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NUMERICAL ANALYSIS AND EXPERIMENTAL SHOCK MEASUREMENT ON A SATELLITE LAUNCHER INERTIAL SENSOR MODULE

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Abstract. *This work describes numerical and experimental shock vibration analyses performed to investigate the accelerations level induced on the inertial sensor module of a satellite launcher. A steel belt is used to assemble two of the rocket's modules, and as the belt is tightened, the tension in the belt is transferred to the structure's skin as localized stresses. A procedure to accommodate the belt, over the modules junction, and distribute the stress load on the structure's skin is through several hammering strikes all over the belt's length. Even though softly applied, the strikes induce shock dynamic loads on the whole structure. These loads were measured in the form of accelerations time-history and the corresponding shock spectrum responses were evaluated. The results called upon the attention for the fact that high amplitudes occur for shock vibrations on certain frequencies, which may damage the rocket's inertial sensor module. The main idea behind the work was to critically evaluate an actual procedure currently used to assemble the vehicle's major subsystems.*

Keywords: *shock, vibration, numerical analysis*

1 Introduction

Designed for the mission of launching small satellites of the order of 150 to 200 kg into low Earth orbit (LEO), the first Brazilian satellite launcher, the VLS system, is a four-stage vehicle in which the first stage is composed of four strap-on boosters around a central core.

The vehicle upper stages are composed of several modules. One of such modules, the so called Equipments Bay, houses the rocket's Mechanical Inertial Sensor (MIS). In several occasions the sensor presented problems which were certainly related to shock induced damage. Since transportation was always carried out with extreme care, there were doubts concerning the entire assemblage procedure, which could be the source of the shock load that caused damage.

This paper presents experimental results obtained from a test that simulates all the steps in the assembly phase involving the Inertial Sensor. Numerical analyses of the shock induced loads show excitations with great potential to have caused the observed damage in the sensor.

2 The Experiment

The VLS's third-stage includes the Equipments Bay, Roll Control Bay, a Solid Propellant Motor, a Movable Nozzle, and the Aft Skirt. The Equipments Bay and the Roll Control Bay are joined at an interface section where a steel belt, the dark narrow stripe shown in Fig. (1), is used to hold the module together. The belt is an assembly of several links through which, under tension, there must be a uniform stress distribution all over the interface's circumference. A torque induced tension is applied on two points over the attaching belt, evidently, causing stress concentrations on those regions. In order to have a smooth stress distribution over the entire area underneath the belt, several strikes of a rubber head hammer are applied on the belt, all over its length, aiming to better accommodate the stress loading over the entire circumference of the interface section. Although very softly applied, the hammering on the belt induces shock accelerations on the structure as a whole, and more specifically on the Equipments Bay's supporting plate, which directly receives the strikes. The resulting signals were captured by accelerometers and recorded for the analyses.

The Mechanical Inertial Sensor module is very sensitive to shock vibrations. Shock specifications for this equipment's Acceptance Testing are defined as a half sinusoidal wave with 7.5 g maximum amplitude and total period of 25 ms.

Figure 1: Assembling the steel belt (the dark narrow stripe in the lower part).

The equipments described below were used to perform the experiments:

- Recorder Kyowa RTP772A S/N: 4Y2740007
- Digital Oscilloscope HP 54201A S/N: A558507
- Accelerometers B&K 4371
- Amplifiers B&K 2626

The specimen instrumentation was done according to the Tab.(1), below, and the data that follow.

Table 1: Instrumentation data

Axis	Acel.	S/N	Sens (pC/g)	Amplif.	S/N	Cable	Channel Record
X	B&K 4371	1127574	9,634	B&K 2626	1242330	07M31	#1
Y	B&K 4371	1228823	9,818	B&K 2626	1130195	06M29	#2
Z	B&K 4371	1376382	9,719	B&K 2626	1242328	08M32	#3

- Record Calibration: Input: 5V – Output: 5V
- Reference: 100 mV/g
- Tape: 001/2003

Begins: 0 Ends: end of the tape Veloc.: 38 cm/s WBx2

Accelerometers placed at the supporting plate monitored the entire assembling phase. Hammering the belt induced accelerations on the entire structure. Accelerations occurring over the sensor's supporting plate act as input loads on the sensor itself. These accelerations time-history were captured and their equivalent shock spectra were evaluated. Throughout the belt's assembling procedure measurements were carried out on the longitudinal direction as well as on both transversal directions.

