Overview of the GRC Stirling Convertor System Dynamic Model

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Overview of the GRC Stirling Convertor
System Dynamic Model

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A Stirling Convertor System Dynamic Model has been developed at the Glenn Research Center for controls, dynamics, and systems development of free-piston convertor power systems. It models the Stirling cycle thermodynamics, heat flow, gas, mechanical, and mounting dynamics, the linear alternator, and the controller. The model's scope extends from the thermal energy input to thermal, mechanical dynamics, and electrical energy out, allowing one to study complex system interactions among subsystems. The model is a non-linear time-domain model containing sub-cycle dynamics, allowing it to simulate transient and dynamic phenomena that other models cannot. The model details and capability are discussed.

Nomenclature

$AreaD$	Displacer area (m^2)		$Rhh_{CondLoss}$	Heat source to heater thermal resistance (K/W)
$AreaP$	Piston area (m^2)		$RTH1$	Heat source to cooler thermal resistance (K/W)
$AreaRod$	Displacer rod area (m^2)		SdP	Heater, regenerator, and cooler pressure drop (kPa)
DD	Displacer damping (N*s/m)		T_{bounce}	Bounce space temperature (K)
DP	Piston damping (N*s/m)		T_c	Compression space temperature (K)
f_{alt}	Force generated by alternator current (N)		T_{disp}	Displacer internal temperature (K)
$HHheatCap$	Heater head thermal capacitance(W*s/K)		T_e	Expansion space temperature (K)
I_{alt}	Alternator current (A)		T_h	Heater temperature (K)
K_{alt}	Alternator constant (N/A)		T_{head}	Heater head temperature (K)
KD	Displacer spring rate (N/m)		T_k	Cooler temperature (K)
$Kmag$	Magnet spring rate (N/m)		T_r	Regenerator temperature (K)
KP	Piston spring rate (N/m)		V_{bounce}	Bounce space volume (m^3)
MD	Effective displacer mass (kg)		V_c	Compression space volume (m^3)
MP	Effective piston mass (kg)		V_{co}	Compression space equilibrium volume (m^3)
M_{tot}	Total mass of fluid in convertor (kg)		V_{disp}	Displacer internal volume (m^3)
$M_{working}$	Mass of working fluid (kg)		V_e	Expansion space volume (m^3)
P	Stirling cycle dynamic pressure (kPa)		V_{eo}	Expansion space equilibrium volume (m^3)
P_m	Mean pressure (kPa)		V_h	Heater volume (m^3)
$Q_{conduction}$	Heater head conduction loss (W)		V_k	Cooler volume (m^3)
Q_{head}	Heat input to heater (W)		V_r	Regenerator volume (m^3)
Q_{source}	Heat input (W)		X_a	Alternator position (m)
$Q_{source loss}$	Heat lost to ambient (W)		X_d	Displacer position (m)
$Q_{thermal mass}$	Heat flow to the heater thermal mass (W)		X_p	Piston position (m)
R_{gas}	Universal gas constant		ΔP_{bounce}	Bounce space mean pressure offset (kPa)
			ΔP_{disp}	Displacer internal mean pressure offset (kPa)
			μ_{alt}	Alternator efficiency

I. Introduction

Computer modeling of Stirling systems at Glenn Research Center (GRC) dates back to the 1970's.[1,2] Most of the early Stirling dynamic models developed at GRC and elsewhere were linear models,[3-5] while more recent models have added nonlinearities.[6] The scope of these models was generally limited to the Stirling convertor and neglected some details of the remaining dynamic system such as the linear alternator and controller.

Recognizing the need for a nonlinear system-level dynamic model, GRC began development of an end-to-end Stirling convertor system model. The results and status of this effort, the GRC Stirling Convertor System Dynamic Model (SDM), are discussed in this paper. The SDM includes the Stirling cycle thermodynamics, heat flow, gas, mechanical, and mounting dynamics, the linear alternator, and the controller. The SDM's scope extends from the

thermal energy input to thermal, mechanical, and electrical energy out, allowing one to study complex system interactions among subsystems (see fig. 1). Thermal, mechanical, fluid, magnetic, and electrical aspects can be studied in one model. The SDM is a non-linear time-domain model containing sub-cycle dynamics, allowing it to simulate transient and dynamic phenomena that other models cannot. The entire range of convertor operation is modeled, from start-up to full power conditions.

The SDM has been developed as a "bottoms-up" model based on first principles. Components are separately modeled, then combined into subsystems. Very few calibration factors are used to correlate SDM simulation results with test data. The SDM can be set up to include multiple convertors in various mechanical and electrical configurations, including dual-opposed, parallel electrical, and series electrical configurations. It is being used to model free-piston convertors from less than 100 W to over 10 kW. The SDM is not designed for Stirling convertor performance development, since it does not have the sophisticated thermodynamics found in dedicated thermodynamic codes such as Sage.[7] The SDM is presently being validated empirically using the 55 We Technology Demonstration Convertor (TDC) Stirling convertor hardware and data available at GRC. [8,9] The TDC is manufactured by Stirling Technology Company (STC). [10]
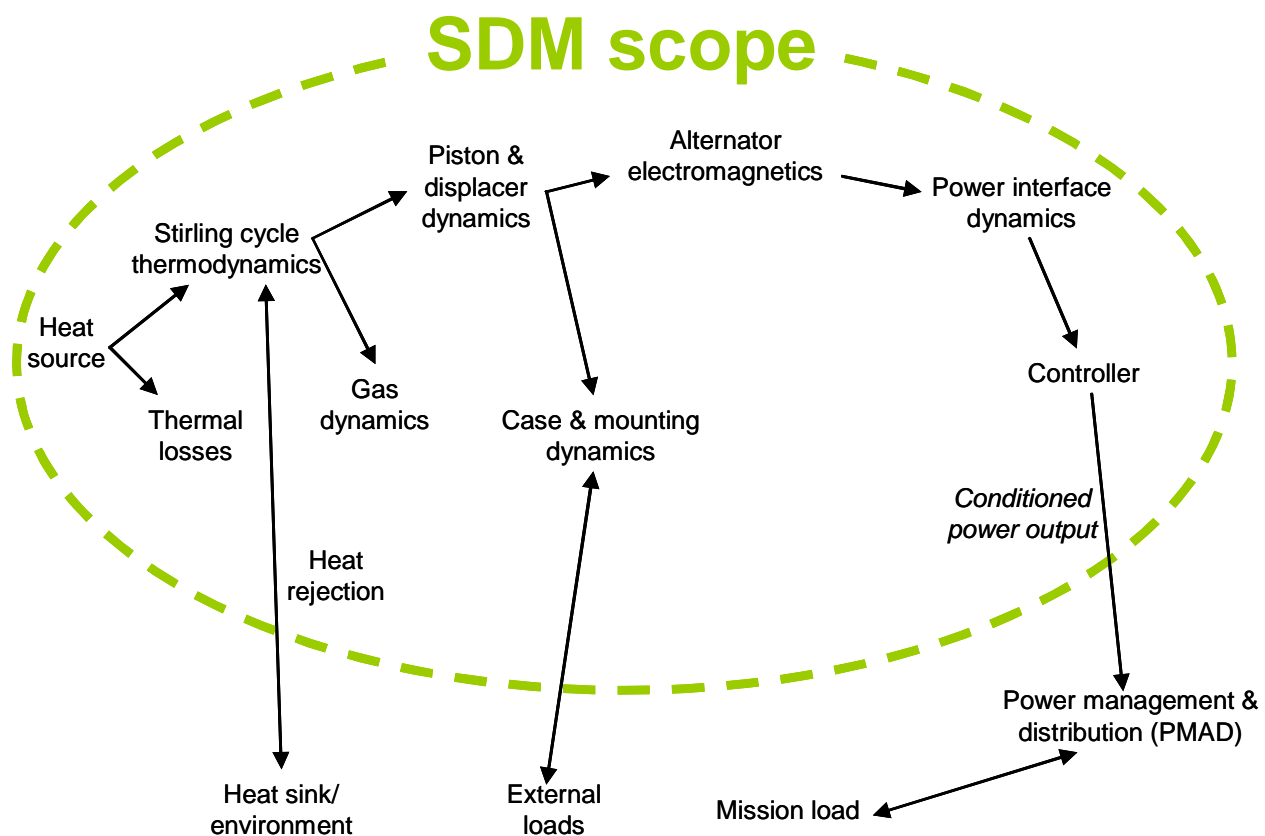

