [4]:

- The first natural frequency, along the lateral direction, and the satellite axis, should be higher than 20 Hz, and 30 Hz, respectively.
- All the safety margins for the satellite design loads should be positive.

Factors such as system characteristics, rigidity of the matrix, and structure mass, affect the natural frequencies and mode shapes in a satellite structure. Therefore, measurement of the variations in natural frequencies and mode shapes may be used to determine the intensity and locations of structure failures.

Cawley and Adams [5], and Adams et al. [6], used natural frequencies for identification of location, and estimation of failure intensity on the basis of ratio of variations in the natural frequencies of two mode shapes of a structure unit. Stubbs and Osegueda [7] used natural frequencies, and measured the changes in mode shapes to study the structural failures. Ren and Roeck [8] have used natural frequencies and mode shapes for visualization of failure in given structures. Also in recent years, several studies have been devoted to incremental forming. Kim and Yang [9] studied the improvement of formability for the incremental sheet forming process. An approximate deformation analysis and FEM analysis for the incremental sheet metal using a ball has been developed by Iseki [10]. Shim and Park [11] studied the formability of aluminum sheet in incremental forming. Filice et al. [12] studied and analyzed the material formability in the incremental forming.

Hemati et al. [13] have previously shown that satellite structures of similar shapes, manufactured by similar manufacturing processes, but made of different materials (Al6061, Al7075), have similar vibration behavior. However, for satellite structures manufactured by different manufacturing processes, it becomes necessary to study and analyze the structures to determine their vibration behavior.

In this paper, the dynamic behavior of three identical satellite structures, manufactured by incremental forming and machining methods, has been analyzed using the Finite Element Method. The results for the two manufacturing methods have been compared to evaluate the better method for manufacturing of satellite structures.

2. THE SATELLITE STRUCTURES

Figure 1 shows the geometrical models of the three satellite structures (A, B and C), which differ only in their lateral plates and manufacturing methods. In model A, weighing 38.45 kg, the lateral plates are machined, whereas in models B and C, the lateral plates have been formed by incremental sheet metal forming process. Structure A is manufactured from 2mm thick Al7075 lateral plates, and has 0.5 mm pocketing on both sides. Structure B, which weighs 36.72 kg has 1.5 mm thick lateral plates. Structure C weighs 36.12 kg, and has 1 mm thick lateral plates. Structures B and C are manufactured from Al6061. The material selection has been influenced by the fact that Al7075 is highly machinable, while Al6061 yields itself well to the forming process.

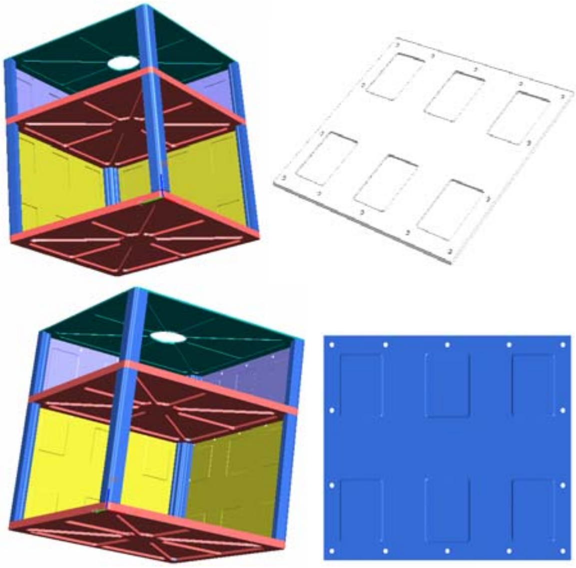

Fig 1: (up) Machined structure A, (down) Model for the formed structures B and C

3. MODAL ANALYSIS THEORY

The modal analysis specifies the natural frequencies and mode shapes. The principal equation for FEM analysis and normal modes is [2]:

$$[M]\{\ddot{x}\}+[K]\{x\}=0 \tag{1}$$

here $\{x\}$ is displacement vector of n degrees of freedom, $\{\ddot{x}\}$ is acceleration vector of n degrees of freedom, [K] is the stiffness matrix, and [M] is the mass matrix.