In the recording procedure, the analog signal was filtered to frequencies above 20 kHz. The sampling frequency used was 50 kHz, allowing for shock spectra frequencies up to 3 kHz, along with 1.8 % error in the

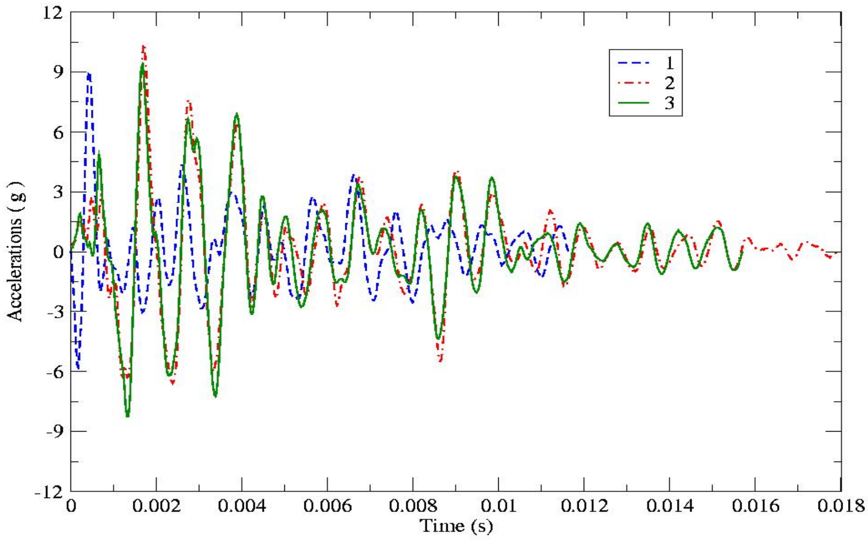

Figure 2: Accelerations in the vehicle longitudinal direction (X).

highest frequencies. On recording the signals, several sets of strikes were imposed on the belt. On digitalizing those signals, only the ones which presented amplitudes higher than 7.0 g (700 mV/g) were computed, and only

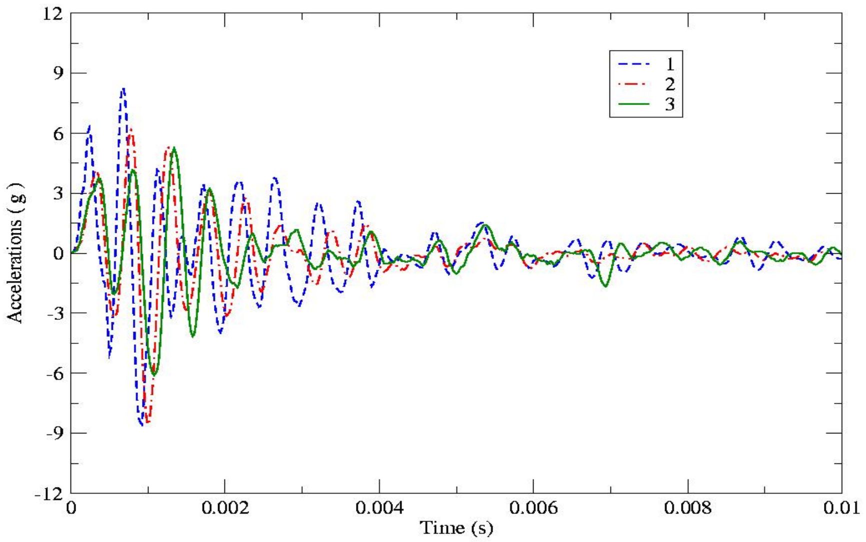

Figure 3: Accelerations in the vehicle transversal direction Y.

three of such sets are presented in Figs. (2, 3 and 4). Notice the short period of the accelerations time-history, 18 ms and 10 ms, which characterize shock induced loads.

The analyses consisted of obtaining the accelerations excitation shock spectra and comparing them to the shock spectra of the acceptance tests accelerations specification for shock, since there was no specification for shock qualification tests.

Figures (2, 3 and 4) present the accelerations induced on the base of the Mechanical Inertial Sensor, due to the hammering on the belt, that presented the highest amplitudes. Notice the accelerations with amplitudes above 9.0 g in the vehicle longitudinal direction, as shown in Fig. (2). These measured accelerations were used to calculate their corresponding shock spectra.

