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Free-Piston Stirling Convertor Controller Development at NASA Glenn Research Center

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March 2004

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FREE-PISTON STIRLING CONVERTOR CONTROLLER DEVELOPMENT AT NASA GLENN RESEARCH CENTER

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Abstract

The free-piston Stirling convertor end-to-end modeling effort at NASA Glenn Research Center (GRC) has produced a software-based test bed in which free-piston Stirling convertors can be simulated and evaluated. The simulation model includes all the components of the convertor – the Stirling cycle engine, linear alternator, controller and load. This paper is concerned with controllers. It discusses three controllers that have been studied using this model. Case motion has been added to the model recently so that effects of differences between convertor components can be simulated and ameliorative control engineering techniques can be developed. One concern when applying a system comprised of interconnected mass-spring-damper components is to prevent operation in any but the intended mode. The design mode is the only desired mode of operation, but all other modes are considered in controller design.

Nomenclature

X_p	Piston Amplitude
K_i	Alternator Force Factor, N/A
K_v	Alternator Voltage Factor, Vs/m
ω_o	operating frequency
P_w	Working pressure
P_{PV}	P-V Power
A_p	Piston Area
SRG	Stirling Radioisotope Generator – DoE system for providing electrical power to deep space missions under development
TDC	55We Technology Demonstration Convertor
SPRE	Space power research engine

Introduction

The Stirling Radioisotope Generator (SRG) is a power source being developed for deep space missions by Lockheed Martin Astronautics (LMA). It is described by LMA's Cokefield and Chan.[1] The convertor used in the SRG is the Technology Demonstration Convertor (TDC) designed and manufactured by Stirling Technology Company (STC). Independently of the work being done by LMA, but closely related to it, engineers at NASA's Glenn Research Center (GRC) have been studying the application of control engineering concepts to the resonant reciprocating free-piston machine in an SRG-like system. The object is to enable the development of advanced controllers. The free-piston Stirling literature is limited in this. It is difficult to find specific guidelines for free-piston Stirling engine control. One paper by Rauch and Kankam[2] reported on the modeling and control of the Space Power Research Engine (SPRE) convertor. It presented a state-variable approach to modeling and some conclusions about stability that followed from the modeling. This paper will communicate what has been learned concerning free-Piston Stirling control as it relates to the TDC and SRG-like systems. Work at GRC has studied three specific styles of controllers. They are classified as:

1. Controllers with parasitic DC loading
2. Controllers with parasitic AC loading
3. Controllers that maintain a reference current

Control Concept for SRG-Like System

The control concept for dual opposed free-piston Stirling convertors studied at NASA GRC is shown schematically in Figure 1. Radioisotope heat sources provide energy to the hot ends of the Stirling TDC's. No provision is made for modulating the heat input. Rather, the system is designed to produce quasi-constant electrical power providing the spacecraft load demand and dissipating the excess in parasitic load. It is termed quasi-constant and not constant because deep space missions last many years, and radioisotope heat output will decay over that time. Although the SRG's electrical power output is not constant over many years, there is no discernable difference in the number of cycles available in a time-domain simulation. The engines are to oscillate in phase electrically but 180° out of phase as far as the motion is concerned so that each engine cancels the motional effects of the other. The Stirling cycle drives linear alternators, which generate an alternating current. The current is regulated by a controller and the regulated current is used to power the spacecraft load. The controller is designed to hold a certain operating point. That is, it is designed to maintain operation at a certain piston amplitude and hot end temperature. The controller allows some adjustment so that the operating point may be moved -- hot end temperature or piston amplitude may be adjusted up or down.

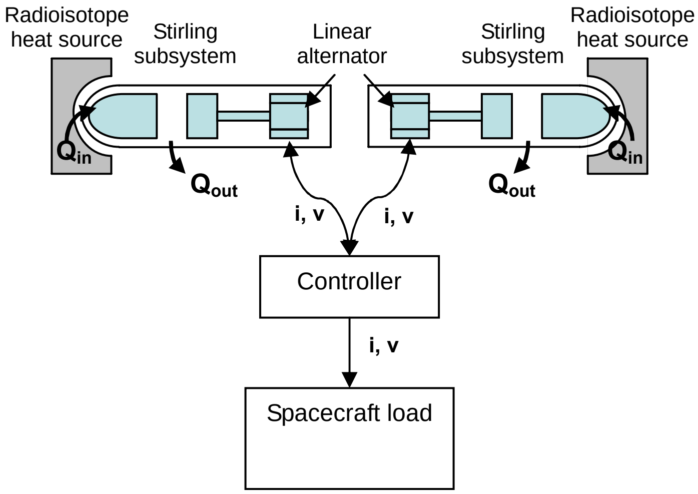

Figure 1. SRG Control Concept

The controller must also sense when a user load is being drawn and compensate for it in a way that keeps the system running at the selected operating point. Regulation of the alternator stator current is the one means available to accomplish the control objectives.

