Development of Multi-Physics Dynamics Models for High-Frequency Large-Amplitude Structural Response Simulation

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Abstract: An analytic approach is demonstrated to reveal potential pyroshock-driven dynamic effects causing power losses in the Thermo-Electric (TE) module bars of the Mars Science Laboratory (MSL) Multi-Mission Radioisotope Thermoelectric Generator (MMRTG). This study utilizes high-fidelity finite element analysis with SIERRA/PRESTO codes to estimate wave propagation effects due to large-amplitude suddenly-applied pyroshock loads in the MMRTG. A high fidelity model of the TE module bar was created with ~30 million degrees-of-freedom (DOF). First, a quasi-static preload was applied on top of the TE module bar, then transient tri-axial acceleration inputs were simultaneously applied on the preloaded module. The applied input acceleration signals were measured during MMRTG shock qualification tests performed at the Jet Propulsion Laboratory. An explicit finite element solver in the SIERRA/PRESTO computational environment, along with a 3000 processor parallel super-computing framework at NASA-AMES, was used for the simulation. The simulation results were investigated both qualitatively and quantitatively. The predicted shock wave propagation results provide detailed structural responses throughout the TE module bar, and key insights into the dynamic response (i.e., loads, displacements, accelerations) of critical internal spring/piston compression systems, TE materials, and internal component interfaces in the MMRTG TE module bar. They also provide confidence on the viability of this high-fidelity modeling scheme to accurately predict shock wave propagation patterns within complex structures. This analytic approach is envisioned for modeling shock sensitive hardware susceptible to intense shock environments positioned near shock separation devices in modern space vehicles and systems.

Keywords: Computational Modeling, Nonlinear Dynamics, Shock Waves, Multi-Physics Simulation, Parallel Computing

Introduction

Severe pyroshock environments due to several shock separation devices in the close proximity of the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) were derived for the Mars Science Laboratory (MSL) project. A series of pyroshock tests was performed as part of the multi-mission qualification testing using an Engineering Unit (EU). During the MMRTG engineering unit's pyroshock test, the power output from the system temporarily decreased, but fully recovered after the shock signature subsided. Additional Qualification Unit (QU) testing was performed as part of standard MSL flight readiness preparations. The QU test was performed at JPL by mounting it on the flight MSL rover chassis, where flight-like separation nuts were fired. The results from the QU pyroshock test confirmed that the generator would respond to a flight level pyroshock event with a temporary power drop, although significantly less severe than that experienced by the EU shock test. An effort is underway to understand the root causes of the RTG temporary power losses, and a detailed system fault tree and associated system analyses have been developed to establish specific root-cause and recovery pathways. As part of this effort, the shock-induced structural response within Thermo-Electric (TE) module bars of the system has been modeled, and the results are presented and discussed in this study.

The activation of pyro-shock devices such as separation nuts, pin-pullers, etc., produces high- frequency transient structural inputs and responses to spacecraft power units, typically from few tens of Hz to several hundreds of kHz. Lack of reliable analytical tools makes the prediction and interpretation of appropriate design and qualification test levels a challenge. In the past decades, several attempts have been made to develop methodologies that predict the structural responses to shock environments. However, there is no validated approach that is viable to capture the full frequency range of interest (i.e., 100

Hz to 10 kHz). Some of the important studies include works by [1], [2], [3, 4, 5], [6], [7], amongst others. Conventional modal analysis tools that are used to predict structural responses are applicable only to low-frequency regions (i.e., a few-hundreds of Hz). In order to capture the structural response due to high-frequency wave propagation in electronics components positioned near separation devices, advanced high-fidelity, wave propagation modeling and analysis methods are needed. Shock analysis techniques can broadly be categorized into three approaches: 1) Empirical Models and Scaling Laws, 2) Statistical Energy Analysis, and 3) Finite Element Analysis. Since the approach used in this study is based on finite element analysis, the discussion will focus on finite-element based approaches.

