Stirling System Modeling for Space Nuclear Power Systems

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Abstract

A dynamic model of a high-power Stirling convertor has been developed for space nuclear power systems modeling. The model is based on the Component Test Power Convertor (CTPC), a 12.5-kWe free-piston Stirling convertor. The model includes the fluid heat source, the Stirling convertor, output power, and heat rejection. The Stirling convertor model includes the Stirling cycle thermodynamics, heat flow, mechanical mass-spring damper systems, and the linear alternator. The model was validated against test data.

Both nonlinear and linear versions of the model were developed. The linear version algebraically couples two separate linear dynamic models; one model of the Stirling cycle and one model of the thermal system, through the pressure factors.

Future possible uses of the Stirling system dynamic model are discussed. A pair of commercially available 1-kWe Stirling convertors is being purchased by NASA Glenn Research Center. The specifications of those convertors may eventually be incorporated into the dynamic model and analysis compared to the convertor test data. Subsequent potential testing could include integrating the convertors into a pumped liquid metal hot-end interface. This test would provide more data for comparison to the dynamic model analysis.

Introduction

Dynamic modeling and simulation play an important role in the development of space nuclear power systems. Because of the cost of prototypes, and complexity of the system, accurate models are beneficial for trade studies, evaluation of design options, dynamic performance prediction, failure effects analysis, design optimization, and controls development.

This paper describes the dynamic modeling of the Stirling convertor, which converts heat energy into electrical energy. The Stirling convertor includes thermal, mechanical, fluid, magnetic, and electrical dynamic elements. While models have been developed for the various elements of the convertor, few models combine them into one model. The model described herein contains all of these elements, allowing the study of complex system dynamic interactions among subsystems. It is a non-linear time-domain model that can simulate transient and dynamic phenomena over the entire range of operating conditions, from start-up to full power.

To facilitate systems development and integration, a linear version of the model was developed. Dynamic model parameters are calculated for the Component Test Power Convertor (CTPC) based on data from published reports (refs. 1 to 4).

Nomenclature

\[
\begin{align*}
A_d & \quad \text{Displacer area (m}^2) \\
A_p & \quad \text{Piston area (m}^2) \\
A_{rod} & \quad \text{Displacer rod area (m}^2) \\
C_d & \quad \text{Displacer damping (N·s/m)} \\
C_h & \quad \text{Heater head thermal capacitance (J/K)} \\
C_p & \quad \text{Piston damping (N·s/m)} \\
C_t & \quad \text{Tuning capacitance (µF)} \\
f & \quad \text{Operating frequency (Hz)} \\
I_{alt} & \quad \text{Alternator current (A)} \\
K_{bounce} & \quad \text{Bounce space spring rate (N/m)} \\
K_d & \quad \text{Displacer spring rate (N/m)} \\
K_{magnet} & \quad \text{Alternator magnet space spring rate (N/m)} \\
K_p & \quad \text{Piston spring rate (N/m)} \\
L_{alt} & \quad \text{Alternator inductance (H)} \\
M_d & \quad \text{Effective displacer mass (kg)} \\
M_p & \quad \text{Effective piston mass (kg)} \\
M_W & \quad \text{Gas molecular weight} \\
N & \quad \text{Number of turns on the alternator winding} \\
P & \quad \text{Stirling cycle dynamic pressure (Pa)} \\
P_c & \quad \text{Compression space pressure (Pa)} \\
P_e & \quad \text{Expansion space pressure (Pa)} \\
P_{exp} & \quad \text{Expansion space PV power (W)} \\
P_d & \quad \text{Displacer pressure factor (Pa/m)} \\
P_p & \quad \text{Piston pressure factor (Pa/m)} \\
Q_{in} & \quad \text{Heat into the Stirling cycle (W)} \\
Q_{out} & \quad \text{Heat rejected (W)} \\
Q_{source} & \quad \text{Heat delivered by the heat source (W)} \\
R_{alt} & \quad \text{Alternator electrical resistance (Ω)} \\
R_c & \quad \text{Compression space thermal resistance (W/m·K)} \\
R_e & \quad \text{Expansion space thermal resistance (W/m·K)} \\
R_{gas} & \quad \text{Gas constant (J/kg·K)}
\end{align*}
\]
The Component Test Power Convertor

The CTPC is a 12.5-kWe free-piston Stirling convertor designed, built, and tested in the late 1980s and early 1990s by Mechanical Technology Inc. (MTI) (ref. 5). The convertor took heat from radiant electric heaters or from heat pipes and converted it to about 70-Hz AC electric power. With an input temperature of 800 K and a temperature ratio of 2.0, overall conversion efficiency was about 22 percent.