Here it is useful to point out two differences between the control of a reciprocating resonant machine like the TDC and rotating machines—which are the type of machines treated in most control engineering literature. In a rotating machine, one rotating field pulls or pushes another and the angular difference between them is controlled. It is some dc quantity. That is, it doesn't reverse directions as a matter of normal operation. In a reciprocating machine, most measurable quantities do reverse direction twice each cycle in normal operation. The control laws of conventional feedback control can be applied to reciprocating machines, but so far only to statistics of the instantaneous quantities such as the rms current or average current. They have not yet been successfully applied to the instantaneous quantities themselves.

The other difference between control of rotating machines and TDC-like machines is due to the fact that the TDC operates at resonance. The damping applied to a resonant reciprocating machine excited at its resonant frequency is the determiner of how quickly the amplitude changes with time. It is the character of the damping that serves as the means of all known methods of free-piston Stirling convertor control. Figure 2 shows a hypothetical engine power characteristic and two hypothetical load characteristics. One load varies exponentially with the piston amplitude. The other varies as the cube of the piston amplitude. The operating point is the point on the curve where the engine power is equal to the load power. For piston amplitudes any greater than the operating point the load is greater than the engine power and amplitude will decrease. For amplitudes smaller than the operating point, engine power is greater than the load power and amplitude will be driven to increase. One would expect that a controller based on the exponential load curve to have better dynamic characteristics than one based on the cubic. The exponential load curve intersects the engine power curve at a steeper angle. This means for the same size step in amplitude above or below the operating amplitude, the exponential-based controller will produce greater net change in the damping and as a result the amplitude will return to operating amplitude in less time.

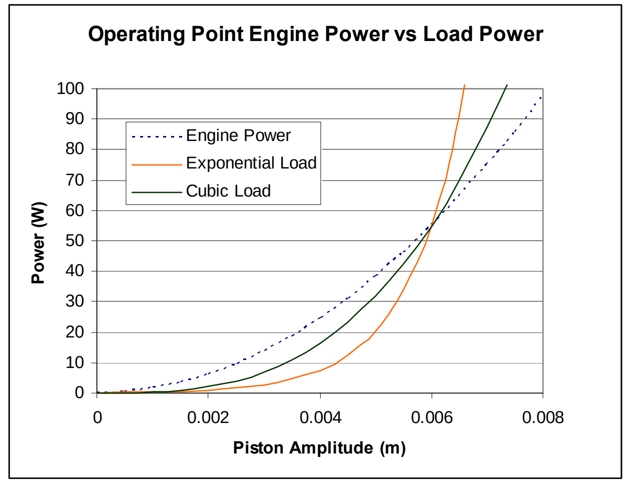

Figure 2. Operating point is where load power crosses engine power.

Pressure Force – Power Relationship

The subject of controllers is concerned with the mechanical power developed by the engine and converted by the alternator and the electrical power dissipated by the load. As a means of introduction then, the mechanical and electrical fundamental relationships are stated. The relationship between working pressure and driving force is developed. The relationship between alternator stator current and damping force is then developed. The criterion for stable convertor operation is that the driving force be equal to the damping force. The consequent relationships between P-V power and alternator power output are also developed.

Pressure force acting on the piston is expressed

$$F_P = A_P P_w \qquad (1)$$

This force has a component leading the piston motion by 90° and a component in phase with the motion. The component in phase with the motion adds to the piston spring force. The quadrature component drives the motion. The power expended by this force for sinusoidal motion of the piston is expressed in (2)

$$P_{PV} = X_P \omega_o F_{P\perp} \qquad (2)$$

where the subscript $\perp$ indicates the component of P_w that leads the piston motion by 90°. Closed form expressions for that component of pressure force involve many terms – all the design parameters of the Stirling engine in fact. Accuracy is improved by considering Fourier components of the parameters so that a closed form expression includes many terms and can go on for pages. Working with simulation models dispenses with such calculations except for use in checking results. All the Fourier components and phase relationships are embedded within the signal as the simulation proceeds. The reader is referred to Berchowitz[3] for more detail concerning the expression for PV power.