Figure 1.—Scope of the Stirling convertor system dynamic model, within the domain of the entire system.

The SDM begins with the heat source to the convertor. Some energy flows into the Stirling cycle, and some is lost to thermal conduction and other losses. At the cold end of the convertor, heat is rejected to the environment.

The Stirling cycle thermodynamics are modeled assuming the Schmidt model. The Schmidt model is the isothermal Stirling cycle. Pumping losses through heat exchangers and internal gas flows through clearance seals are considered. The piston and displacer masses are included, along with case masses. The case mass is connected to ground through a compliant damped linkage. The alternator model includes the output current, voltage, and electromagnetic force. Any interface between the alternator and controller (e.g., capacitor) is modeled on the component level. Controller models are also created at the component level, and can include state machines and block diagrams.

From figure 1, one can see that portions of the spacecraft power system are currently outside the scope of the SDM. The GRC SDM is designed to be extensible, and these portions may be added in the future if deemed necessary. Since the model is implemented in Ansoft Simplorer 6.0, various mechanical, electrical, or thermal components can be added or rearranged through the user interface with minimal effort. In the future, the SDM will be linked with Sage to provide enhanced thermodynamic capability.

This paper provides an update on Stirling convertor dynamic modeling since the last publication (ref. 11). Significant improvements have been made to the heat source, Stirling cycle thermodynamics, and piston and displacer dynamics subsystems (fig. 1). Gas dynamics and case and mounting dynamics have been added. Extensive model validation has been done.

II.   The model

The free-piston Stirling convertor is a reciprocating resonant system driven by heat energy. The convertor consists of a pressure vessel in which are located a displacer, a piston, and a linear alternator. The vessel is filled with a working fluid such as helium. The key components are illustrated in figure 2. This illustration depicts a generic Stirling convertor having annular heat exchangers and regenerator. There have been many variations in free-piston Stirling convertor designs; however the model discussed in this paper is based on the configuration shown in figure 2.
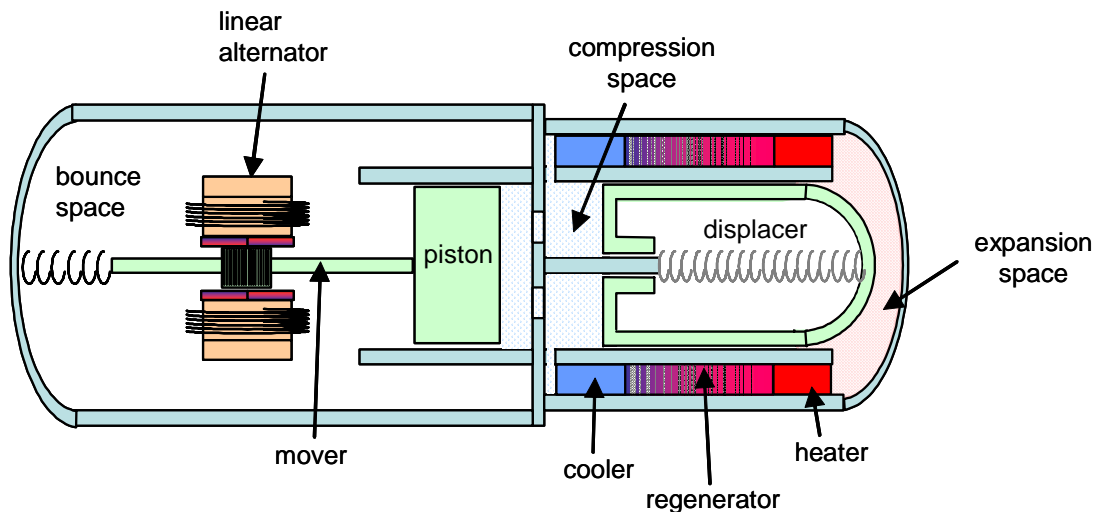

Figure 2.—Cross-section schematic of the TDC Stirling convertor.

A. Heat source

The primary energy flow into the Stirling convertor system is through an external thermal energy heat source, as shown in figure 3. *Qsource* may represent heat input from a heater or General Purpose Heat Source (GPHS) module. Some of that heat, *Qsource loss*, is lost through the insulation, leaving *Net Q*. Additionally, some heat, *Qconduction*, flows directly from the hot end to the cold end of the convertor without performing work. During hot-end temperature transients, some heat goes into heating up (or cooling down) the hot-end mass. This is represented by *Qthermal mass*. The remaining heat goes into the heater as *Qhead*. There are additional smaller heat flows such as the displacer radiation loss, and the regenerator metal conduction loss, but those are neglected for now.

The SDM uses an electrical circuit analogy to model the heat flows, as shown in figure 4. Current represents heat flow in watts; voltage represents temperature. Thermal losses are modeled using resistors and thermal masses by capacitors.

The user specifies a fixed heat input in watts to the hot end of the TDC. The model then calculates the hot-end temperature based on thermodynamic considerations.