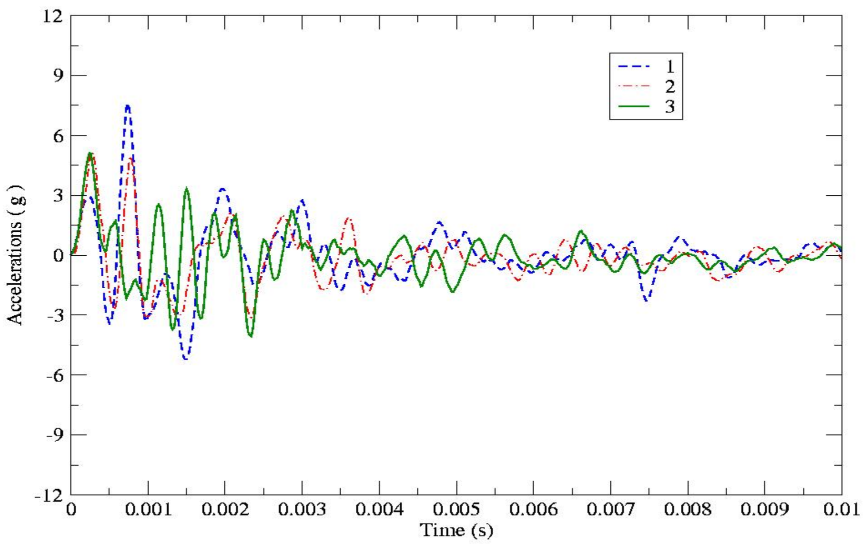

Figure 4: Accelerations in the vehicle transversal direction Z.

3 Numerical Analyses

According to Harris and Crede (1976), a shock measurement is a trace giving the time-history of a shock parameter over the duration of the shock. The shock parameter may define motion, such as acceleration, which is the case studied in this work. However, a shock measurement in the form of a time-history of a motion parameter is not useful directly for engineering purposes. Reduction to a different form is necessary.

3.1 Calculation of Shock Spectrum

The relative displacement response resulting from a shock defined by the acceleration $\ddot{x}(t)$ is given by the Duhamel integral

$$\delta(t) = \frac{1}{\omega_d} \int_0^t \ddot{x}(\tau) e^{-\xi\omega_n(t-\tau)} \sin \omega_d (t-\tau) d\tau, \tag{1}$$

where ω_n is the system's natural undamped frequency, $\omega_d = \omega_n(1-\xi^2)^{1/2}$ is the system's natural damped frequency, and ξ is the damping factor. From a random vibration test the damping factor $\xi = 5\%$ was obtained for this module under analysis.

Once the relative displacement response is obtained, the Response Spectrum is given by

$$A_e q(\omega_n, \xi) = \omega_n^2 \delta_{max}(\omega_n, \xi). \tag{2}$$

The shock spectrum for each curve was obtained and the results are presented and discussed as follows.

4 Results

Figure (5) presents the input spectrum for the Mechanical Inertial Sensor random qualification test. Notice the sensible reduction in the excitation for the frequency range between 700 Hz and 1400 Hz. This is a certain indication that the Inertial Sensor presents high sensitivity to excitations at this frequency range.

However, it can be seen in Fig. (6) that at this frequency range the shock induced vibrations due to the belt's hammering produces the highest response spectra amplitudes, probably indicating the possibility of potential problems. Figures (6, 7 and 8) present the three highest intensity shock spectra calculated for each one of the

