

# Incorporating Vibration Test Results for the Advanced Stirling Convertor into the System Dynamic Model

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The U.S. Department of Energy (DOE), Lockheed Martin Corporation (LM), and NASA Glenn Research Center (GRC) have been developing the Advanced Stirling Radioisotope Generator (ASRG) for use as a power system for space science missions. As part of the extended operation testing of this power system, the Advanced Stirling Convertors (ASC) at NASA GRC undergo a vibration test sequence intended to simulate the vibration history that an ASC would experience when used in an ASRG for a space mission. During these tests, a data system collects several performance-related parameters from the convertor under test for health monitoring and analysis. Recently, an additional sensor recorded the slip table position during vibration testing to qualification level. The System Dynamic Model (SDM) integrates Stirling cycle thermodynamics, heat flow, mechanical mass, spring, damper systems, and electrical characteristics of the linear alternator and controller. This paper presents a comparison of the performance of the ASC when exposed to vibration to that predicted by the SDM when exposed to the same vibration.

## Nomenclature

AC	=	Alternating Current
ASC	=	Advanced Stirling Convertor
ASRG	=	Advanced Stirling Radioisotope Generator
CSAF	=	Cold Side Adapter Flange
DOE	=	Department of Energy
EU	=	Engineering Unit
GPHS	=	General Purpose Heat Source
GRC	=	Glenn Research Center
LM	=	Lockheed Martin Corporation
NASA	=	National Aeronautics and Space Administration
rms	=	Root Mean Square
SDL	=	Structural Dynamics Laboratory
SDM	=	System Dynamic Model
SRG110	=	110 Watt Stirling Radioisotope Generator
TDC	=	Technology Demonstration Convertor

## I. Introduction

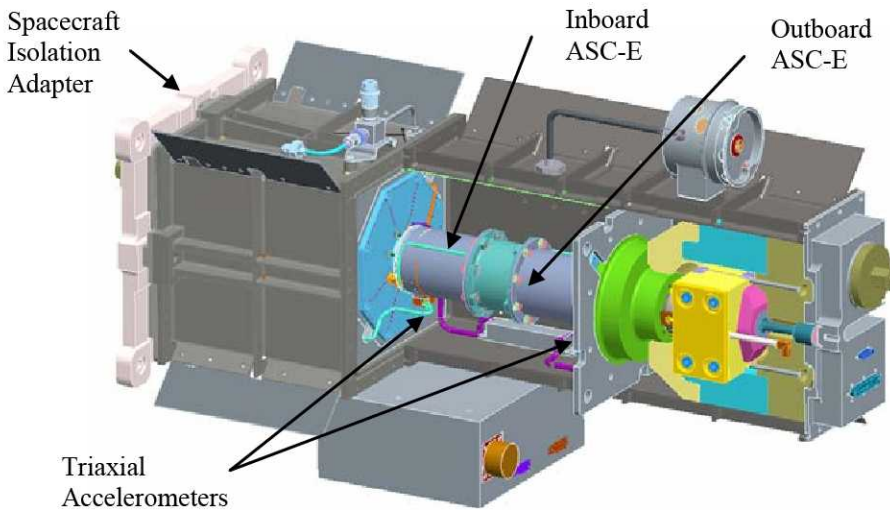
THE Department of Energy (DOE) plans to develop the Advanced Stirling Radioisotope Generator (ASRG) for the National Aeronautics and Space Administration (NASA) for use on future science missions, such as Mars rovers and deep space missions. Lockheed Martin Corporation (LM) Energy Systems of Valley Forge, PA, serves as the system integrator under contract to DOE. Sunpower, Inc., of Athens, OH, is developing the Advanced Stirling

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Convertor (ASC) for the ASRG under a NASA Research Announcement award with NASA Glenn Research Center (GRC) of Cleveland, OH. GRC also provides technology development for the ASC. The ASRG provides substantial efficiency and specific power improvements over radioisotope power systems utilizing heritage designs.