The user-defined heat input is represented by *Qsource*, and has units of watts. Between the heat source and the hot-end heat exchanger there is a small temperature drop, which is modeled by *RTH1*. The conduction loss is represented by the resistor *RhhCondLoss*. The conduction losses are driven by the temperature difference between

the hot end and the cold end, *Th - Tk*. Additional thermal losses can be readily modeled by adding more resistor legs to the circuit. The current model uses linear resistances, but these can easily become nonlinear functions of temperature if necessary.
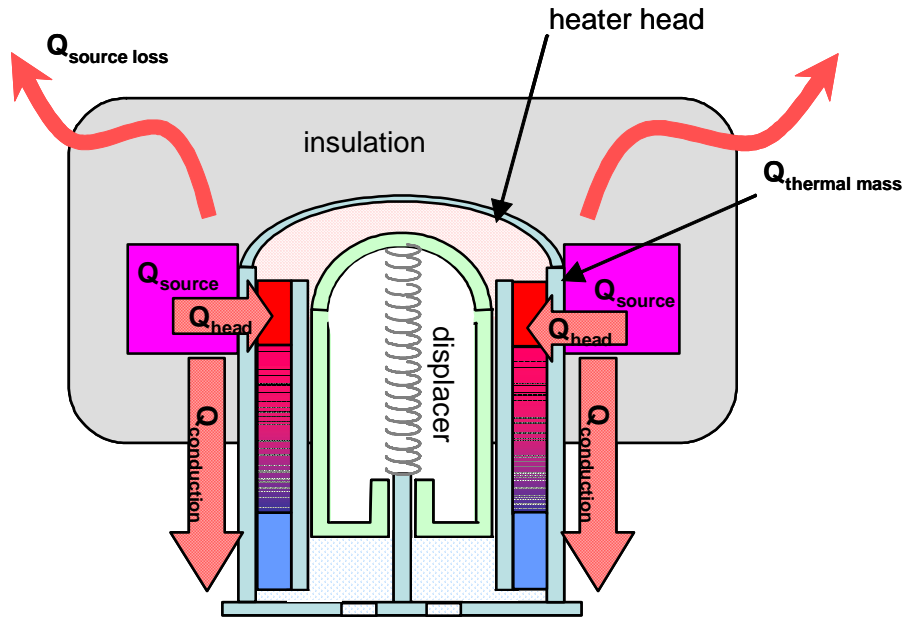

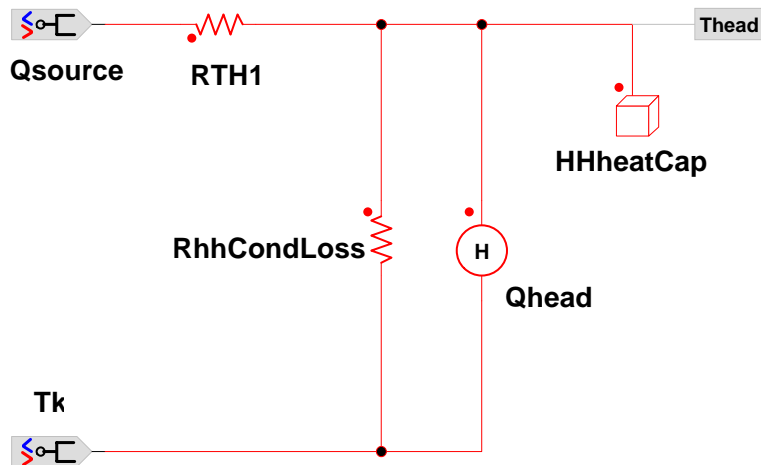Figure 3.—Stirling convertor hot end cross-section showing the major heat flows.

Figure 4.—SDM heat source and thermal loss model.

In the Stirling convertor, there is a time lag between a change in heat input and a change in the hot-end temperature due to the thermal mass of the heater and heater head. This effect is modeled by the thermal capacitance *HHheatCap*. Often during simulation runs, a smaller than typical value for *HHheatCap* is used to transition quickly from one operating condition to another.

For some simulations, especially those that mimic specific lab tests, the temperature *Thead* needs to be held constant rather than the heat input *Qsource*. For this purpose, the SDM has a proportional-integral-derivative (PID) control loop that regulates temperature, simulating the fixed-temperature input scenario.

1. Interface between heat source and Stirling cycle thermodynamics

The heat source section of the model and the Stirling cycle thermodynamics section are connected via the parameters heater head temperature T_{head} and the heat source Q_{head}. One challenge with connecting them is that the former section is modeled as flowing energy continuously, while the latter section receives a pulsed energy flow at the operating frequency. To address this issue, it was recognized that over one cycle the net heat input to the working fluid is approximately equal to the P-V work in the expansion space. The model calculates P-V work over one cycle by numerically integrating $P\,dV$. The heat source Q_{head} is then set so that it flows that equivalent amount of work over the next cycle. In this way the energy going into the fluid through the heater matches the expansion space P-V work from the previous cycle. While this approach does introduce an error in the energy flows during transients due to the one-cycle offset, this error is relatively small for realistic values of heater head thermal capacitance. This approach is able to couple the periodic energy flow of the Stirling cycle to the heat input modeled as a continuous energy flow.

B. Stirling cycle thermodynamics

The SDM assumes a variation on Schmidt's analysis of the Stirling cycle when modeling the Stirling cycle thermodynamics. This assumption introduces some error, generally resulting in a reduced pressure amplitude but higher pressure phase angle than in the true Stirling cycle. Free-piston machines generally have lower pressure ratios than kinematic Stirling machines, so the isothermal assumption does not introduce as much error. The SDM makes the following Schmidt analysis assumptions:

- Working fluid follows ideal gas law
- Isothermal heat transfer
- Expansion space, heater, and associated dead volume at equal instantaneous temperature
- Compression space, cooler, and associated dead volume at equal instantaneous temperature
- Linear temperature gradient between the hot and cold ends of the regenerator
- Perfect regeneration
- Instantaneous pressure is uniform throughout the working space

The SDM does not follow the Schmidt analysis assumptions that the expansion and compression space volumes vary sinusoidally. The piston and displacer positions are determined through numerical integration and can take any form.

Based on the above assumptions it can be shown that the instantaneous pressure as a function of compression and expansion space volumes (and thus piston and displacer positions) is given by:[12]

$$P = M_{working} \cdot R_{Gas} \div \left(\frac{Vh}{Th} + \frac{Vr}{Tr} + \frac{Vk}{Tk} + \frac{Ve}{Te} + \frac{Vc}{Tc} \right) \tag{1}$$

Also by the above assumptions, the expansion space temperature is set equal to Th (i.e., Te = Th). The compression space temperature is assumed to be equal to the cold-end temperature Tk (i.e., Tc = Tk). In practice these temperatures are not equal, resulting in some modeling error.