Stator Current – Force Relationship

The function of the linear alternator is to transform reciprocating motion of the piston into a voltage that can be used to energize load circuits. As load circuits cause current to flow in the alternator stator, such current causes a mechanical damping force to be felt on the mover. Of course, this is just what one expects from conservation of energy. Alternators produce voltage according to Faraday's law, that is, the voltage is equal to the rate of change of the magnetic field cutting the stator windings. The amount of field that cuts the stator windings varies according to the design of the alternator. Alternators are designed to be efficient so that as a first order approximation

$$v(t) = K_v \omega_o X_P \cos(\omega_o t) \tag{3a}$$

$$V = \frac{1}{\sqrt{2}} K_v \omega_o X_P \tag{3b}$$

that is, K_v is the constant of proportionality between speed and voltage. K_v encompasses the effects of both the magnetic field and its coupling. If this voltage were applied to a load circuit consisting of a resistor, R, the resulting current is

$$i(t) = \frac{K_v}{R} \omega_o X_P \cos(\omega_o t) \tag{4a}$$

$$I = \frac{1}{\sqrt{2}} \frac{K_v}{R} \omega_o X_P \tag{4b}$$

As a first order approximation, for an efficient linear alternator, the force felt by the mover and piston when load current i flows in the stator is proportional to current. If the constant of proportionality is taken as K_i then the force may be expressed as K_i times the current as expressed in (4a,) or

$$F_i = \frac{K_v K_i}{R} \omega_o X_P \cos(\omega_o t) \tag{5}$$

The instantaneous piston power required to drive the force F_i is the product of the force and the piston velocity.

$$p_{alt}(t) = \frac{K_v K_i}{R} \omega_o{}^2 X_P{}^2 \cos^2(\omega_o t) \tag{6a}$$

The average piston power is the average over a period:

$$P_{Alt} = \frac{K_v K_i}{RT} \omega_o^2 X_P^2 \int_0^T \cos^2(\omega_o t) dt \tag{6b}$$

and evaluated,

$$P_{Alt} = \frac{K_v K_i}{2R} \omega_o^2 X_P^2 \tag{7}$$

As long as the voltage and the current are in phase, the electrical power dissipated in the load is just the product of the rms voltage and rms current (3b) and 4(b) or,

$$P_{Load} = \frac{K_v{}^2}{2R} \omega_o^2 X_P^2 \tag{8}$$

Now it is seen that the power dissipated in the load is equal to the power exerted in driving the alternator if K_v is numerically equal to K_i. This is so even though the two constants do not have the same units. K_v has units of volt-seconds per meter. K_i has units of Newtons per Ampere In system modeling, values for K_v and K_i must be selected. In general, if the power output rating and operating frequency are known, reasonable values can be chosen. Electric machine design techniques and software can be used to obtain values that accurately account for iron loss, copper loss and magnetic field coupling coefficient

TDC Modeling

The model developed for the Stirling convertor has been described in Regan, Gerber and Roth.[4] With reference to Figure 3b, the items labeled TDC #13 and #14 are models of