Figure 1 depicts the ASRG Engineering Unit (EU) with part of the outer housing removed to show the internal components. This non-nuclear generator replaces the General Purpose Heat Source (GPHS) modules with electrically powered heat sources to validate the generator's performance. LM assembled the ASRG EU in 2007 and performed system-level testing on the unit in 2008. The ASRG EU uses two Sunpower-designed ASCs inside a beryllium enclosure that acts as structure, radiator, and micrometeoroid shield. The generator housing also supports the two convertors, which a controller synchronizes to minimize the forces generated by the motion of the internal



**Figure 1. Advanced Stirling Radioisotope Generator Engineering Unit cutaway view.**

converter components. The GRC contribution to the development of the ASC comes in project management and supporting technology, including tasks in reliability, high-temperature materials, structures, advanced analysis, organics, permanent magnets, and converter testing.<sup>1</sup>

The GRC has been involved with past work on vibrational testing of Stirling converters. Previous work included dynamic testing of an operating Stirling Technology Demonstration Converter (TDC) to levels required for vibration qualification<sup>2</sup> and vibration modal characterization using base shake input.<sup>3</sup> Most recently, work on the 110-Watt Stirling Radioisotope Generator (SRG110) developed a dynamic model of the generator under vibration, used this model to recommend several improvements to the SRG110 configuration and mounting,<sup>4</sup> and validated the model with experimental results.<sup>5</sup>

GRC also developed the System Dynamic Model (SDM), a non-linear model that simulates Stirling converter system dynamics for systems of arbitrary complexity. Most early Stirling dynamic models developed at GRC and elsewhere generally focused on the Stirling converter and neglected some details of the remaining dynamic system such as the linear alternator and controller.<sup>6-9</sup>

Recognizing the need for a nonlinear system-level dynamic model, GRC developed an end-to-end Stirling converter system model. The SDM includes the Stirling cycle thermodynamics, heat flow, gas, mechanical, and mounting dynamics, the linear alternator, and the controller, enabling the study of complex system interactions and all aspects of a complete Stirling machine with a single, nonlinear, time-domain model. The SDM can simulate the entire range of converter operation, including transient and dynamic phenomena that other models cannot, from startup to full power conditions.

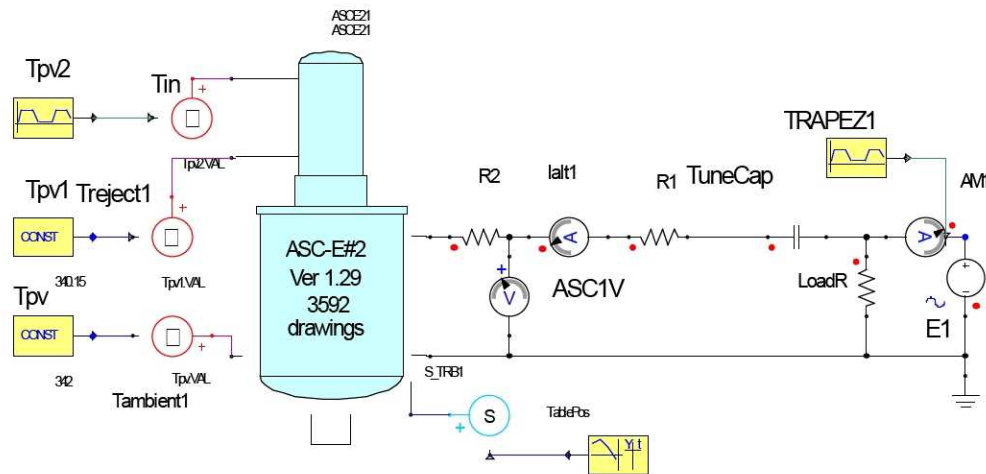
The SDM begins with the heat source to the converter and includes energy flows into the Stirling cycle and losses to thermal conduction. The cold end of the converter rejects heat to the environment. The Stirling cycle thermodynamics in SDM utilize the Schmidt model, an isothermal Stirling cycle. The mechanical model includes the piston and displacer masses, along with the case mass. The alternator model incorporates the output current, voltage, and electromagnetic force. The SDM allows specification of the electrical controller at the component level, and can include state machines and block diagrams. Since SDM is implemented in the Ansoft Simplorer 8.0 environment, various mechanical, electrical, or thermal components can be added or rearranged through the user interface with minimal effort.<sup>10</sup>