The Schmidt analysis assumes that the regenerator temperature distribution changes linearly between Th and Tk along its length. Berchowitz[12] showed that when this assumption is made, the effective regenerator temperature Tr is given by the log mean temperature

$$Tr = \frac{Th - Tk}{\ln\left(\dfrac{Th}{Tk}\right)} \tag{2}$$

Since the displacer sees a similar temperature environment as the regenerator, the model assumes that the fluid temperature in the displacer is the same as that for the regenerator:

$$T_{displ} = Tr \tag{3}$$

While the pressure drops through the regenerator and heat exchangers are neglected for the purposes of calculating the instantaneous pressure P, they cannot be neglected in the dynamic model. They provide damping to the system, determining the steady-state amplitude and phasing of the piston and displacer.

In the SDM, basic fluid flow equations are used to calculate the instantaneous pressure drops through the regenerator and heat exchangers. The pressure drops impact the forces acting on the piston and displacer.

C. Heat Sink

The heat sink in the SDM is a fixed temperature, as shown in figure 4. This matches how Stirling convertors are often tested in the lab. A radiant heat sink may be added to the model in the future to better represent environments such as deep space or thermal vacuum.

D. Gas Dynamics

Most free-piston convertors have additional gas volumes beyond the working space. These volumes can include piston and displacer bounce spaces and internal volumes, and are often connected to the working space through close clearance seals or centering ports. The gas in the displacer and the bounce space are neglected in equation (1) because the amount of gas moving into or out of the working space during one cycle should be small relative to the total gas in the working space. However, over many cycles, as gas temperatures change, the gas reapportions itself between working and non-working spaces. The SDM corrects for the amount of gas leakage between the working spaces and the bounce spaces and displacer internal volume. If it did not, the pressure in the working space would rise more than appropriate as the temperatures rise during start-up and changes in operating conditions.
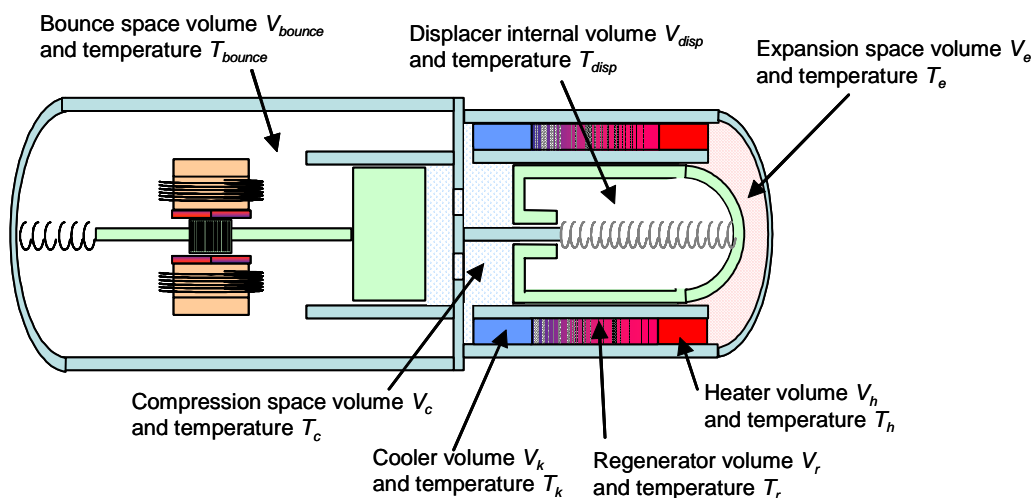

Bounce space volume V_{bounce} and temperature T_{bounce}

Displacer internal volume V_{disp} and temperature T_{disp}

Expansion space volume V_e and temperature T_e

Compression space volume V_c and temperature T_c

Cooler volume V_k and temperature T_k

Regenerator volume V_r and temperature T_r

Heater volume V_h and temperature T_h

Figure 5.—TDC convertor fluid volumes and temperatures.

1. Working fluid mass

The SDM redistributes gas among the various volumes using a mass-based approach that considers the temperature of each volume at every integration step. It calculates the working fluid mass assuming that the fluid mass is distributed among all of the various volumes in the convertor at an equilibrium pressure Peq.

Consider the TDC configuration as shown in figure 5. Besides the working fluid volumes, this convertor has a bounce space on one side of the piston and a displacer internal volume. Assume that the mass is distributed among the various volumes based on the equilibrium condition that would occur with each volume at its appropriate temperature, but all volumes at an equilibrium pressure Peq. The varying expansion and compression space volumes are considered to be at their equilibrium values V_{eo} and V_{co}. Assuming the ideal gas law, one can solve for the mass in each volume. These equations can be represented by an electrical circuit analogy shown in figure 6. In this analogy, the total mass $Mtot$ is shown as a current source. The pressure Peq represents the voltage across each resistor. The resistors in parallel represent the ratio of temperature to volume for each volume. As temperature increases for a given volume, the "resistance" increases, which decreases the "current" (mass) through that leg.
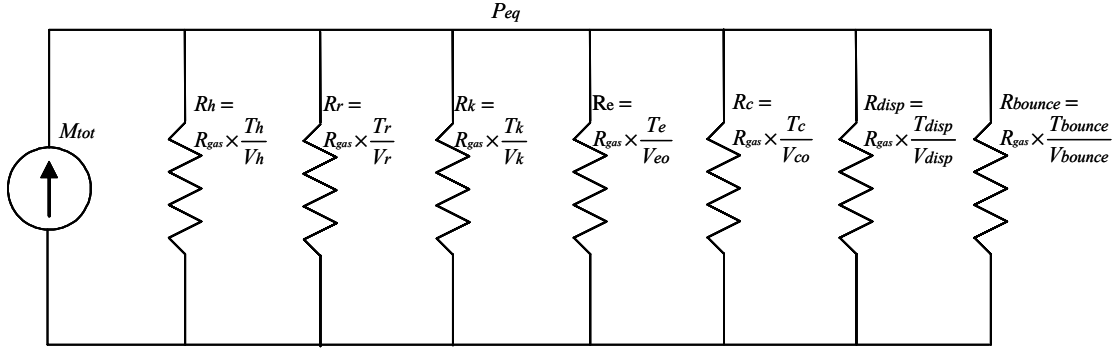
Figure 6.—Circuit analogy used to calculate the working fluid mass $M_{working}$.

