Dynamic Analysis of Satellites Used for Side-Airbag System

C Gozman-Pop, D Simoiu, I Crăciuță, E Nyaguly, E N Oanță and L Bereteu*
Mechanics and Materials Strength Department, Politehnica University Timișoara, Bd. Mihai Viteazul, nr. 1, 300222, Timișoara, Romania

*Corresponding author: liviu.bereteu@upt.ro

Abstract. Satellites are mechanical components that make the interface between the outside environment and the Electronic Central Unit (ECU). The Electronic Central Unit receives signals from the satellites it interconnects with environment. The signals are given, after a collision, by capacitor-type accelerometers. The multiple caps of the condenser are connected to a seismic mass and elastic element, thus achieving a vibrating mechanical system with a single degree of freedom. The deceleration produced during the collision generates displacements of the movable armatures of the capacitor, proportional to the value of this decay. This analogy signal is modulated and transmitted to the ECU. For correct processing of the acceleror signal, the bearer's frequency must be not allowed. For these reasons, a dynamic analysis of the accelerometer support satellite is performed. Dynamic analysis involves a finite element mesh for the use of the Modal Analysis Method in order to determine the resonance frequencies. In this paper we will analyze the influence of the different geometric types of finite elements, which, combined with the effects given by the nature of the component materials and the disagreement of the satellite, will lead to the requirements imposed in the limitations of the low resonance frequency values.

1. Introduction
In a broad sense, a sensor is a device or module that detects and responds to physical input phenomena from the outside environment characterized by specific sizes. These input sizes can be given by movement (displacement, velocity, acceleration, temperature, light, pressure, humidity or others in the multitude of physical phenomena. The answer is sent in the form of electrical signals to electronic device, usually ECU or the processor of a computer.

With the need to increase passenger safety, more means of protection have developed. The airbags are an important roll of these. During collisions, large decelerations occur in a short period of time [1]. Therefore, the command of opening the airbags gives it a category of sensors called accelerometers. There are several physical phenomena that underlie the operation of accelerometers. The most known are piezoelectric accelerometers. In the last three decades, with the development of technological processes, the production of Micro-Electro-Mechanical Systems has taken place. Based on these technologies, condenser type accelerometers could be produced [2]. The silicon-based capability of a MEMS capacitive sensor enables mass production at low cost due to mature technology on surface micromachining [3]. In recent years, various techniques have been developed to study MEMS capacitive accelerometers to optimize their performance and robustness [4]. The purpose of the paper is to perform an FEA analysis of a type of satellite that incorporates a MEMS capacitor accelerometer and validates the results based on the dynamic analysis of its behavior.
2. Capacitive MEMS Accelerometer

The simplest capacitive sensor consists of two parallel-plate between which is a dielectric material, which can even be the air. Capacitance $C$ of the capacitor formed by the two armatures is expressed by the known relationship:

$$
C_0 = \varepsilon_0 \varepsilon_r \frac{A}{d} = \varepsilon \frac{A}{d} \quad (1)
$$

where $\varepsilon_0$ is the permittivity of the air, $\varepsilon_r$ is the relative permittivity of the dielectric, $A$ is the area of the plates, and $d$ is the distance between them. Changing any of the three parameters leads to capacity modification and consequently each of the three variables can be used as sensitive capacitor elements. A MEMS condenser type accelerometer is schematically represented in the figure 1. The central part is a proof mass and when acceleration is applied to the reference frame, the proof mass has an opposite movement. This means that between the fixed plates and the movable plate, two capacitors of variable capacities $C_1$ and $C_2$ are formed as in the figure 1. In fact, every accelerometer has lots of condenser sets. In the equilibrium position of the mobile plate, $x = 0$, therefore the two capacitors will have the same capacitance $C_0$. By neglecting the end effects, the two variable capacitors will have the capacities given by the following relations [6]:

$$
C_1 = \varepsilon_0 \varepsilon_r \frac{A}{d - x} = \varepsilon \frac{A}{d - x} = C_0 + \Delta C; \quad (2)
$$

$$
C_2 = \varepsilon_0 \varepsilon_r \frac{A}{d + x} = \varepsilon \frac{A}{d + x} = C_0 - \Delta C. \quad (3)
$$

The movable plate $x$ displacement results due to acceleration movable mass and, there is a difference between the two capacities, which is

$$
C_1 - C_2 = 2\Delta C = 2\frac{x}{d^2 - x^2}\varepsilon A. \quad (4)
$$

If the difference capacities $\Delta C$ is measured, the displacement $x$ can be determined from the following algebraic equation of the second degree

$$
\Delta Cx^2 + \varepsilon Ax - \Delta C d^2 = 0. \quad (5)
$$

In micromechanical systems the capacities are very low, then for small movements the term $\Delta Cx^2$ can be neglected. From the equation (4) can determine the displacement $x$ [7-8]
This means that the displacement is approximately proportional to the capacitance difference $\Delta C$. On the other hand, if one takes account of Hook’s law for elastic element, and write Newton's second law for moving mass

$$ma = kx = k \frac{\Delta C d^2}{\varepsilon A}.$$  

(7)

It is found that acceleration is a measure of the difference $\Delta C$ in capacities of the two variable capacitors.

The total electrical charge on the movable plate is zero, which gives to the next relationship between the potentials and capacities

$$(V_i + V_o)C_1 + (V_1 - V_0)C_2 = 0.$$  

(8)

From this relationship, the potential of the mobile armature $V_x$ is determined

$$V_x = \frac{C_1 - C_2}{C_1 + C_2}V_0 = \frac{\Delta C}{C_0}V_0.$$  

(9)

Replacing the difference $\Delta C$ from equation (7) to equation (9) is obtained

$$V_x = \frac{m a}{k d}V_0.$$  

(10)

It can be seen from the equation (10) that if an oscillator gives the square waves $V_0$, at the input of the electric circuit, represented in the figure 2, then the output signal $V_x$ is proportional to the acceleration and has the same waveform as $V_0$. This output voltage gives not only a signal proportional to acceleration but also its sign. The Electronic Central Unit can evaluate this signal and make decision how to act based on this information.