This paper presents the first results of the work to integrate these two disciplines: the vibrational testing of Stirling converters and SDM. Section II describes a method for introducing vibration into the SDM. Section III details the collection of the experimental data necessary. Finally, Section IV compares the experimental results from vibration testing of ASC-E #1 at qualification level to those predicted by the SDM. While the Stirling

convertors undergo vibrational testing in both lateral and axial directions, this work focuses on vibration in the axial direction, since the convertors have shown a greater response to disturbances in this direction during testing.

## II. System Dynamic Model

The current model of the Stirling convertor utilized in SDM benefits from a great deal of previous development work. The schematic shown in Fig. 2 depicts the upper level of the Stirling convertor connected to an alternating

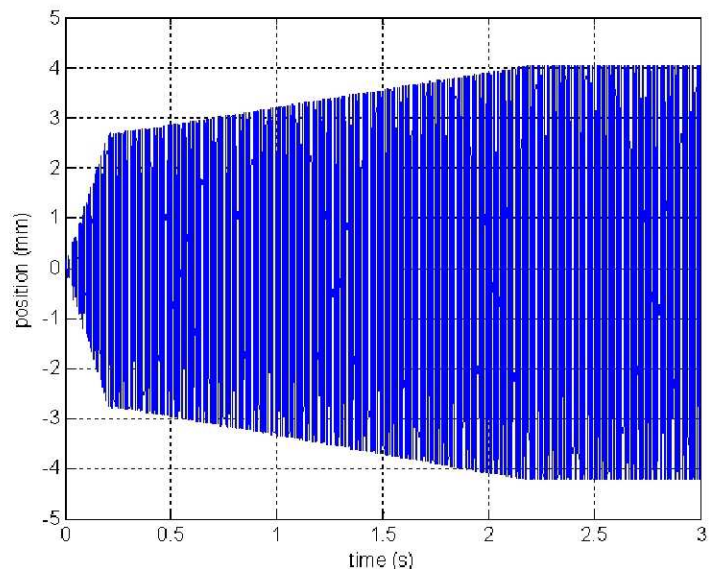


**Figure 2. SDM schematic for vibration input.**

current (AC) bus controller. The component labeled ASC-E #2, Version 1.29, incorporates most of the Stirling convertor dynamics into this sub-model, parameterized for easy customization to a specific set of convertor characteristics. As shown in Fig. 2, the model includes five interface ports to the outside world: 1) a hot-end temperature ( $T_{in}$ ), 2) a cold-end, or rejection, temperature ( $T_{reject}$ ), 3) an ambient temperature ( $T_{ambient}$ ), 4) the electrical power connection, and 5) the displacement of the convertor case. During most simulations, this displacement remains firmly connected to ground. The modification required for this work involved the addition of a position source to the case displacement input. A two-dimensional lookup table based on experimentally recorded data provided input to this position source.

SDM allows monitoring and display of numerous internal variables as well as the interface variables displayed in Fig. 2, including piston and displacer position, output voltage, current, and power, and various temperatures throughout the system. For the purpose of this paper, the quantities of interest include the piston position, the displacer position, the case position, and the differences between these positions.

Figure 3 plots the piston position as a function of time during a normal simulation startup sequence. Note that the convertor reaches steady-state operation at the excitation frequency of the AC bus controller within 2.5 seconds.