The working fluid mass $M_{working}$ is the mass "flowing" through the resistors Rh, Rr, Rk, Re, and Rc. The current flow through each leg is proportional to the mass in each volume. Equivalent resistances can be calculated for resistances in parallel. Solving for $M_{working}$ gives the following equation:

$$M_{working} = \frac{G'_{working} \times M_{tot}}{G'_{working} + \dfrac{V_{disp}}{Tr} + \dfrac{V_{bounce}}{T_{bounce}}} \quad (4)$$

where

$$G'_{working} = \frac{Vh}{Th} + \frac{Vr}{Tr} + \frac{Vk}{Tk} + \frac{Veo}{Te} + \frac{Vco}{Tc} \quad (5)$$

and T_{disp} is assumed to equal T_r.

2. Pumping effects and piston or displacer offset

In the previous section it was assumed that the mean pressure is equal throughout the Stirling convertor. In fact the bounce space pressure often has a higher mean pressure than the working space. This is because the leakage through gas seals between the compression space and the bounce space is biased towards the bounce space, resulting in a small increase in bounce space mean pressure, or so-called "pumping effect".

The SDM models the piston or displacer offset through an increase in the bounce space mean pressure or displacer internal mean pressure, ΔP_{bounce} or ΔP_{disp} respectively. The increased mean pressure causes a shift in the piston or displacer mean position. The pressure offset is scaled as a percent of the pressure wave amplitude, since the pressure wave amplitude roughly determines the offset magnitude for a given gas seal geometry. The offsets in mean pressures can be incorporated into the circuit analogy (fig. 6) as voltage sources.

E. Piston and displacer dynamics

The SDM incorporates the dynamics of the piston and the displacer based on the equations derived from free-body diagrams. Forces acting on the piston and displacer include flexure spring forces, pressure wave forces, bounce space pressure forces, damping forces, and alternator (load) forces. Note that the spring component of the pressure wave does not need to be included as a separate term, since it is simply a component in the pressure wave.

There are a variety of free-piston convertor configurations, resulting in a variety of dynamic equations for the piston and displacer. In this paper, the TDC will be used as an example. figure 7 shows the free-body diagram for the TDC displacer. Pressures act on each end of the displacer, as well as on the inside. The pressure inside the displacer is assumed equal to the mean pressure Pm, neglecting the oscillation due to displacer motion. The pressure drop SdP is applied to the compression space end pressure only as a simplification. Summing the forces to zero yields the following second-order equation:

$$KD \times Xd + DD \times \dot{X}d + MD \times \ddot{X}d = (P_m - P + SdP) \times AreaRod - SdP \times AreaD \quad (6)$$
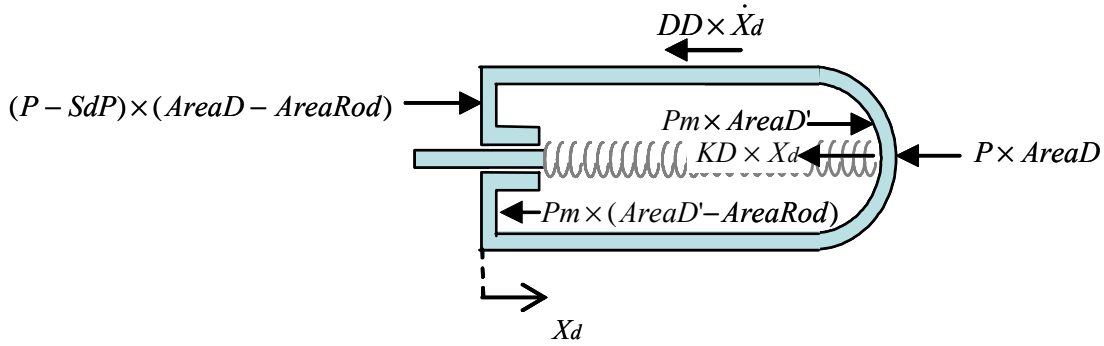
Figure 7.—Free-body diagram of the displacer.

The same analysis can be performed on the TDC piston-mover assembly. figure 8 shows the free-body diagram for the piston-mover assembly. The piston has mass *PistonMass*, and is acted upon by the reaction force from the alternator *Falternator*, as well as pressure and damping forces. The mover has mass *MoverMass*, and is acted upon by the driving force from the piston *Fpiston*, as well as magnetic forces.
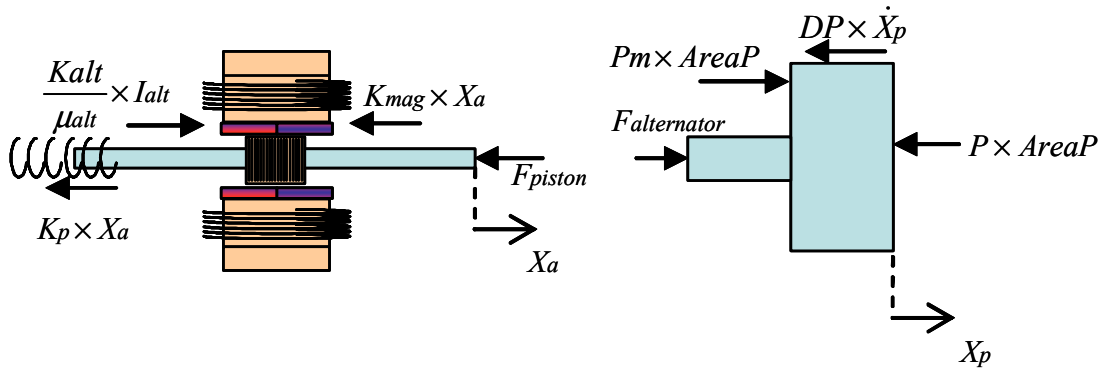

Figure 8.—Free-body diagram of the piston and alternator mover.

The force *Fpiston* is equal and opposite to *Falternator*. It is assumed that the mover and piston are rigidly coupled, so the position *Xp* also represents the position of the mover *Xa*. Summing forces, the second-order equation describing the dynamics is:

$$KP \times X_p + DP \times \dot{X}_p + MP \times \ddot{X}_p = (P_m - P) \times AreaP + \frac{K_{alt}}{\mu_{alt}} \times I_{alt} \tag{7}$$

where

$$MP = PistonMass + MoverMass$$

F. Case and mounting dynamics

The SDM models the dynamics of the convertor case and the mounting. Using the component libraries available in Simplorer, a variety of mounting configurations can be simulated. To determine net resultant forces, the case can be attached to ground with a force meter. To study the motion of a structure or the interaction between a flexible structure and the convertor, the appropriate spring, damping, and mass elements can be added.