This paper summarizes the modeling of the CTPC system using NASA Glenn Research Center (GRC) System Dynamic Model (SDM) (refs. 6 and 7). The SDM models the system from the heat source to the Stirling convertor to output power and rejected heat. The heat source model includes insulation loss and the temperature drops from the heat source to the Stirling convertor heater. The Stirling convertor model includes the Stirling cycle thermodynamics, heat flow, mechanical mass-spring damper systems, and the linear alternator. The heat rejection system model assumes a fixed temperature heat sink, but could be expanded to include a more realistic radiator system.

CTPC Dynamic Model

A high-level schematic of the model is shown in figure 1. Starting at the bottom of the figure, the heat input to the Stirling cycle was represented by the heat input $Q_{source}$, shown with two flow paths emanating from it. One flow path represents the heat lost through the insulation to ambient temperature and has the thermal resistance $R_{ins}$. The other flow path represents the heat conducted to the heater. There is a temperature drop from the heat source to the heater. The temperature drop was modeled by the resistance $R_{h}$. The thermal time constant of the heat input system was modeled by the thermal capacitance $C_{h}$. This parameter was determined based on the mass of the CTPC heater and its heat capacity.

Not all of the heat entering the heater of the Stirling convertor goes into the Stirling cycle. Some is conducted to the cold end through paths including the heater head wall,
inner cylinder, helium gas, regenerator matrix, and the displacer. This loss was modeled by the heat flow through the thermal resistance $R_{\text{hhCondLoss}}$.

The Stirling cycle thermodynamics are modeled based on the Schmidt model (ref. 8), which assumes an isothermal Stirling cycle. Pumping losses through heat exchangers and the regenerator are considered. The thermodynamic portion of the model determines the internal expansion space and compression space gas pressures $P_e$ and $P_c$. These pressures generate the driving forces on the displacer mass $M_d$ and the piston mass $M_p$. Gas spring and damping forces on the displacer are represented by $K_d$ and $C_d$. The piston is subjected to spring force $K_p$, the sum of the bounce space spring $K_{\text{bounce}}$ and the magnet spring $K_{\text{magnet}}$.

The alternator produces a damping force on the piston based on the alternator current. Alternator electrical dynamics are determined by the alternator resistance, inductance, motor constant, and the tuning capacitor.

The Stirling convertor was assumed to be rigidly connected to the ground. Casing motion, dual-opposed dynamics, and the effect of a dynamic balancer could be added to this model if desired.

The model shown in figure 1 captures the major dynamics of the CTPC system. These include the thermal, mechanical, electrical, controller, fluid, and gas dynamics. With these characteristics captured in one system model, dynamic interactions and effects can be studied and analyzed.

**Linear Dynamic Stirling Model**

The ultimate selection of a model configuration is determined by a number of factors, including:

- Dynamics required based on simulation objectives
- Simulation time
- Model platform

In order to provide a model that captures the necessary Stirling convertor dynamics but does not require excessive simulation time and can be easily ported to other platforms (e.g., Matlab/Simulink) (The MathWorks, Inc.), a linear model of the CTPC was developed based on the nonlinear SDM model (ref. 9). The nonlinear model captured physics-based details of the CTPC and determined linearized parameters. These linearized parameters can be used to create a model in Matlab/Simulink or any other dynamic modeling tool that can be integrated into a larger system.