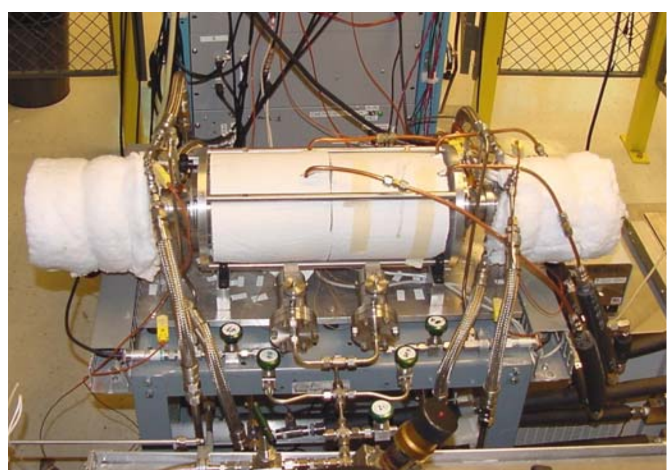

Figure 3a. TDC #13 #14 Test bed arrangement

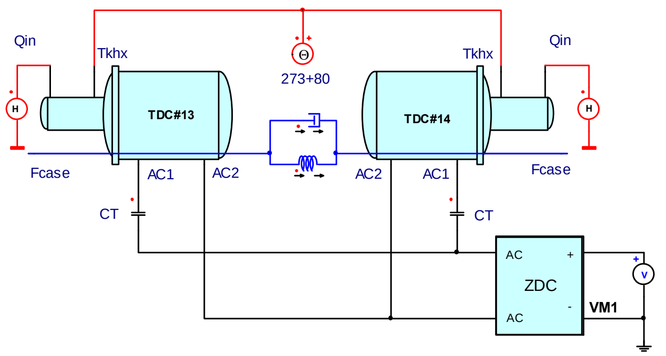

Figure 3b. TDC #13 #14 Test bed simulation arrangement

the TDCs under test at GRC. Inside each are two mass spring damper systems driven by a common pressure. One is referred to as the displacer and the other as the piston. The block labeled ZDC is the Zener diode controller. The ZDC block is connected to the TDC's electrical alternator terminals. The lines labeled *Fcase* at each TDC are force nodes carrying the force caused by the reciprocating motion of the displacer and the piston inside the case. The *Fcase* nodes from each TDC are connected to each other through spring and damper elements that model the coaxial mounting of the two TDCs in the test cell. That is, the TDCs are mounted along a common axis and are connected to each other by means of rods. A heat source, labeled H, models the radioisotope heating element. A temperature source, labeled Θ, models the radiator as a constant 353K temperature. In a time-domain simulation, waveform information is available, including P-V power, piston displacement, displacer displacement, temperatures, fluid velocity, heat exchanger pressure drop and pressure.

Another type of simulation performed on the same model is referred to as an ac frequency response analysis. It is used to generate frequency response curves such as Bode plots. Frequency response data is valuable since all of classical control theory is understood in terms of frequency response.

Frequency response is a linear systems tool but the information can also be obtained for linearized non-linear systems and used in much the same way. The frequency response is the ratio of an output signal to an input signal as the input signal's frequency is swept over the range of interest. The output and input signals are complex, so the ratio has a magnitude aspect and a phase shift aspect. The Simplorer software model of the TDC contains some non-linear elements. The controllers especially use state-diagram based switching which give non-linear results. The TDC itself has important features for which non-linear models are the only valid models to use. For linear systems, the frequency response is fixed and independent of the operating point. That is not the case for the TDC. The frequency response analyzer (FRA) is a test equipment item that measures and records frequency response. The equipment injects a small voltage at a swept frequency into the control loop. The frequency is filtered out of the input and measured in magnitude and phase by means of a fast fourier transform. FRA testing of TDC#7 and TDC#8 with the ZDC will be performed at GRC. The same type of plot can be obtained from the Simplorer software by mimicking the setup of the FRA test.

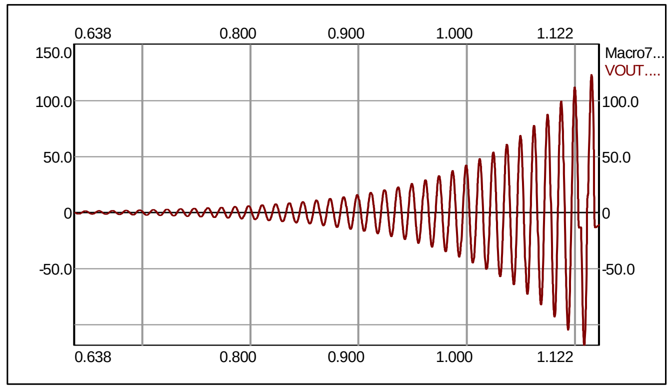

Figure 4. Open start-up loop transient response of TDC output voltage

Figure 4 shows the open loop transient start-up response of one TDC – also useful in control design. Open loop refers to the fact that there is no controller. The rate of rise of the open loop voltage at start up indicates the worst case voltage changes to be encountered at start-up. This characteristic was used to detect a start up condition by the controller and to initiate control action counter the effect of too energetic a response. The resulting controller model was able to go through start up without hitting the end stops.