Finite Element Analysis can be used to predict structural response to transient full-frequency dynamic loads. However, in order to capture the high-frequency shock wave propagation, the model has to be meshed into very small elements. Large numbers of elements can lead to computational challenges and long model run times. More importantly, simulating the correct physics for high-frequency wave propagation is a daunting task, and most classical finite element approaches are not feasible to solve this problem [8]. In the recent years, important studies have been published relevant to FEA-based modeling. Ramajeyathilagam et al. studied the non-linear transient dynamic response of rectangular plates under shock loading [9]. Qiu et al. investigated the finite element analysis of the dynamic response of clamped sandwich beams subject to shock loading [10]. Lee et al. analyzed a finite element response of a rotor-bearing system to base shock excitations using the space Newmark scheme and compared it with experiments [11]. Kalman et al. published on the numerical analysis of the dynamic effects in shock-load-induced ice shedding on overhead ground wires [12]. Mace and Manconi modeled wave propagation in 2-dimensional structures using finite element analysis [13]. Liu et al. studied the impact of sand slugs against beams and plates using coupled discrete particle and finite element simulations [14]. Pagani et al. simulated the dynamic response of aerospace structures by means of refined beam theories [15]. Derkevorkian et al. investigated the viability of using advanced computational modeling approaches for shock response prediction [16].

However, there is paucity of high-fidelity computational tools, and corresponding explicit finite element solvers that can potentially be utilized for shock simulation problems of complex structures. One such numerical tool (i.e., SIERRA/Presto) is used in this study to model the TE module bar within a MMRTG structure, and to predict its response to pyro-shock-induced dynamic loads.

Modeling Methodology

An explicit finite element solver, called Presto (part of the SIERRA – Solid Mechanics suite), was used to simulate the dynamic effects due to shock wave propagation in the TE module bar. The SIERRA suite is a Lagrangian, three-dimensional numerical tool developed for finite-element analysis of large-scale multi-physics phenomena. Its explicit dynamics features are designed to solve models that have various contact surfaces and are subjected to large, suddenly applied loads, such as the model and structures under investigation in this paper. Further details on SIERRA's technical multi-physics capabilities can be found in [17] and [18]. The Cubit mesh generation environment, which meshes volumes and solid models for finite element analysis, was used to generate three-dimensional finite element mesh of the TE module bar. Some of the algorithms embedded in Cubit include paving, mapping, and sweeping, to discretize a given geometry into a finite element mesh. More information on Cubit's features is available in [19].

A top view of the TE module bar is shown in Fig. 1. The bar is made of various materials and it consists of multiple springs, contact surfaces, and joint discontinuities. Using Cubit, the module bar was discretized into ~11.5 million elements. About 30% of the elements are tetrahedral elements (used to mesh the interior springs), and the rest are hexahedral elements used to discretize and mesh the rest of the components. The finite element model size was chosen to maximize detail to capture the right physics within reasonable CPU time on the supercomputers at the NASA AMES Research Center. The system loading was applied in two analytic steps. The springs within the model were compressed in the vertical direction by applying a quasi-static pre-load in the gravity direction, before the shock environment was applied as an input to the model. Then, a displacement time-history, derived from a measured 3-dimensional shock acceleration record from a previous qualification test was applied to the model (in all three direction, simultaneously). The acceleration record was measured during the shock qualification test of the Engineering Unit (EU) mentioned earlier. The shock input signatures obtained from EU pyro-firing test were band-pass filtered using Finite Impulse Response (FIR) filter of 20th order to include shock signatures between 500-10000 Hz. The frequencies below 500 Hz were filtered in order to eliminate the low-frequency dynamic effects of supporting structures, such as the steel plate on which the MMRTG was mounted during the shock qualification test. Furthermore, numerically integrated displacements were used as inputs instead of the accelerations, in order to avoid to numerical errors and integration errors that might be associated with the explicit solver. The acceleration time-histories and the corresponding displacements in all three directions are shown in Fig. 2. The displacement time-histories were applied as inputs to the FE model at the short edge of an interface plate located on top of the module bar, to predict the nonlinear dynamic response of the module bar's inner components. The short edge, where the shock displacement record was applied, is shown in Fig. 4b. Non-reflecting surface boundary conditions were applied on the other sides of the top interface plate. The module bar model was placed in between two interface plates at the top and the bottom. The bottom plate was fixed in all directions with no slippage allowed. Several contact surfaces were modeled with frictional force applied within the inner components of the system. A coefficient of friction of 0.5 was assumed. The assumed coefficient of friction will be experimentally verified and will be reported in the upcoming papers. The quasi-static pre-load was applied for the first 5 milliseconds. Then the shock displacement inputs (shown in Fig. 2) were applied. The reaction forces at the bottom of the FE model, as well as the Von Mises stresses at various locations were recovered at the end of the simulation. The total running time was about 60 hours using 3000 processors.