### 3. Finite element analysis

In order to determine the natural frequencies of a G-type satellite, a satellite that incorporates an acceleration sensor, the software provided by ANSYS 13 was used, and the finite element modeling was followed by the Finite Element Analysis (FEA).
In the construction of the mathematical model based on finite elements a three-dimensional (3D) model was used, with geometric elements having the hexahedral shape and each node having three degrees of freedom. For the modal analysis of free satellite vibrations, i.e. the determination of natural frequencies and natural vibration modes, the ANSYS module solves numerically a matrix differential equation of an undamped vibrant system given in the form:

$$\begin{bmatrix} M \end{bmatrix} \{ u \} + \begin{bmatrix} K \end{bmatrix} \{ u \} = \{ 0 \},$$

where $\{ M \}$ and $\{ K \}$ are mass and rigidity matrices, respectively $\{ u \}$ are nodal displacements. In the absence of damping, the vibrations of the nodes can be expressed by harmonic functions such as:

$$\{ u \} = \{ \phi \}_i \cos(p_i t + \phi_i),$$

where $\{ \phi \}_i$ are the eigenvectors and $p_i$ are corresponding natural circular frequencies. The eigenvalues problem leads to solve the determinant:

$$- p^2 \begin{bmatrix} M \end{bmatrix} + \begin{bmatrix} K \end{bmatrix} = 0.$$  

In these case, for the construction of the 3D model, it was chosen the geometry of a solid element named SOLID 186, which is defined by 20 nodes, each having three degrees of freedom representing displacements in three perpendicular directions. This type of finite element exhibits quadratic displacement behavior. A G-type satellite is meshed into finite elements as can be seen in the figure 3 and includes: a housing, a bushing, a Printed Circuit Board (PCB) and a polyurethane potting.

**Figure 5.** First mode in OXY plane for fixed bushing.

**Figure 6.** First mode in OXZ plane for fixed bushing.

The mechanical characteristics of the component materials are as follows: for housing with harness connector the density is 1550 kg/m$^3$, the longitudinal elastic modulus is 9.7 GPa, the Poisson coefficient is 0.3; - for bushing the density is 7,850 kg/m$^3$, the modulus of longitudinal elasticity is 200 GPa and Poisson ratio is 0.3; - for potting the density is 1100 kg/m$^3$, the modulus of longitudinal elasticity is 10 MPa, and the Poisson ratio is 0.3; for PCB, the density is 2 500 kg/m$^3$, the longitudinal elastic modulus is 18.4 GPa, the Poisson coefficient is 0.39.

Figure 5 shows the first mode of vibration in free-free border conditions. This mode has the frequency $f_1 = 2411.8$ Hz and the dynamic deformations occur in the OXY plane. Figures 6, and 7 show two bending modes of vibrations. The first one is located in the OXY plane and has its natural frequency $f_1 = 1130.8$ Hz and the other one is located in the OXZ plane and has its natural frequency $f_2 = 1419.8$ Hz.
4. Experimental technique

To validate the results obtained by the numerical modeling of the dynamic behavior of a satellite, the technique of the resonance diagram method was used. For this purpose an experimental setup was made consisting of the following components: 1 laser vibrometer, 2 shaker, 3 specimen, 4 accelerometer, 5 charge amplifier, 6 function generator, 7 power supply, 8 oscilloscope, 9 computer display and 10 data acquisition board and PC. The function generator has the role of producing a sinusoidal function with the required frequencies and is placed in the experimental chain at the input of the power amplifier to give excitation to the shaker. The vibration generator receives the signal from the power amplifier via the function generator and vibrates the specimen at the given frequency range. To view the excitation signal of the specimen through the shaker, an oscilloscope is used. The signal from the piezoelectric accelerometer enters the charge amplifier and then is applied to the oscilloscope. Given that the mass of the satellite is smaller than the mass of a piezoelectric accelerometer, which would affect the measurement accuracy, a laser vibrometer is used to determine the specimen vibration amplitudes.

![Experimental stand for vibration measurements.](image)

5. Experimental results and conclusions

To obtain the experimental results, the satellite was attached to a shaker in the same way it is attached to the car. An anti-rotation device was also used, so the specimen was vibrated in the vertical direction in the 250-1800 Hz range. The measurement of the amplitudes of the forced vibrations was given by an Ometron type Vibrometer. By rotating the shaker to 90°, measurements were made with the vibrating satellite in the horizontal direction.

The graphical representation of the amplitude values given by the laser vibrometer for the excitation frequencies generated by the function generator is shown in Figure 8. It is the resonance diagram of the satellite. From the measurements, but also from the graph, it results that it has two peaks in the range 250-1800 Hz. The two peaks of the amplitudes determine the frequencies at which the resonances occur. In the OXZ plane the resonance takes place at the frequency \( f_1 = 1087.5 \) Hz, and in the OXZ plane it takes place at the frequency \( f_2 = 1437.5 \) Hz.
Modal Analysis (MA) based on the Finite Element Method (FEM), for the satellite that was the similar boundary conditions to those in the dynamic testing, gives for the two frequencies modes $f_1=1130.8\text{Hz}$ and $f_2=1419.8\text{Hz}$ respectively. Experimental validation of the numerical evaluations obtained by FEA is found.

![Resonant diagram](image)

**Figure 8.** Resonant diagram.

6. **References**

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