Electronic Load Controllers

As the SRG application does not modulate the thermal input power, there is a need to assure that the electric power dissipated in the load is constant and is equal to the power input less losses. Since end-use loads must be considered as disturbances, the load controller must determine how much load is connected and adjust whatever electrical load is required to bring the load back to its setpoint value. Controlling the magnitude of stator current and controlling the time of its application and removal gives control over the load power. As an illustration, consider a cycle running with a PV power of 50W and a peak piston velocity of 3m/s. If a current of 0.7A is applied to the stator windings only during the peak 40% of the velocity cycle (during which the average velocity of the piston is about 0.9 times the peak), then the power transmitted in the half cycle is

$$3 \cdot 0.9 m/s \cdot 0.7 A \cdot K_i N/A \cdot 40\% = 0.756 K_i W$$

For K_i=35N/A, this is a power of 26W or a cycle power of a little over 50W. Using the illustration, it is easy to see that at least two parameters are available for manipulation by the controller: the magnitude of the stator current and its timing. Schemes can be envisioned in which stator current is applied in patterns that will not only convert rated power but also achieve other useful objectives such as the cancellation of vibration. Kopasakis and Cairelli[5] at GRC have developed a Stirling cryocooler controller that alters the current waveform to achieve reduction in cryocooler vibration. GRC has plans to use similar techniques as a feature in Stirling engine controllers.

Controllers with Parasitic DC Loading

A style of controller that has been very successful makes use of a characteristic of the common rectifier circuit. Rectifier diodes allow current flow in only one direction. The output voltage of the rectifier resembles the absolute value of the sinusoidal input voltage. The increasing portion of the rectifier output voltage is used to charge the filter capacitor. When the capacitor voltage is greater than the absolute value of the input voltage, the capacitor is charged and no more charging current is drawn from the ac source. DC loads draw their energy directly from the filter capacitor. Thus, a rectifier circuit is seen to make a good load for the Stirling convertor as long as the input voltage signal is in phase with the piston velocity. The reason is that filter capacitor charging current is always drawn while rectifier input voltage is at its peak. It is at its peak when the piston velocity is greatest. This is the case regardless of the timing of the dc side load since it is only the charging of the filter capacitor that draws stator current.

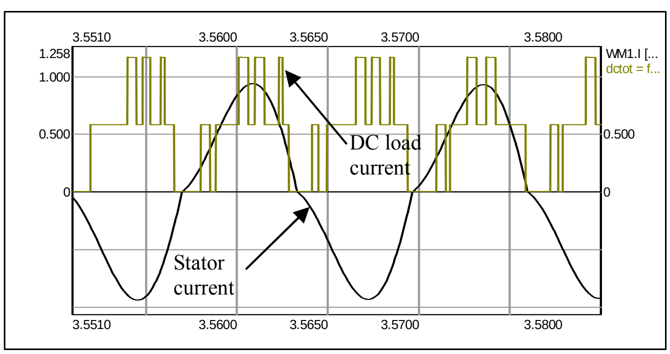

Figure 5. Stator current and DC load current due to the controller identified as ZDC in Figure 3b.

The fixed dc load is not a practical controller unless it allows user loads to be drawn from the dc bus. This can be done if the load on the dc bus is regulated. It is regulated by monitoring the instantaneous dc voltage and switching loads on whenever the bus voltage is too high and removing loads when it is too low. Figure 5 shows total dc parasitic load current superimposed on the ac stator current. The dc current is switched according to the instantaneous dc voltage. With such a circuit, the user load can draw any dc current up to the rated load. As the user load is increased, the parasitic load is removed so that the total load remains constant.

A number of regulator schemes are available for use. The one used to produce the waveforms shown in Figure 6 bases its regulation on a zener diode voltage reference.

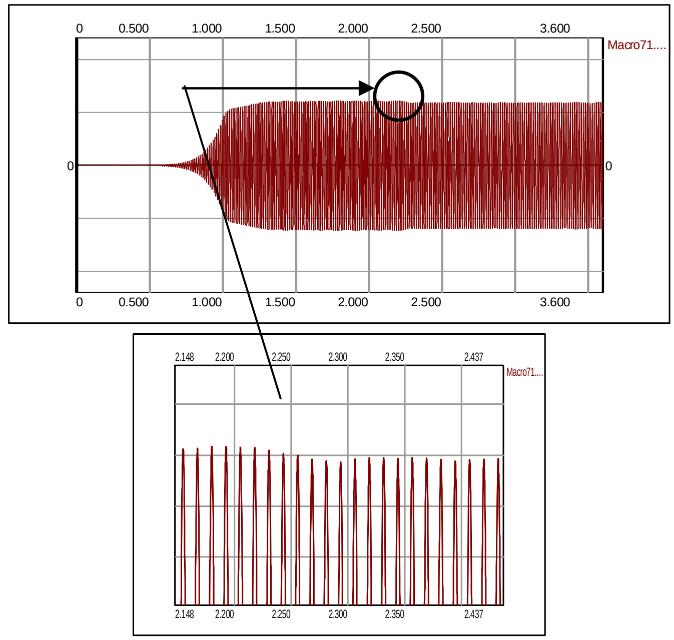

Figure 6. Piston amplitude for TDC with Zener diode controller with 200Ω Load applied at t = 2.2s.