G. Alternator electromagnetics

One of the forces on the right-hand side of equation (7) is the force of electro-magnetic origin,

$$f_{alt} = \frac{K_{alt}}{\mu_{alt}} \times I_{alt} \tag{8}$$

The force f_{alt} is the force that the linear alternator mover feels as load current is drawn from the circuit. The load current flows through the windings of the alternator stator windings and gives rise to a force proportional to the current. The constant of proportionality is K_{alt}. The current itself is caused by the electromotive force, or EMF, generated by the alternator. The EMF is a voltage that is proportional to the velocity of the mover by Faraday's law. In the operation of a free-piston Stirling convertor with load, a portion of the load current is in phase with the EMF. The component of the force in phase with EMF is felt by the piston as damping because it is also in phase with piston velocity. The remainder of the force is orthogonal to piston velocity and it is felt as spring force. Alternator losses are represented simply by the alternator efficiency μ_{alt}.

In the SDM, the alternator is modeled as an EMF source with inductance and resistance as shown in figure 9.
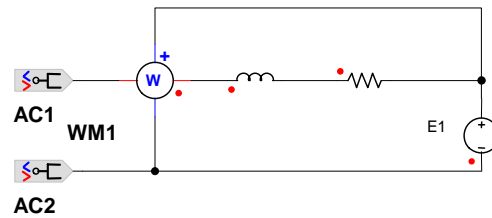

Figure 9.—Alternator model.

H. Power interface dynamics

The components between the alternator and the controller and the electrical arrangement of multiple convertors can significantly affect the dynamics of the system. Especially important are the tuning capacitors, which help counteract the stator inductance so the net load seen by the convertor is largely dissipative, not reactive. This reduces the current required for a given power output.

The SDM models these components using the circuit elements from the Simplorer libraries.

I. Controller modeling

The SDM has been operated with various controllers, including a zener diode controller and the GRC active power factor correction controller.[13] Any other controllers can be readily modeled using the library of electrical components available in Simplorer. Alternatively, it is possible to interface a P-Spice model of a controller to Simplorer.

III.   Model Validation

Data from the TDC Stirling convertor was used to validate the SDM. Validation included parameter validation, steady-state validation, and transient validation. Parameter validation was performed through review of component drawings, component simulation (mechanical and electromagnetic finite element analysis (FEA)), and testing. Parameters such as masses and nonlinear spring rates were measured empirically. Data from Sage[7] was used to estimate some parameters such as damping.

Steady-state and transient validation involved comparing model output with TDC performance data gathered at GRC. Results compared favorably, although as much as a 20% difference in power was observed in some cases. The isothermal assumption and other heat transfer simplifications limit the performance accuracy. By incorporating Sage to model the thermodynamics, it is expected that the performance accuracy will improve.

The model accurately predicted dynamic performance including start-up transients and dynamic oscillations during various test conditions. Some of these examples are discussed in the companion paper (ref. 14).

IV.   Simulation Example

The SDM was run using typical parameters to illustrate the capability of the model. Further examples of the application of the model can be found in reference 14.

A. Simulation of start-up

The SDM simulates the start-up of a Stirling convertor, as heat is applied to the hot end. figure 10 shows the increase in piston position Xp and displacer position Xd at start-up. A smaller thermal mass $Q_{thermal\ mass}$ is used than is typical in order to shorten the time required to start the convertor. However, if the true thermal mass was used, the actual start-up transient would result.
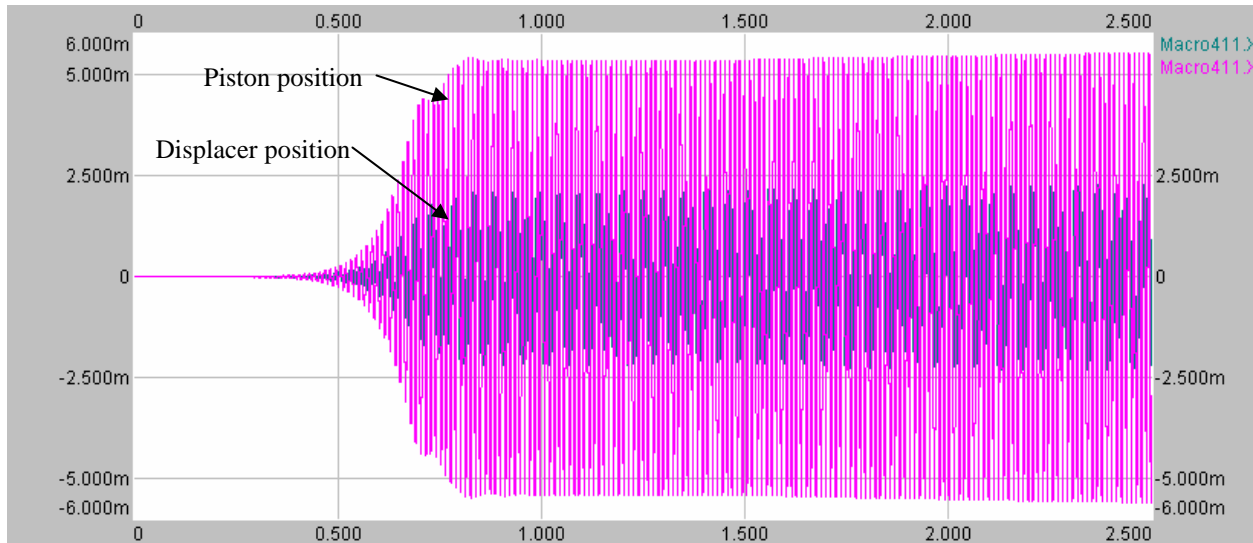

Figure 10.—Piston position Xp and displacer position Xd vs. time (sec) during start-up.