Two methods are used to derive the mass matrix: the lumped mass method, in which element mass is applied to the nodes as concentrated mass (this matrix is diagonal and non-coupled), and the coupled mass method, in which the mass matrix is calculated using the following equation:

$$[M]=\int N^T N\rho\, dV \tag{2}$$

where N is the shape function matrix, ρ is the density, and dV is the element volume.

The harmonic solution for Eq. (2) is given as:

$$\{x\}=\{\phi\}\sin\omega t$$

Thus, the following equation can be formulated:

$$\left([K]-\omega^2[M]\right)\{\phi\}=0 \tag{3}$$

If $\lambda=\omega^2$, Eq. (3) can be changed to the Eigen value problem:

$$\left([K]-\lambda[M]\right)\{\phi\}=0 \Rightarrow \det\left([K]-\lambda[K]\right)=0 \tag{4}$$

Finally, the natural frequencies of structures were calculated using the following equation:

$$F_k=\frac{\omega_k}{2\pi}=\frac{\sqrt{\lambda_k}}{2\pi} \tag{5}$$

4. FEM ANALYSIS

We have used CATIA software to construct the geometrical models of the three satellite structures. For the FE model, the preprocessor used is PATRAN software, and NASTRAN software has been used as the postprocessor.

The nodal scheme and number of elements used for construction of the models are very important. Sufficient number of elements has been considered for the accurate presentation of the mode shapes. The elements consist of square elements for modeling of the plates, mass elements for modeling of internal equipment and units, and beam elements for modeling of the satellite connections.

The structures are connected to the launcher by the main plate at the bottom of the lower module, with 10 bolts in a circular pattern. Using mass elements, the communication and electronic units, weighing 11 kg, are modeled in the lower module, while the two battery packages of 3.5 kg each and the Gravity Gradient Boom, weighing 4 kg are modeled in the upper module.

We have considered structures A and B. Figures 2 and 3 show the FEM models for these structures. Models for structure C are similar to those of Fig. 3. Since the two models B and C are similar in configuration and manufacturing method, modal analyses were performed only for the two structures A and B. The modal analysis of the structures was performed on the basis of two materials with mechanical properties shown in Table 1.

Table 1: Materials properties [13,14]

Material	E (GPa)	ρ (Kg/m3)	ν
Al 7075	72	2770	0.33
Al 6061	69	2770	0.33

Figures 4 and 5 show the mode shapes of the effective normal frequencies for the lateral plates of satellite structures A and B. As shown, in the first mode the amount of displacement for structure B is less than that of structure A, and the middle plate vibrates in an up-down fashion. In the second mode, shape of displacement is similar but amount of displacement for structure B is less than that of structure A. In the seventh mode, maximum displacement in structure A is 1.7 mm, and in structure B is 1.1 mm. In the ninth mode maximum displacement in structure A is 2.13 mm, and in structure B is 1.69 mm.