Linear dynamic models have been used for many years to design and analyze free-piston Stirling engines. These models show the piston and displacer masses are acted upon by spring forces and damping forces. The spring forces can include both mechanical components and components produced by the Stirling cycle pressure wave. The alternator is considered rigidly coupled to the piston, and the electrical load is assumed to be purely resistive. The equations for this model are as follows:

\[
\frac{dx_d}{dt} = \dot{x}_d
\]  
(1)

\[
\frac{dx_d}{dt} = \left( K_d + A_d \frac{\partial P}{\partial x_d} \right) \frac{1}{M_d} x_d + \left( A_d \frac{\partial P}{\partial x_d} - C_d \right) \frac{1}{M_d} \dot{x}_d + \left( A_d \frac{\partial P}{\partial x_d} \right) \frac{1}{M_d} \ddot{x}_d
\]  
(2)

\[
\frac{dx_p}{dt} = \ddot{x}_p
\]  
(3)

\[
\frac{dx_p}{dt} = -A_p \frac{\partial P}{\partial x_p} \frac{1}{M_p} x_d - \left( K_p + A_p \frac{\partial P}{\partial x_p} \right) \frac{1}{M_p} x_p - \frac{C_p}{M_p} \dot{x}_p + \frac{N}{dx_p} \frac{d\Phi}{\eta_{\text{mag}}} \frac{1}{M_p} I_{\text{alt}}
\]  
(4)

Equations (1) through (4) represent the dynamic equations for the displacer and the piston. In equation (2), the force due to the pressure wave’s action on the displacer area $A_d$ has been accounted for in two parts. This is because the pressure is expressed as a linear combination of the piston and displacer positions. In order to reconstruct the pressure wave, the contribution of both components must be considered. The same discussion applies to the pressure force on the piston in equation (4).

**Thermal System Model**

Figure 2 shows the thermal system modeled as a series of thermal resistances with a heat capacitance, heat input, and temperature sinks. It is analogous to figure 1 with the electromechanical components removed. The schematic shows the system as it is configured in Ansoft Simplorer (Ansoft Corporation) the platform used for the CTPC model. Thermal energy from the heater $Q_{\text{source}}$ is divided between two flow paths: (1) heat lost through the insulation to ambient is determined from $R_{\text{ins}}$ and (2) heat transferred to the heater head is determined from $R_h$. The resulting heat flow to the heater head causes an increased convertor hot-end temperature $T_h$.  

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Figure 2.—Schematic of the thermal system model.

Thermal energy from $T_b$ is divided among three flow paths: (1) heat lost via conduction through the convertor housing and displacer is determined from $R_{hhCondLoss}$, (2) heat transferred to the gas in the expansion space is determined from the gas dynamics, and (3) heat transferred to the heater head material is determined from the heater head thermal capacitance $C_h$. Thermal capacitance only becomes apparent during transient analysis; at steady-state operation, the heater head temperature is constant, and heat flow is divided between the conduction loss and heating of the gas expansion space, with the bulk of the heat being transferred to the latter.

Heat is rejected from the convertor to the cold sink temperature $T_c$. Most of the rejected heat flows from the working fluid. The remainder of the heat rejected is from the conduction losses.

The thermal model determines the hot and cold gas temperatures ($T_h$ and $T_c$) for the Stirling cycle, but does not calculate cycle performance or convert heat energy into mechanical energy. This is accomplished by coupling the linear Stirling model to the thermal system model. The next section will further discuss how the model coupling is performed.

**Coupling Stirling Linear Model and Thermal System Model**

To complete the linear model of the CTPC, the Stirling linear model has to be coupled to the thermal system model. Because the response time of the Stirling cycle is on the order of milliseconds, while the response time of the thermal system is on the order of seconds or minutes, the two systems were algebraically coupled together through the pressure factors.

The pressure factors are the partial derivatives of the pressure wave $P$ with respect to displacer position $x_d$ and piston position $x_p$. The equations to couple the systems can be derived from the Stirling cycle equations as derived by Urieli and Berchowitz (ref. 8).

\[
P = M_w \cdot R_{gas} \cdot \left(\frac{V_h}{T_h} + \frac{V_r}{T_r} + \frac{V_k}{T_k} + \frac{V_e}{T_e} + \frac{V_c}{T_c}\right)^{-1}
\]  

(6)

In equation (6) the volumes $V_e$ and $V_c$ are functions of $x_d$ and $x_p$. The other variables are assumed to be fixed over a given cycle.