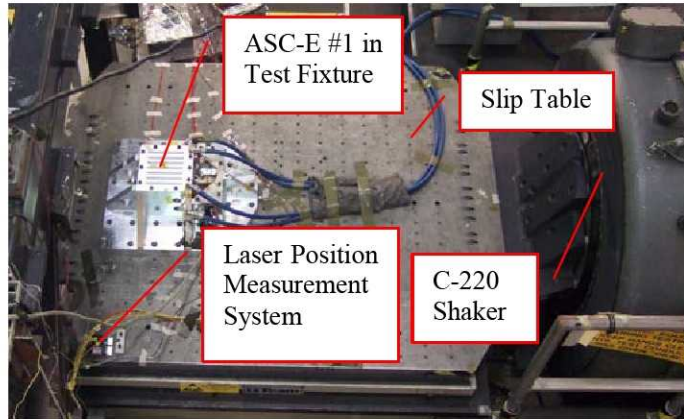
**Figure 3. Piston motion during startup.**

This simulation includes a few parameters tuned to allow the simulation to reach steady state quickly. The temperature profiles have also been adjusted to ramp the three input temperatures to their steady-state values within 2 seconds.

An early attempt at incorporating vibrational input into SDM used accelerometer readings recorded in the GRC Structural Dynamics Laboratory (SDL) at 5120 Hz, integrated those values twice, and input the calculated positions to the SDM case position. The data sample rate, however, proved insufficient for the frequency content of the signal and the calculated position tended to drift to an unrealistic value given the constraints of the slip table. To address this problem, a means of measuring the slip table position was devised and implemented, as described in the next section.

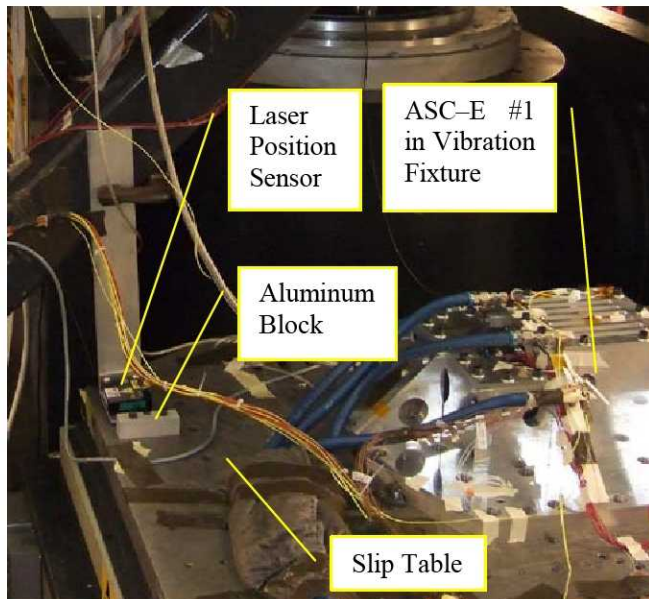
### III. Experimental Data Collection

Figure 4 shows a typical configuration for structural dynamic testing of a Stirling converter. The vibration test fixture holds the Stirling converter, including the electric heat source and insulation. The fixture supports the converter using the same interfaces utilized in the ASRG EU, attachment at the cold-side adapter flange (CSAF), pressure vessel flange, and a heat source preloaded against the heat collector. Over 30 3/8"x24 bolts attach the test fixture to the slip table driven by the actuator. Figure 4 depicts the converter mounted for axial, or Y-axis testing, with vibration along the direction of motion of the converter piston and displacer.



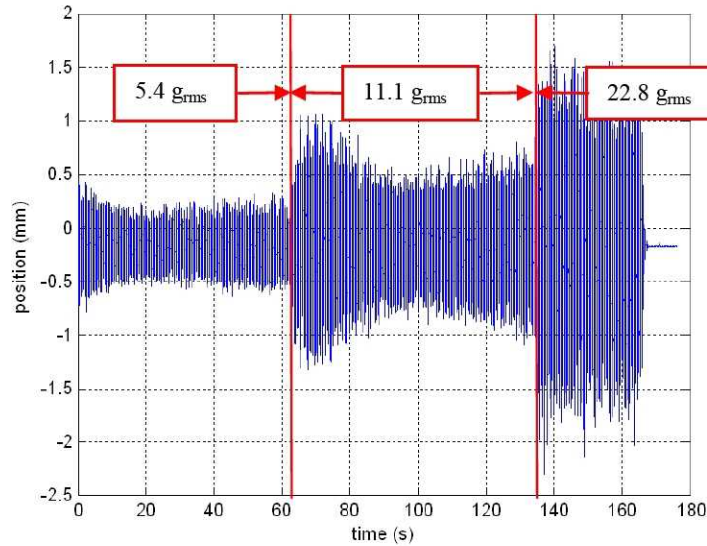
**Figure 4. Experimental configuration for axial vibration testing of ASC-E #1.**