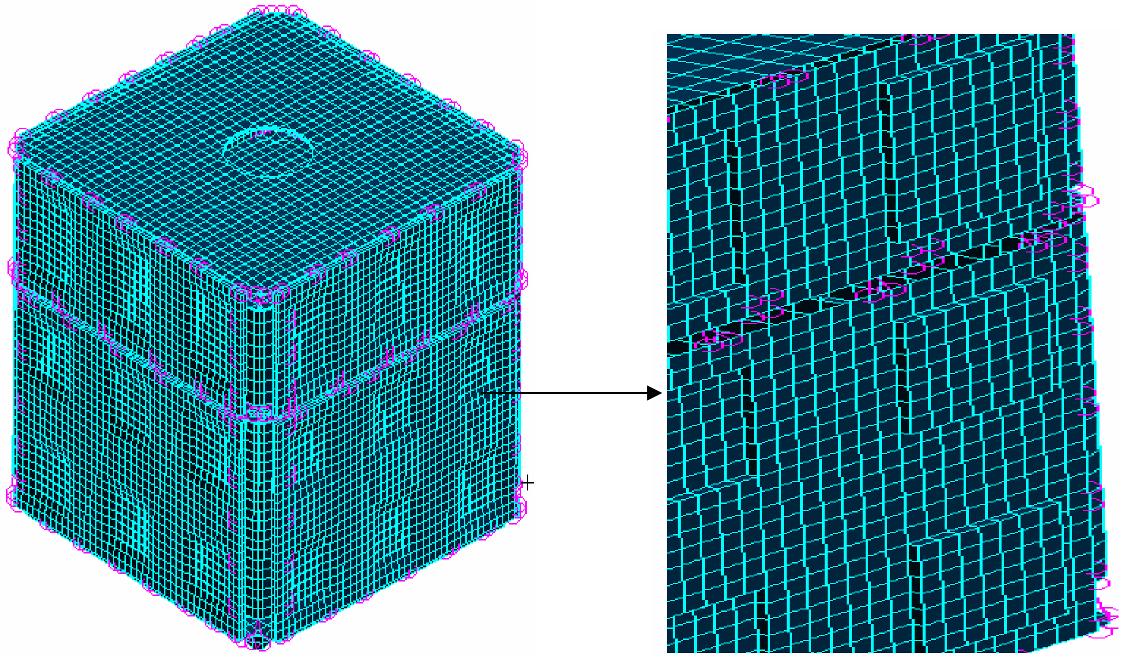

Fig 2: Geometrical and FEM models of the machined structure A

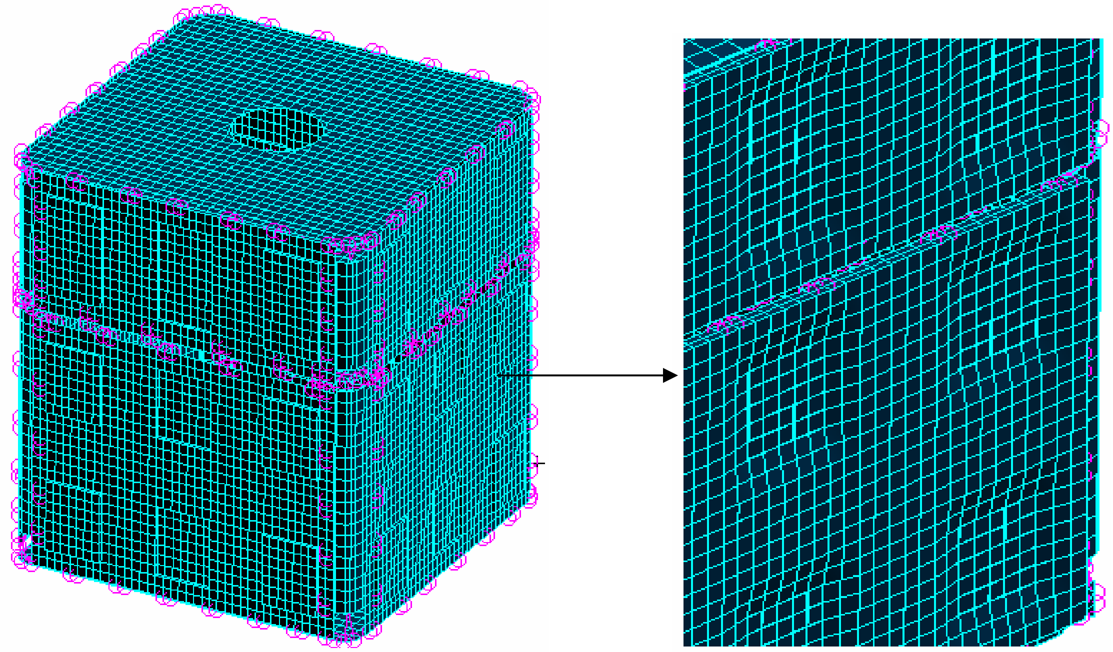

Fig 3: Geometrical and FEM