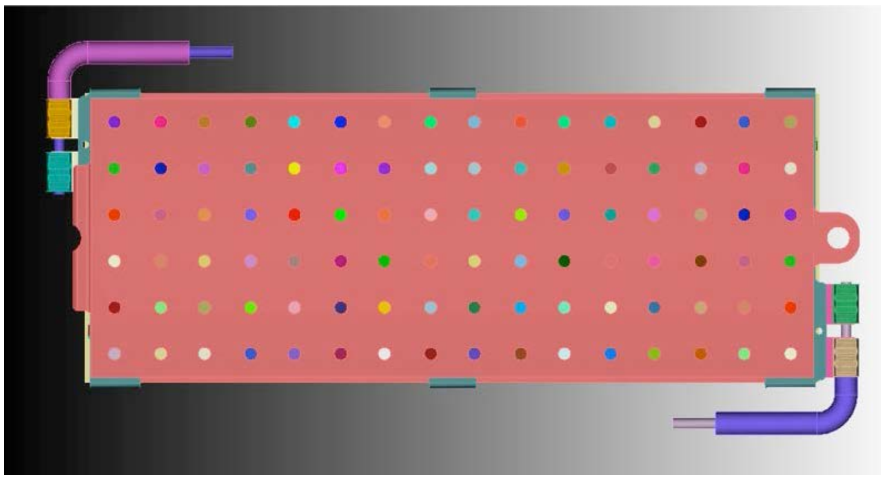

Figure 1: Top view of the TE module bar extracted from the preprocessor, Cubit.

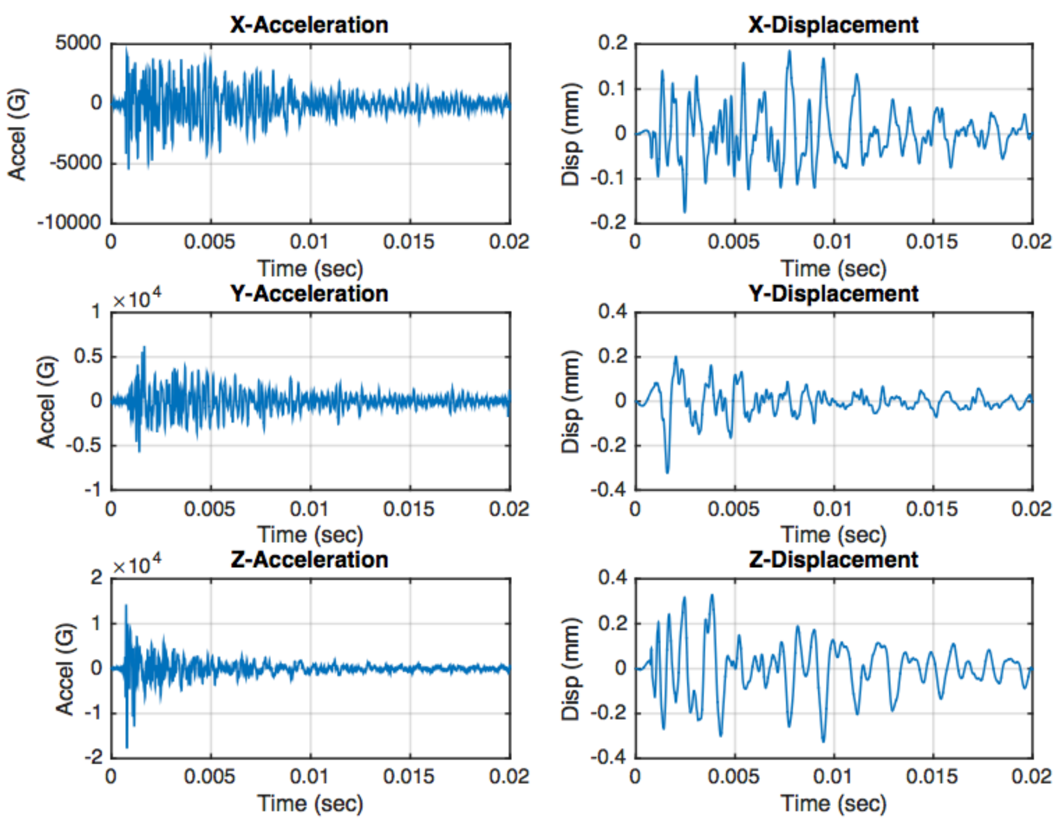

Figure 2: Measured shock acceleration signatures in X, Y, and Z directions (left column), and the displacement signatures obtained by numerical integration (right column).