B. Change in heat input

The SDM can simulate changes in temperature or heat input. figures 11 through 13 show the results of simulating a ramp in input temperature from 377 °C to 650 °C. Again, a small thermal mass is used for illustration purposes. figure 12 shows the increase in operating frequency with increasing heat input. The decrease in working fluid mass $Mworking$ as temperature increases is shown in figure 13.
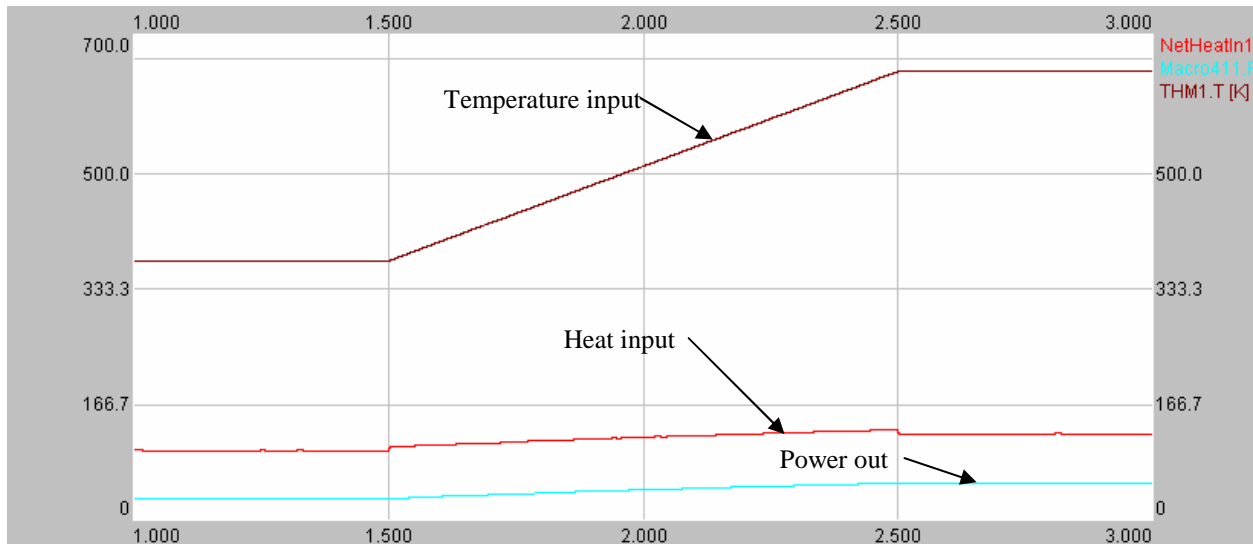

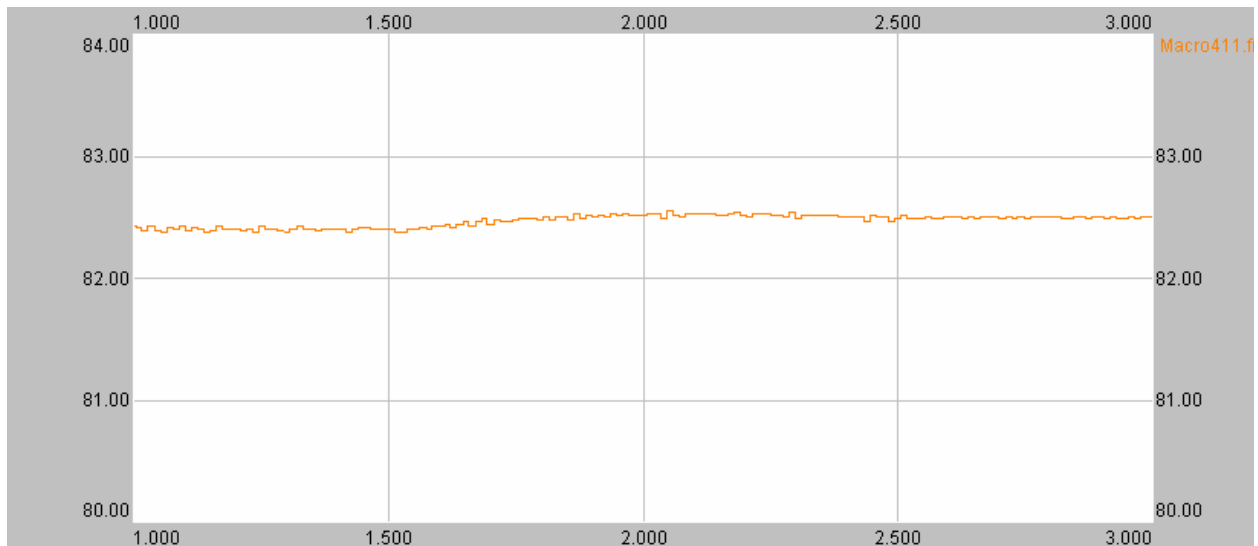**Figure 11.—Temperature input (C), heat input (W), and power out (We).**

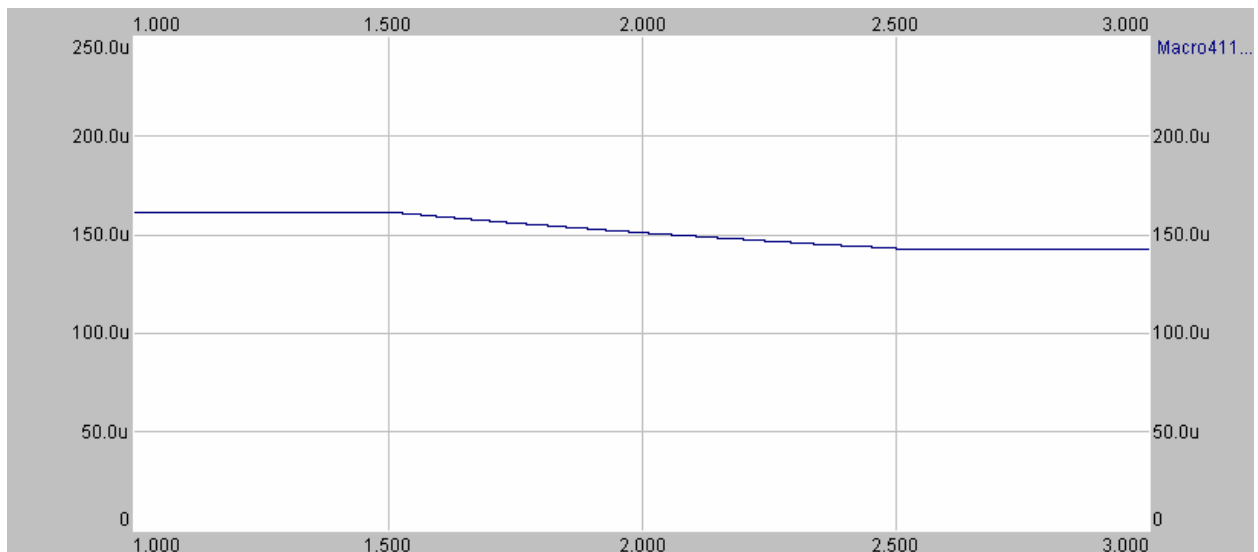**Figure 12.—Convertor operating frequency vs. time (sec) during transient**.

Figure 13.—Working fluid mass *Mworking* vs. time (sec) during increase in hot end temperature transient.