\[
V_e = V_{xo} - A_d x_d
\]  

(7)

\[
V_c = V_{co} - A_p x_p + (A_d - A_{rod}) x_d
\]  

(8)

Substituting equations (7) through (10) into equation (6) and differentiating yields the following expressions for the pressure factors:

\[
\frac{\partial P}{\partial x_p} = \frac{A_p M_w R_{gas}}{Q_h R_c + T_k} \cdot \left[\frac{V_{eo} - A_p X_p + (A_d - A_{rod}) X_d}{Q_h R_c + T_k} + \frac{V_k}{T_k}\right] \cdot \left[\frac{V_e}{T_h - T_k} + \frac{V_{eo} - A_d X_d}{T_h - Q_h R_c}\right]^{-2}
\]  

(12)

\[
\frac{\partial P}{\partial x_d} = -M_w R_{gas} \cdot \left[\frac{(A_d - A_{rod})}{Q_h R_c + T_k} \cdot \frac{A_d}{T_h - Q_h R_c}\right] \cdot \left[\frac{V_{eo} - A_p X_p + (A_d - A_{rod}) X_d}{Q_h R_c + T_k} + \frac{V_k}{T_k}\right] \cdot \left[\frac{V_e}{T_h - T_k} + \frac{V_{eo} - A_d X_d}{T_h - Q_h R_c}\right]^{-2}
\]  

(13)
The pressure factors are now functions of $T_h, T_k, Q_h$, which can be determined based on the dynamics of the thermal system. The pressure factors are also functions of $x_p$ and $x_d$.

To algebraically couple the thermal system with the Stirling model, it is also necessary to calculate the expansion space PV power $P_{\text{exp}}$. The expansion space PV power is approximately equal to the heat flow into the Stirling cycle:

$$Q_h \approx \int PdV$$

For the expansion space,

$$V_e = V_0 - A_d x_d$$

Since

$$x_d(t) = x_{d,\text{amp}} \sin(\omega t + \phi_d)$$

$$x_p(t) = x_{p,\text{amp}} \sin(\omega t)$$

then

$$\frac{dV_e}{dt} = -A_d x_{d,\text{amp}} \omega \cos(\omega t + \phi_d)$$

Also, the pressure in the expansion space is a function of the pressure factors.

$$P(t) = P_{d} x_d(t) + P_{p} x_p(t)$$

Substituting equations (18) and (19) into equation (14) and integrating, then multiplying by the frequency $f$ to give the expansion space PV power:

$$P_{\text{exp}} = \pi A_d f x_{d,\text{amp}} x_{p,\text{amp}} P_p \sin \phi_d$$

**Simulation Results**

The CTPC was modeled in SDM based on parameters available in a NASA document “Stirling Space Engine Program, Volume 1—Final Report.” (ref. 1) Key model parameters are provided in the table A–I in appendix A. A comparison of CTPC test data, SDM simulation, and linearized model simulation are summarized in table I. The SDM model shows good correlation between the test data for most parameters, with the larger differences attributable to the isothermal model assumption used in SDM. This assumption results in a reduced pressure amplitude but higher pressure phase angle. Further refinements to the SDM model of the CTPC could be made if necessary to improve model fidelity, including enhancement of the thermodynamic model (ref. 10).

The linearized CTPC model tracks well to the nonlinear model for most parameters.

**Future Modeling Efforts**

The CTPC was the first benchmark for the SDM against a multi-kilowatt converter. However, the CTPC represents hardware that was developed in the late 1980s for which there is limited available test data. NASA GRC is in the process of procuring dual-opposed 1-kW Stirling convertors with the intent to investigate heater head concepts. The convertor will not be flight-like, but does represent state-of-the-art hardware.

The new hardware provides the opportunity to compare the SDM analysis to test data from another high-powered Stirling convertor. The convertor specifications will be incorporated into the SDM to generate both linear and non-linear models with the goal of simulating dynamic performance. The convertor will initially be tested at GRC with an electric cartridge heater as the heat source. This test will provide data for comparison to analytical predictions generated by the SDM. Because the SDM emphasizes convertor electromechanical behavior, it would be desirable to obtain data that involves changes in load and piston amplitude and/or frequency. There is potential for tests that include various controller set points to capture the off-nominal electromechanical behavior of the convertor in addition to its steady-state design operating point.