As shown in Figure 6, the ZDC is able to absorb the effects of application of a 200Ω load with very small effect on the piston amplitude.

Controllers with Parasitic AC Loading

Parasitic electrical load can also be applied on the ac bus. One such controller scheme was the GRC Digital Controller developed by GRC during the 1990's for the SPRE project. It also makes use of a tuning capacitor to bring load current in phase with piston velocity. A schematic is shown in Figure 7. The controller synthesizes a voltage-controlled resistive load for the Stirling convertor. The method used to determine the resistance versus voltage function is to measure the controller input voltage using a voltage divider and an Analog Devices AD536 chip. The resulting dc voltage is converted to a proportional binary number in an analog-to-digital converter. The binary number at the output is used to close or open relays which connect/disconnect resistors at the ac bus. The result is a resistance that decreases as the applied voltage increases. It is an ideal load for the free-piston Stirling convertor. A load characterized by a constant resistance increases as the square of the voltage across it. The engine output load increases in much the same way – the result is that there is not a clear intersection of the engine output power with the load power for such loads. To overcome this effect, the SPRE controller changes the load resistance as the applied voltage changes. The resistance changes according to the RLoad expression found in Figure 7. The result is a load versus voltage characteristic as shown in Figure 8.

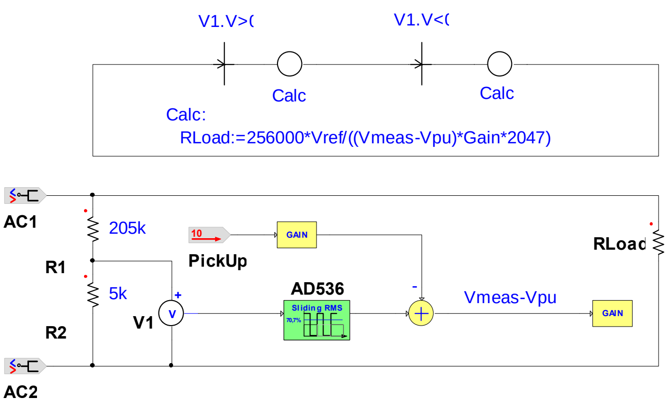

Figure 7. GRC Digital Controller

The resistance of the load has an adjustable pick-up point and an adjustable gain. Adjustment of the pick-up point has the effect of translating the load characteristic to the left or right. Adjusting the gain changes the slope of the characteristic. Adjusting either the pick-up or the gain will change the operating point. This controller switches resistors in and out only at zero crossings of the input. The SPRE controller was modified for use with the TDC engines and logged a number of hours during TDC tests in the past two years. Due to its full-cycle conduction, it maintains a fairly sinusoidal voltage at the alternator terminals. This is important

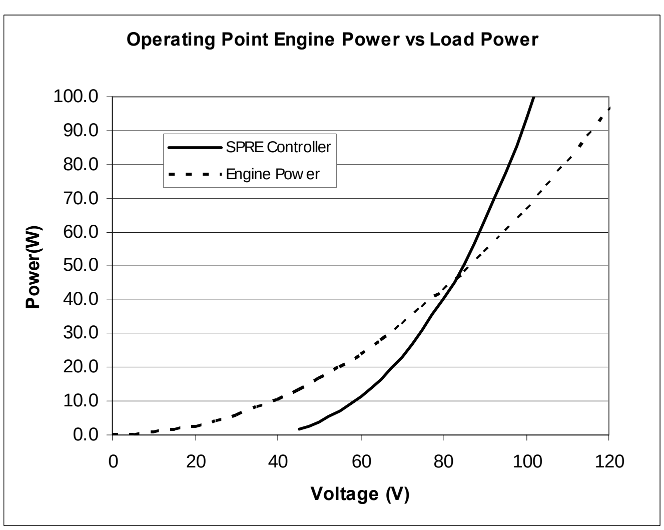

Figure 8. GRC Digital Controller characteristic

in some EMI testing. In TDC testing, the digital controller was used alone as a load bank. The original SPRE application fitted the controller with a PID front-end that operated to automatically adjust the horizontal position of the characteristic to maintain a setpoint of amplitude under various conditions of end-use loading.