Figure 5 details the additional instrumentation required to measure the slip table position, including an MTI Microtrak II-SA laser position sensor with a range of +/- 10 mm and an accuracy of +/- 2.5  $\mu$ m, and an aluminum block mounted to the slip table. The output of the laser position sensor ran into the SDL data system and was recorded during testing at 5120 Hz.



**Figure 5. Laser system for measurement of slip table position.**

Figure 6 shows the output of the laser position sensor from a typical data run while testing at qualification level using a spectrum shaped to reflect the vibration exposure experienced by the ASC during launch of the ASRG EU.<sup>11</sup> This data reflects a vibration profile up to qualification level at 22.8  $g_{rms}$  measured at a triaxial accelerometer mounted on the converter pressure vessel.<sup>11</sup> The typical profile employed in the SDL steps up the vibration in 6 db intervals, so this plot captures the table position at vibration levels of 5.4  $g_{rms}$  for the first 60 seconds, 11.1  $g_{rms}$  for the next 60 seconds, and 22.8  $g_{rms}$  for the final 28 seconds. The qualification level vibration for a period of 1 minute was broken into two parts because the vibration control system shutdown due to an overly conservative tolerance.



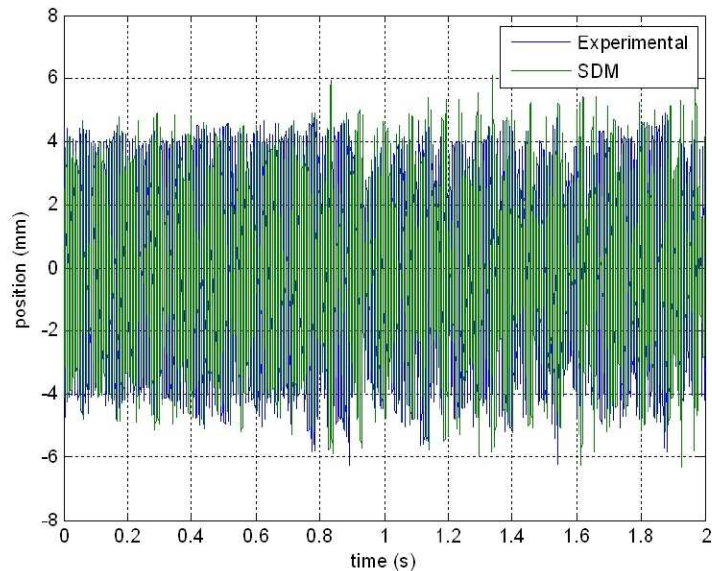
**Figure 6. Slip table position recorded during vibration testing of ASC-E #1 to qualification level.**

difference stands out upon closer examination of this data. Note that, in discussion of the piston position, a positive position indicates motion towards the heater head of the convertor, or inward, while a negative position means motion away from the heater head, or outward. While the simulated piston position varied equally in the positive and negative direction, the experimental data showed a greater deviation from the nominal value of 4.25 mm in the negative, or out direction. This tendency has been observed consistently throughout vibration testing of the ASC convertors. The results do show better agreement between the simulated and experiment results in the negative, or outward direction, although the simulation results do exhibit a slightly greater disturbance response to the vibration than the experimental results.

#### IV. Comparison between Simulation and Experimental Results

Figure 7 compares the piston position recorded during the experimental testing of ASC-E #1 to qualification level, using the spectra shaped based on ASRG EU vibration testing, to the simulated piston position from the SDM model. The input to the case position used in the SDM model was collected during the vibrational testing of ASC-E #1. As the figure shows, the characteristics of the experimental and simulated positions share many of the same characteristics.