Numerical Results

The first row in Fig. 3 shows the reaction force in the vertical direction at the bottom of a sample location in the module bar. The second row in Fig. 3 shows the applied vertical displacement at one of the short edges of the interface plate located on top of the module bar (i.e., short edge #1). The locations of the retrieved reaction force and the applied displacement signature are shown in Fig. 4. In the first row of Fig. 3, it is shown that a preload of ~25 Newton is applied as a slowly varying cosine function during the first 5 milliseconds of the simulation. Then, the shock signature is applied as a prescribed displacement, resulting in a maximum reaction force of ~120 Newton at about 6.5 milliseconds. The maximum reaction force corresponds to more than 4 times increase in the initial preload. Another very important observation is that the reaction force becomes zero at multiple instances throughout the simulation (i.e., the spring/piston system in the module bar unloads). This phenomenon was observed in other locations throughout the TE module bar as well, and may potentially be one of the significant reasons that contribute to the overall power drop in the MMRTG. The second row of Fig. 3 shows the applied vertical displacement at one of the short edges of the interface plate on the top of the module bar. The two plots in Fig. 3 are placed after each other to detect potential correlation between the peaks of the applied displacement and the unloading that occurs at the bottom. It is seen that most of the peaks in the pyroshcok displacement signature are correlated, relatively well, with the instances where the reaction force is zero. This observation supports the argument that the spring/piston unloading at the bottom is due to high intensity waves in the input shock signature.

The numerical results were further processed using a powerful postprocessing tool called, Paraview. Sample results are shown in Fig. 4. Figure 4a shows the Von Mises stresses at a sample cross-section in the module bar. The springs shown in the figure are modeled to have friction contacts at the top and the bottom. After applying the quasi-static preload, the springs tilt sideways and contact the interior sidewalls at the top and the bottom. The tilting is due to the asymmetric nature of the springs' ends. The contact of the springs' coils with the surrounding walls during pyroshock dynamic loading/unloading can affect the thermal properties of the TE module bar, which in turn might affect the corresponding power output. The animation of Fig. 4a also reveals that after applying the shock signatures, the springs exhibit a strong response at a frequency of ~ 3 kHz. Figure 4b shows the displacement of the overall module bar with the top and the bottom interface plates. The figure shows significant amount of displacements along the insulation sheet in the middle of the bar. It is seen that the high-fidelity modeling approach adopted in this study reveals important information about the nonlinear dynamic behavior of the inner components of the TE module bar and provides critical insights into potential causes of MMRTG power loses during pyroshock events.

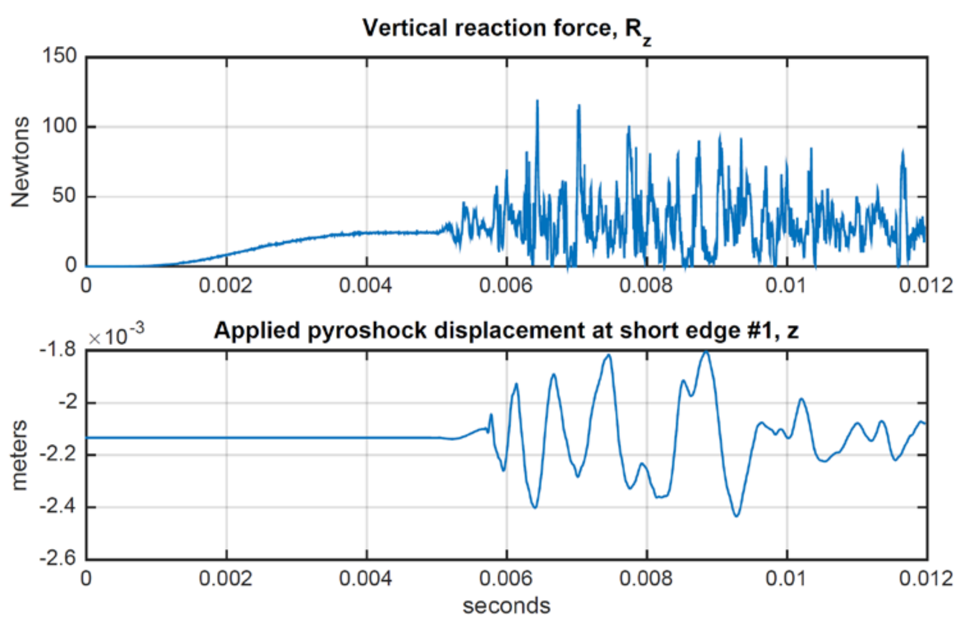

Figure 3: The reaction force (Newton) at the bottom of a sample section shown in Fig. 4 (first subfigure). The displacement (meters) applied during the preload and the pyroshock, at the edge of the interface plate (second subfigure).