models of the formed structure B

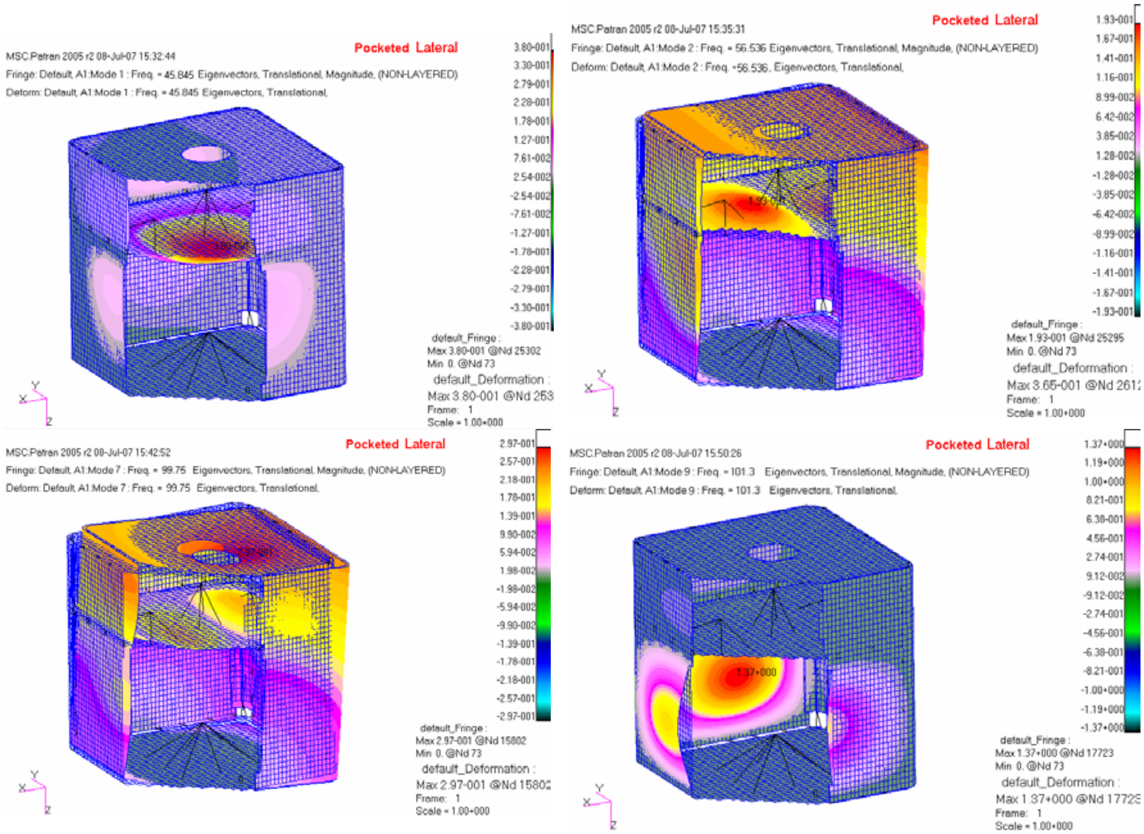

Fig 4: Mode shapes of the effective normal frequencies for the lateral plates of satellite structure A