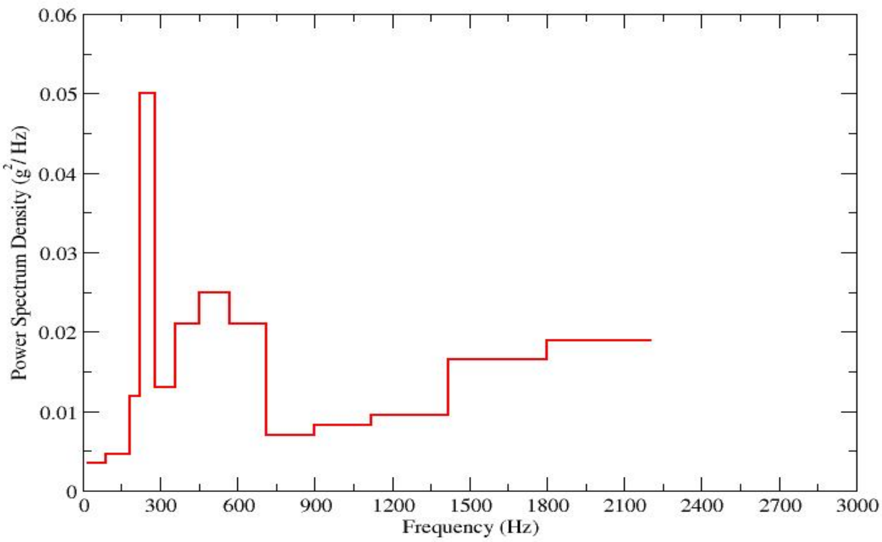

Figure 5: Spectrum for the Random Qualification Tests of the Mechanical Inertial Sensor Module in the vehicle longitudinal direction (X).

directions X, Y, and Z, respectively. Figures (6, 7 and 8) also show the shock spectrum for the acceptance testing accelerations specification for shock (half sinusoidal wave with 7.5 g amplitude and period of 25 ms) with values around to 10 g and a 12 g peak, for frequencies below 150 Hz. However, for higher frequencies the values remain constant and equal to 7.5 g. Nevertheless, results due to the shock induced accelerations present considerably increasing amplitudes for frequencies above 500 Hz, as it can be seen in Fig. (6). The shock response spectra in the vehicle longitudinal direction present values up to 40 g, for frequencies around

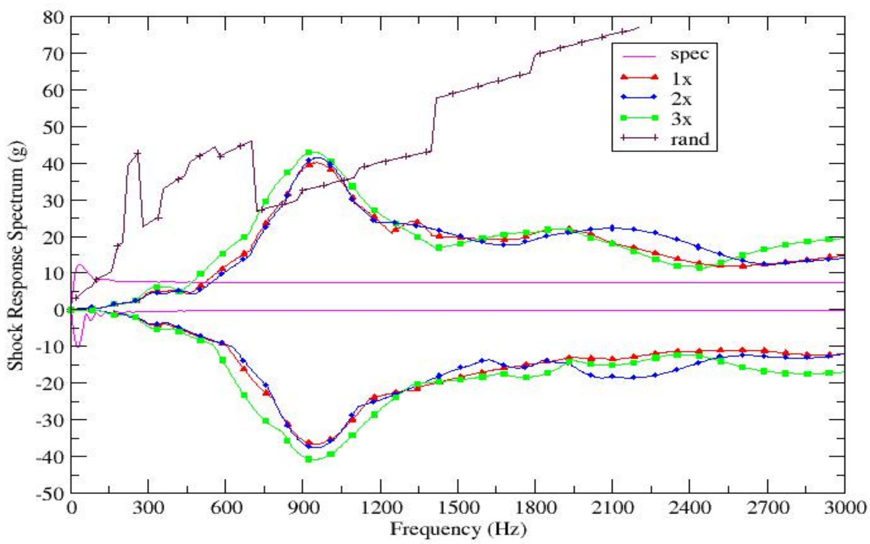

Figure 6: Shock Response Spectra in the vehicle longitudinal direction (X).

1000 Hz. It is interesting to notice that this direction is orthogonal to the plane of excitation. Thus, the large response values certainly indicate excitation of the supporting plate's transverse modes of vibration.

Similar behavior can be observed in the transversal directions Y and Z, however, with high amplitude values mainly for frequencies above 1800 Hz. This fact is due to the plate in-plane high stiffness, which results in the loading excitation inducing vibrations on the higher frequency modes.