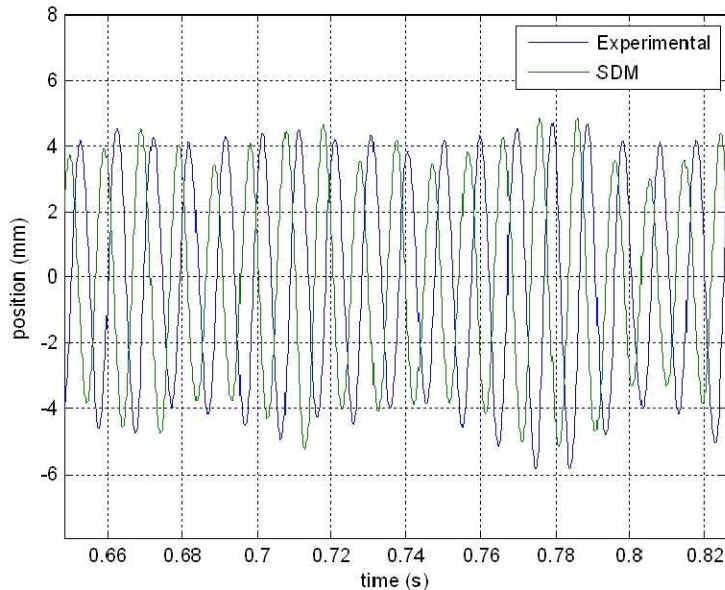
Table 1 includes the maximum and minimum piston positions and piston strokes recorded during this 2 second time slice of the vibration response. One area of



**Figure 7. Comparison of experimental and simulated piston positions during vibration at qualification level.**

**Table 1. Comparison of experimental and simulation piston position parameters.**

	Simulation Result	Experimental Result
Minimum position	-6.34 mm	-6.27 mm
Maximum position	6.12 mm	4.87 mm
Minimum stroke	5.25 mm	5.45 mm
Maximum stroke	11.99 mm	10.98 mm



**Figure 8. Comparison of piston position motion characteristics during qualification level vibration.**

adding a laser position sensor to the slip table in the NASA Glenn Research Center (GRC) Structural Dynamics Laboratory and recording table position during testing of ASC-E #1 to qualification level. Plugging these table positions into the SDM model produced simulation results that shared many characteristics with experimentally observed results on piston position disturbance, including the overall quality of the disturbances as well as the amplitude in the negative, or out, direction. The one fundamental difference between the simulation and experimental results was that the simulation results showed greater variation in the positive, or inward, piston position disturbance than the experimental results. Based on the success of the simulations, the SDM model can provide valuable predictions regarding the behavior of the ASC convertors under vibration without exposing the hardware to unnecessary risk, particularly at higher vibrational levels.

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Figure 8 zooms in on a smaller time slice of the signals displayed in Fig. 7 to show the characteristics of the variation in piston position. Note that the piston position still follows a roughly sinusoidal trajectory in both the experimental and simulation results. The amplitude of the motion does vary with the disturbances introduced by the external vibrations, often within a single cycle.

### V. Conclusion

This paper presents results of the first effort to integrate the vibrational testing of Advanced Stirling Convertors (ASC) with the System Dynamic Model (SDM), a nonlinear simulation model of the ASC convertors. The modification to the SDM involved the introduction of a case motion position variable. The input for this new variable came from

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<sup>7</sup>Wood, James Gary, "A Program for Predicting the Dynamics of Free-Piston Stirling Engines," Report for the Ohio University, Mechanical Engineering Department, 1980.

<sup>8</sup>Benvenuto, G., and de Monte, F., "Electrodynamic Analysis of Free-Piston Stirling Engine/Linear Alternator Systems," *Proceedings of the 29th Intersociety Energy Conversion Engineering Conference*, pp. 1866-1872, 1994.

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<sup>11</sup>Meer, David W., Hill, Dennis, and Ursic, Joseph, "Advanced Stirling Converter Dynamic Test Approach and Results," *Proceedings of the 7th International Energy Conversion Engineering Conference*, AIAA 2009-4552, Denver, CO, 2009.