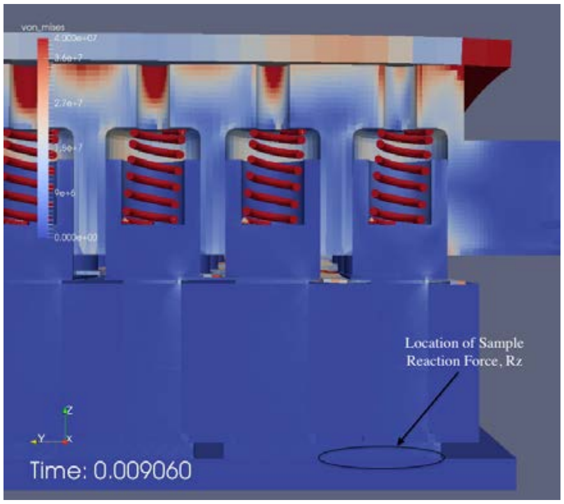

Figure 4a: Von Mises stresses at a sample cross-section in the module bar.

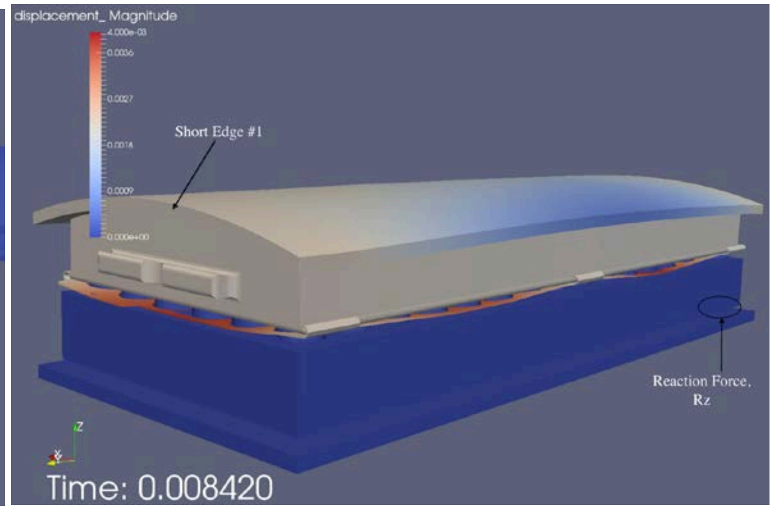

Figure 4b: The displacements at the various sections of the module bar.

Figure 4: Simulation results obtained from the postprocessing tool, Paraview.

Conclusion

This work is part of a large ongoing effort in understanding the risks associated with the output power drop and recovery observed during various levels of MMRTG pyroshock testing. In this study, a finite-element based high fidelity modeling approach is adopted to simulate shock wave propagation in a relatively complex structural system (i.e., the MMRTG TE module bar). The complexity of the system underlies in its multiple contact mechanisms and interfaces and the preloaded interior springs. A sophisticated explicit solver (i.e., Presto) is utilized to estimate the response of the system to transient shock signatures measured from system level shock qualification tests. It is shown that the proposed approach can provide valuable information regarding the structural behavior as shock waves propagate through the system's various components and interfaces. Some of the important findings from this study include the unloading of the reaction force multiple times during the pyroshock event, tilting of the springs during the preload, the unexpected contact between the springs and the sidewalls of the bar during the pyroshock event, and the strong oscillation of the springs at about 3 KHz. These findings were not obvious before the shock qualification test and could not be obtained from traditional modal-based low-frequency finite element transient analysis approaches. These findings are crucial and provide guidance for potential improvements and refinements to the existing design of the MMRTG system and its TE module bars. Performing large-scale multi-physics numerical simulations is associated with certain challenges. Some of these challenges include the physical interpretation of the results (i.e., distinguishing between potential numerical errors and actual physical responses), sensitivity to uncertain input parameters, and the need for significant computational capabilities and run time. Hence, verification and validation is needed to evaluate the efficacy of such tools. A tunable-beam shock testing is currently being planned at JPL to validate the numerical results presented in this paper. Currently, there is a paucity of viable approaches to predict shock wave propagation and the corresponding structural response of complex structures. The approach presented in this study provides an improved method to be considered for high-frequency shock wave propagation predictions.

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