A 2nd Generation Digital Controller is now being tested at GRC. It makes use of the zero-switched discrete parasitic resistors but the controller switches them not to synthesize a specific voltage controlled resistance characteristic but to directly maintain a voltage setpoint. The analog-to-digital converter (ADC) is again used but it looks at the difference between terminal voltage and the setpoint voltage. The resulting binary representation of the error present at the ADC output is added to a binary register containing the representation of the connected parasitic resistance. Thus the error adds to or subtracts from the connected load. Positive errors resulting from a measured voltage higher than the setpoint result in more resistance being connected to the bus. Negative errors result in resistance being removed from the bus. The simulation model of the GRC second generation digital controller is shown in Figure 9 with waveforms in Figure 10. The controller shown has a "measurement – Setpoint = error" configuration because it is used to iteratively calculate the parallel resistance correction to the convertor load. When the output voltage is greater than the setpoint, a positive resistance is computed. When the output voltage is too small a resistance needs to be removed from the bus and so a negative resistance is computed. The state transitions shown in the state diagram of Figure 9 regulate the calculation of

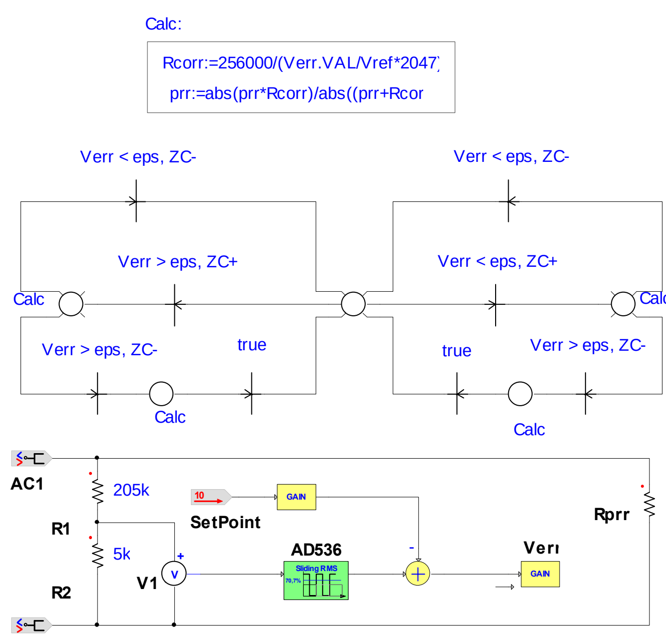

Figure 9. Simulation model of the GRC 2nd Generation Digital controller.

correction resistance, Rcorr so that the calculation is made only at zero crossings of the ac voltage and only when the error voltage is large enough to result in connection or disconnection of a parasitic load that is at least as large as the smallest increment of load. In the present design, the smallest increment of load is 256kΩ. The present implementation of the controller is in discrete analog and digital ICs, but a board has been laid out and software written for a microcontroller implementation as well.