A power conversion system for space applications might consist of a set of Stirling convertors coupled to a liquid metal-cooled nuclear fission reactor. Therefore, the test convertors could be modified at the header head to permit operation with a liquid metal heat transfer loop such as the NaK-cooled reactor simulator recently installed at NASA Marshall Space Flight Center (MSFC) (ref. 11). This test
would provide the opportunity to enhance the hot-end thermal modeling in the SDM and supply additional convertor test data.

Conclusions

Dynamic modeling of high powered Stirling convertors facilitates for the development of space nuclear power systems. An accurate dynamic model that comprises all aspects of the convertor—from the heat source to heat rejection to electromechanical power generation—can assist in the design of an optimized system. Developing such a model requires a firm understanding of the Stirling convertor subsystems, as well as methods for validating the model’s accuracy.

This paper presented the model configuration and methodology employed to simulate a free-piston Stirling converter. The model was designed to represent the hardware for the multi-kilowatt CTPC, and results were compared to the limited test data available. Discrepancies between the simulation results and data are attributed to the model assumptions. Further refinement of the model is possible in order to achieve a higher fidelity model.

Additional simulations of multi-kilowatt convertors will take place as test data and hardware specifications become available. The more opportunities one has to validate the model, the more valuable it will be for the successful design of a dynamic power conversion system.

References

## Appendix A

### TABLE A–I.—CTPC MODEL PARAMETERS

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<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Description</th>
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</thead>
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<tr>
<td>Cd</td>
<td>42.7</td>
<td>N·s/m</td>
<td>Displacer damping</td>
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<td>Cp</td>
<td>40.1</td>
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<td>Piston damping</td>
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<td>Md</td>
<td>2.17</td>
<td>kg</td>
<td>Effective displacer moving mass</td>
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<tr>
<td>Mp</td>
<td>13.176</td>
<td>kg</td>
<td>Effective piston moving mass</td>
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<td>DiaD</td>
<td>0.1143</td>
<td>m</td>
<td>Displacer diameter</td>
</tr>
<tr>
<td>Odp</td>
<td>0.13716</td>
<td>m</td>
<td>Piston diameter</td>
</tr>
<tr>
<td>OdRod</td>
<td>0.0244835</td>
<td>m</td>
<td>Displacer rod diameter</td>
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<td>Vco</td>
<td>1.2091e-3</td>
<td>m³</td>
<td>Mean compression space volume</td>
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<td>Mean expansion space volume</td>
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<td>Heater number of channels</td>
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<td>HHxDia</td>
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<td>m</td>
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<td>Vr</td>
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<td>Regenerator fill factor (porosity)</td>
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<td>Rdw</td>
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<td>Rgas</td>
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<td>gammaHe</td>
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<td>Alternator resistance at operating temperature</td>
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<td>Laht</td>
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<td>Thermal resistance to model temperature drop between $T_s$ and $T_e$</td>
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</table>
14. ABSTRACT

A dynamic model of a high-power Stirling convertor has been developed for space nuclear power systems modeling. The model is based on the Component Test Power Convertor (CTPC), a 12.5-kWe free-piston Stirling convertor. The model includes the fluid heat source, the Stirling convertor, output power, and heat rejection. The Stirling convertor model includes the Stirling cycle thermodynamics, heat flow, mechanical mass-spring damper systems, and the linear alternator. The model was validated against test data. Both nonlinear and linear versions of the model were developed. The linear version algebraically couples two separate linear dynamic models; one model of the Stirling cycle and one model of the thermal system, through the pressure factors. Future possible uses of the Stirling system dynamic model are discussed. A pair of commercially available 1-kWe Stirling convertors is being purchased by NASA Glenn Research Center. The specifications of those convertors may eventually be incorporated into the dynamic model and analysis compared to the convertor test data. Subsequent potential testing could include integrating the convertors into a pumped liquid metal hot-end interface. This test would provide more data for comparison to the dynamic model analysis.

15. SUBJECT TERMS

Stirling cycle; Dynamic models