C. Sub-cycle dynamics

The SDM simulates sub-cycle dynamics, including the piston and displacer positions and the pressure wave. Since the model makes no assumptions about the shape of these variables, the waveforms are not exactly sinusoidal. figure 14 shows the voltage and current waveforms. Note the highly non-sinusoidal waveforms. Variables such as the phase angle and pressure angle can be estimated by comparing zero crossings of the waveforms.
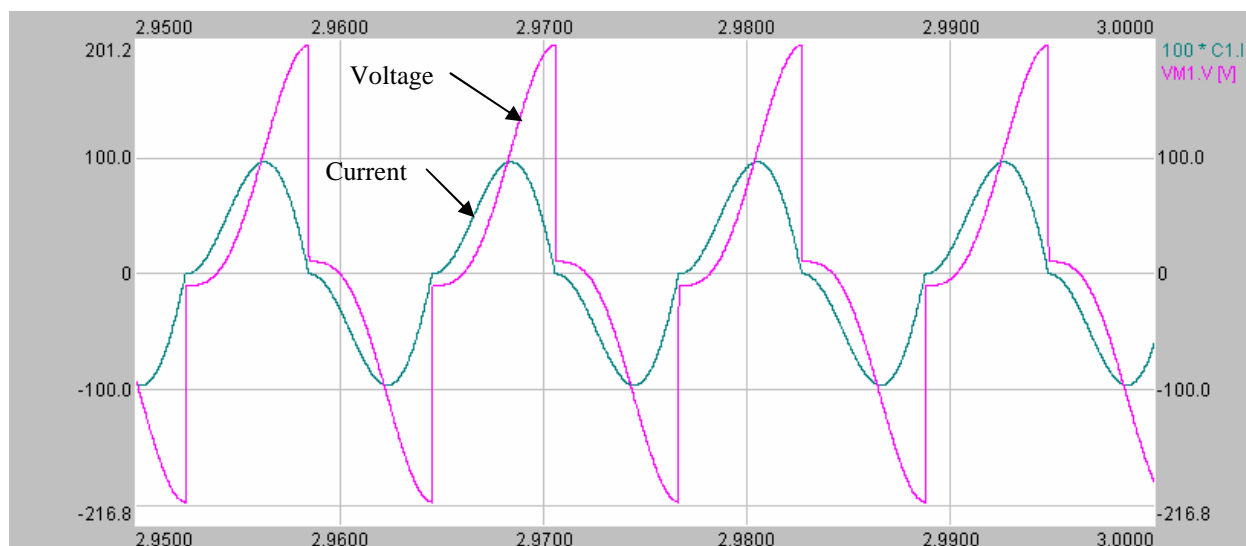
Figure 14.—Output current and voltage waveforms (current multiplied by 100).

V.   Conclusion

The GRC Stirling convertor System Dynamic Model is a powerful tool that can be used for controls, dynamics, and systems development. The model's scope extends from the thermal energy input to thermal, mechanical, and electrical energy out, allowing one to study complex system interactions among subsystems. Future enhancements will expand the model capability even further.

REFERENCES

[1]Tew, Roy C., Jr. "Computer Program for Stirling Engine Performance Calculations," DOE/NASA/51040-42, NASA/TM-82960, January, 1983.

[2]Daniele, Carl J., Lorenzo, Carl F., "A Four Cylinder Stirling Engine Computer Program With Dynamic Energy Equation," DOE/NASA/51040-44, NASA/TM-83053, May, 1983.

[3]Berchowitz, D. Urieli, I., Rallis, C.J., "Computer Simulation of Stirling Cycle Machines," *Proceedings of the 12th Intersociety Energy Conversion Engineering Conference (IECEC 1977),* pp 1512-1521, 1977.

[4]Wood, James Gary, "A Program for Predicting the Dynamics of Free-Piston Stirling Engines," Report for the Ohio University, Mechanical Engineering Department, 1980.

[5]Benvenuto, G., de Monte, F., "Electrodynamic Analysis of Free-Piston Stirling Engine/Linear Alternator Systems," *Proceedings of the 29th Intersociety Energy Conversion Engineering Conference (IECEC 1994),* pp 1866-1872, 1994.

[6]Ulusoy, N. and McCaughan, F., "Nonlinear analysis of Free Piston Stirling Engine/Alternator System," *Proceedings of the 29th Intersociety Energy Conversion Engineering Conference (IECEC 1994)* pp 1847-1852

[7]Gedeon, David, "Sage: Object-Oriented Software for Cryocooler Design," *Cryocoolers 8,* Edited by R.G. Ross, Jr., Plenum Press, New York, pp. 281--292, 1995.

[8]Schreiber, J.G, and Thieme, L.G., "Overview of NASA GRC Stirling Technology Development," *Proceedings of the First International Energy Conversion Engineering Conference (IECEC 2003)* American Institute for Aeronautics and Astronautics, 2003.

[9]Roth, M.E., Schreiber, J.G, and Pepper, S.V., "Extended Operation of Stirling Convertors," *Proceedings of the Second International Energy Conversion Engineering Conference (IECEC 2004)* American Institute for Aeronautics and Astronautics, 2004.

[10]Qiu, S., Augenblick, J.E., White, M.A., Pererson, A.A., Redinger, D.L. and Peterson, S.L., Developing a Free-Piston Stirling Convertor for Advanced Radioisotope Space Power Systems," in *Proceedings of the Space Technology and Applications International Forum, (STAIF 2002)*, American Physical Society.

[11]Regan, T.F., Gerber, S.S. and Roth, M.E. "Development of a Dynamic, End-to-End Free Piston Stirling Convertor Model," in *Proceedings of 37th Intersociety Energy Conversion Engineering Conference (IECEC 2002)*, Institute of Electrical and Electronics Engineers, Piscataway N.J., 2002.

[12]Berchowitz, "Stirling Cycle Engine Design and Optimisation", Ph.D. Dissertation, University of the Witwatersrand, Johannesburg, South Africa, 1986.

[13]Gerber, S.S., Jamison, M., Regan, T.F., and Roth, M.E., "Advanced Controller for the Free-Piston Stirling Convertor," *Proceedings of the Second International Energy Conversion Engineering Conference (IECEC 2004)* American Institute for Aeronautics and Astronautics, 2004.

[14]Regan, T.F., Lewandowski, E.J., "Application of the GRC Stirling Convertor System Dynamic Model," *Proceedings of the Second International Energy Conversion Engineering Conference (IECEC 2004)* American Institute for Aeronautics and Astronautics, 2004.

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A Stirling Convertor System Dynamic Model has been developed at the Glenn Research Center for controls, dynamics, and systems development of free-piston convertor power systems. It models the Stirling cycle thermodynamics, heat flow, gas, mechanical, and mounting dynamics, the linear alternator, and the controller. The model's scope extends from the thermal energy input to thermal, mechanical dynamics, and electrical energy out, allowing one to study complex system interactions among subsystems. The model is a non-linear time-domain model containing sub-cycle dynamics, allowing it to simulate transient and dynamic phenomena that other models cannot. The model details and capability are discussed.

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