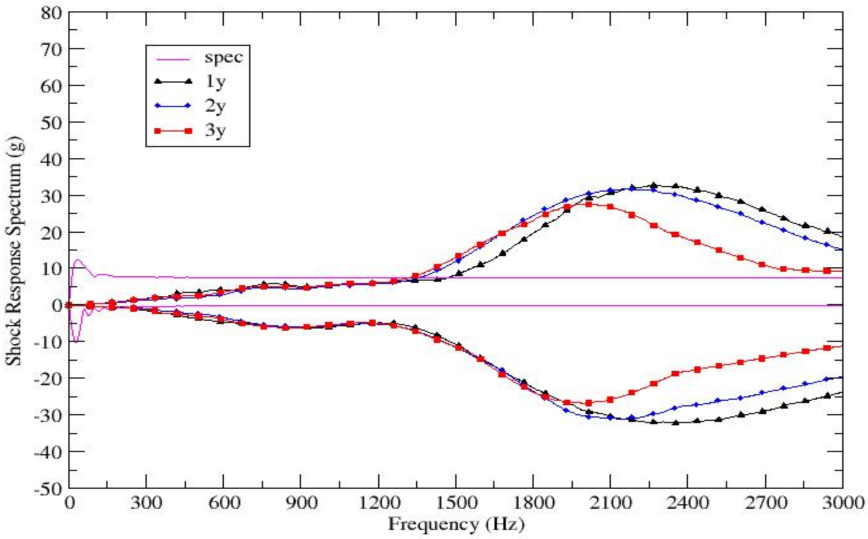

Figure 7: Shock Response Spectra in the transversal Y direction.

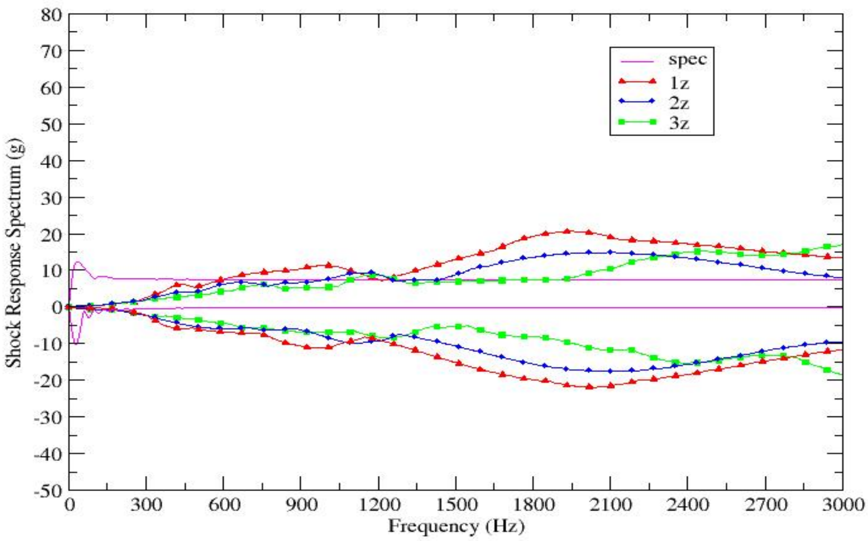

Figure 8: Shock Response Spectra in the transversal Z direction.

5 Conclusions

Accelerations due to shock induced vibration were experimentally obtained. Such excitations are the results of an assembling procedure used to mount the several subsystems of a satellite launcher. More specifically, during the assembly phase of the Equipment Bay and Roll Control Bay, a steel belt is used to attach them together, and a series of hammering strikes are applied all over the belt's length in order to better distribute the stresses imposed on it by a torque induced tension. These excitations are used to calculate their equivalent shock spectra, herein presented. It is very noticeable the amplification of the spectra in the vehicle longitudinal direction X, resulting values much higher than those specified for the Shock Acceptance Testing of the Mechanical Inertial Sensor Module. Actually, for frequencies close to 1000 Hz, these values are very high; looking at the Excitation Spectrum for Random Qualification Testing, Fig. (5), of the same module, a noticeable reduction in load for frequencies between 700 Hz and 1400 Hz is observed, probably indicating a high sensibility of the system to vibrations for that frequency range. Based on these observations the results certainly indicate a source of potential overload of the Inertial Sensor.

Figure (2) shows that the induced excitations already impose high amplitudes accelerations *per se* in the vehicles longitudinal direction, which may go as high as 10 g. However, when studied as shock inputs, due to their nature, the corresponding results show values of up to 40 g in the same longitudinal direction for frequencies around 1000 Hz.

Based on the results herein presented, the assembling procedure involving the Mechanical Inertial Sensor Module must be reviewed and modified. Evidently, the system is subjected to much more severe load conditions during flight; however, throughout the flight the Mechanical Inertial Sensor Module is in operation, which highly increases its capacity in resisting such loads. On the contrary, during the assembly procedures the Mechanical Inertial Sensor Module is more sensible to the types of loads herein presented, since, when in resting condition, the module must be handle with extreme care to avoid any unnecessary stresses on it.

6 References

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7 Responsibility notice

The authors are the only responsible for the printed material included in this paper.