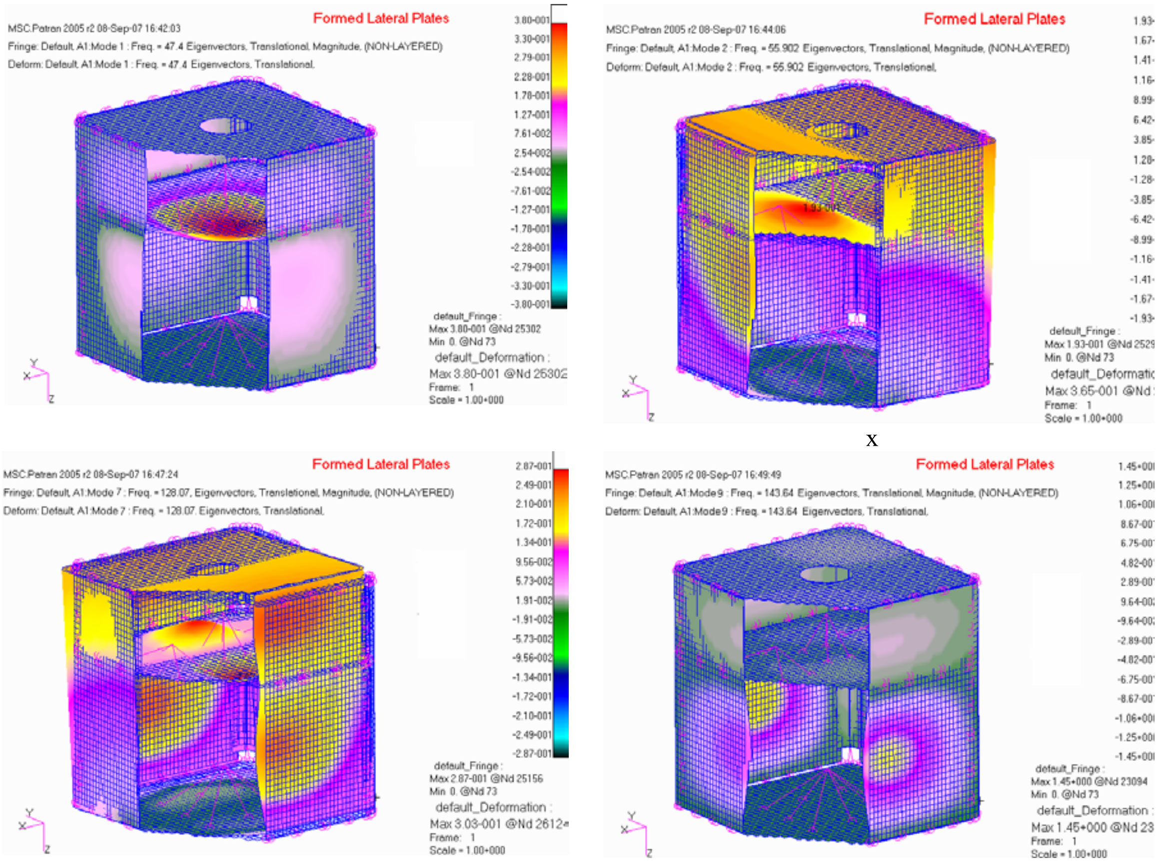

Fig 5: Mode shapes of the effective normal frequencies for the lateral plates of satellite structure B

Comparison of normal frequencies of the three structures for 20 modes is shown in Fig. 6. It is clear that for modes higher than four, the formed structures (B, C) have higher normal frequencies than the machined structure (A).

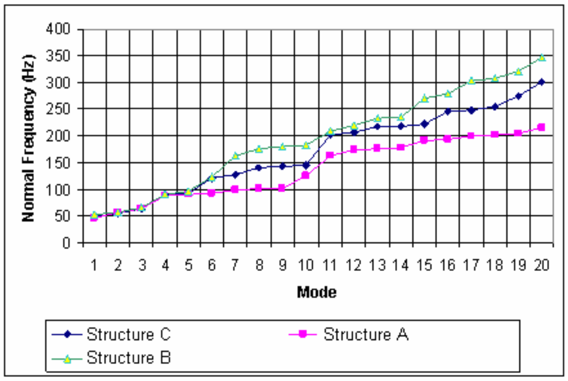

Fig 6: Comparison of normal frequencies of the three structures for 20 modes

Our analysis shows a reduction in the weight of the incrementally formed structure B of about 2 kg as compared to structure A. Therefore, on the basis of the normal frequencies of the two structures (Fig. 6), and the mode shapes of the effective normal frequencies of the two, it may be concluded that the vibration behavior of the incrementally formed satellite structure B is better than that of the machined satellite structure A. Also the incrementally formed structure C weighs 2.6 kg less than the machined structure A. Also, the analysis results (Fig. 6) for structure C show an increase in the vibration modes after the forth mode. The mode shapes of structure C are similar to those of structure B, but the displacement values are lower than those of structure B. Therefore, on basis of the effective mass distribution in vibration modes, the displacement of lateral plates in model C is considerably lower than that of model B. Also, the work hardening during bending of Al6061 sheets acts to strengthen the material, which increases safety margins.

5. RESULTS

- The results of the analysis show that the formed structure C configuration has a better vibration behavior compared with the other two configurations.
- On basis of the effective mass distribution in vibration modes, the displacements of lateral plates in models B and C are considerably lower than that of model A.
- Lower volumes of material used and less manufacturing cost in forming of Al6061 sheet are notable advantages over machining of *Al7075*.
- The work hardening during bending of Al6061 sheets acts to strengthen the material, which increases safety margins.
- Machining process has negative effect as far as strength is concerned.
- The analysis results demonstrate the suitability of the FEM software for qualification of the design, prior to manufacturing of the structure, which will avoid the performance of expensive tests.
- Replacement of machining process by forming process for other satellite elements shall be studied and evaluated as the future work.

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