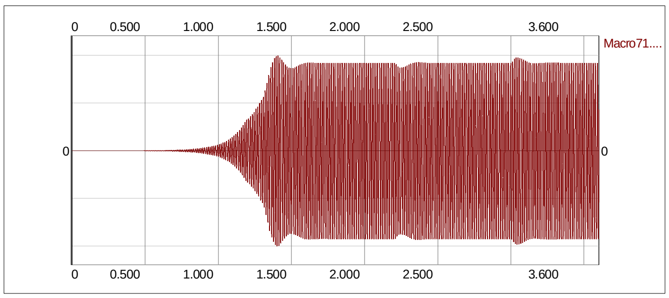

Figure 10a. Piston amplitude single TDC with 2nd Generation Digital Controller

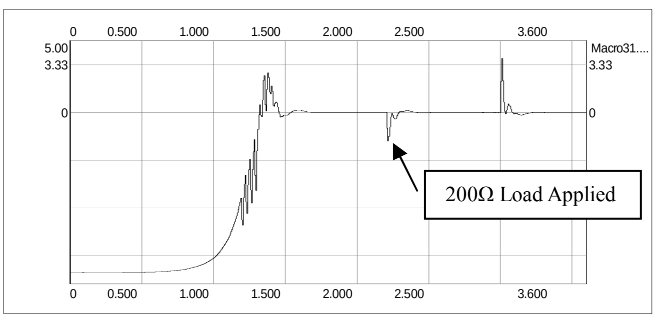

Figure 10b. Error Voltage TDC with 2nd Generation Digital Controller

Controllers that Maintain a Reference Current

The controllers discussed so far have required a tuning capacitor. The reason is that stator current must be in phase with piston velocity in to achieve stable operation. However, load current flows as a response to terminal voltage. When a tuning capacitor is used, terminal voltage is in phase with piston velocity. The phase discrepancy is caused by the inductance of the stator. It must be balanced out by a capacitance to make the complete circuit resistive. In resistive circuits, the voltage and current are in phase. A controller developed at GRC makes use of another method of estimating bringing the current into phase with the piston velocity. A piston position sensor is used to generate a position signal. The derivative of the position signal is the piston velocity. When piston velocity information is gained in this way the need for the tuning capacitor can be eliminated. The GRC advanced controller uses power electronics techniques to synthesize that required current waveform. Assume that the rated power of the convertor is W and the rated piston velocity is X_pDot m/s peak. The rated current is

$$I = \frac{W}{K_v X_p Dot} \tag{9}$$

The controller synthesizes a sinusoidal current in phase with the piston velocity and having rated amplitude that is based upon (10). A control loop varies the current amplitude in order to maintain a certain operating point.

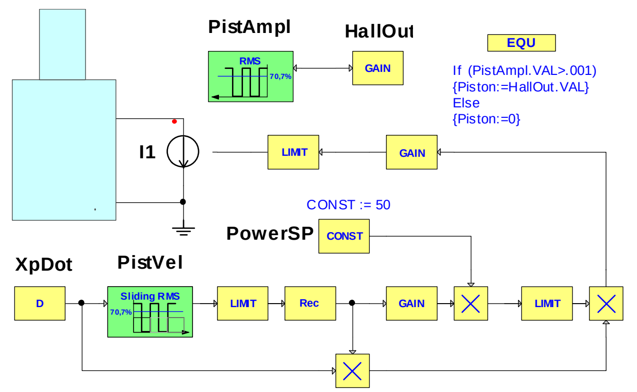

Figure 11. Current source used to control the load power.

Forcing a current to flow when the current is in phase with the piston velocity is yet another way of applying parasitic load. The current is used to charge capacitors downstream that are not shown in Figure 11. Just as in the case of the ZDC, that capacitor voltage will have to be managed in some way each half cycle for the system to operate properly. The voltage must be used to energize spacecraft loads or parasitic resistive loads. The capacitor is needed every half cycle to cause the correct amount of current to flow in the stator. A block diagram model of such a current source connected to the TDC model is shown in Figure 11. The usual connection for dual opposed TDCs is to connect the two alternator outputs together through tuning capacitors. Unless the two convertors are locked together electrically in such a way, it has been found that they drift out of synchronism. Using a controller like the GRC advanced controller, it may be possible to run without electrically connecting the two outputs. They will be forced to follow a synthesized current signal and the control system has some latitude in determining how the current signal should be synthesized. The signals must have identical frequencies and they must each provide a load that satisfies the basic stability criterion. Piston strokes could be controlled independently of one another.

Future Work

A vibration modeling feature has been added to the GRC end-to-end dynamic model. It can now be used to simulate the vibrational response of various mounting methods. The Simplorer language's circuit components for mechanical elements are used. Individual convertors can be interconnected with rods or mass-spring-damper elements.

Future work will use the vibration modeling to study the topic of tolerances and matching of machine components in a pair. If one piston is exactly the same as its counterpart piston in a pair, then the machines can be expected to run perfectly. How much difference is allowable is something that can be found out by simulation. The same technique can be used to study spring constants and alternator magnetic components.

Another topic for future study addresses what can be done if the convertors are not as closely matched as one would like. The performance of the system can be studied to simulate conditions of gradual loss of charge pressure over time and gradual change in values of tuning capacitance over time.

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13. ABSTRACT ***(Maximum 200 words)***

The free-piston Stirling convertor end-to-end modeling effort at NASA Glenn Research Center (GRC) has produced a software-based test bed in which free-piston Stirling convertors can be simulated and evaluated. The simulation model includes all the components of the convertor—the Stirling cycle engine, linear alternator, controller, and load. This paper is concerned with controllers. It discusses three controllers that have been studied using this model. Case motion has been added to the model recently so that effects of differences between convertor components can be simulated and ameliorative control engineering techniques can be developed. One concern when applying a system comprised of interconnected mass-spring-damper components is to prevent operation in any but the intended mode. The design mode is the only desired mode of operation, but all other modes are considered in controller design.

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Stirling engines; Design analysis; Block diagrams; Electromechanics; Dynamic models; Simulation; AC generators; Linear alternators; Stirling cycle

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