**A Study on Effect of Tuning Capacitor in Dynamic Radioisotope Power Systems**

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*This study presents the effect of the tuning capacitor on stability and electrical power output of a gas-bearing based free-piston Stirling convertor (FPSC) when operating on a fixed-frequency type controller. It has been widely accepted that the tuning capacitor is an important circuit component of the FPSC to stabilize piston amplitude and maximize electrical power output by correcting the power factor. Models suggest the stability of the FPSC is strongly coupled to the tuning capacitance, while the coupling to the electrical power output is weak. This applies to cases where the operating frequency of the FPSC is fixed by a fixed-frequency controller and other operating conditions, such as the hot-end and cold-end temperatures, piston amplitude, and pressure are constant. To verify the modeling analysis results, an Advanced Stirling Convertor (ASC) was controlled by an AC power supply and the piston amplitude, hot-end temperature, cold-end temperature, and pressure are actively controlled to 4.3mm, 760˚C, 40˚C and 485psig, respectively, while the tuning capacitor value was changed from 840μF to 1040μF and 1240μF. Furthermore, the vibration test results of the ASC with different tuning capacitor values are also presented to show the effect of the tuning capacitor on stability. The experimental test results verified that the effect of tuning capacitor on electrical power output is negligible while the effect on stability is rather noticeable. Therefore, the ideal tuning capacitor value should be selected based on required stability of the FPSC.*

## I. INTRODUCTION

The free-piston Stirling convertor (FPSC) is one of the most promising space power conversion technologies to convert heat energy to electrical energy with very high efficiency and specific power[1]. The FPSC is a dynamic technology with a piston moving in reciprocal motion. Therefore, an alternator and a controller are required for power generation and stable operation. In general, as shown in Fig. 1, a tuning capacitor is placed between the FPSC and an Alternating Current (AC) Bus to improve the power factor, which is inadvertently degraded by the alternator, and to enhance the piston stability. Moreover, it has been widely accepted that the power output and the system stability are greatly affected by the tuning capacitor value, and the calculated values for the maximum power output and the highest stability are usually not identical. As a result, in flight mission planning with the dynamic radioisotope power system (DRPS), it has been suggested that the tuning capacitor value should be changed to the value for the highest stability momentarily during launch and changed back to the value for the maximum power output after launch.

However, recent modeling analyses by NASA Glenn Research Center (GRC) suggest that while the tuning capacitor value affects the stability of the FPSC, it does not affect the power output if the convertor is controlled by a fixed-frequency controller at a fixed frequency. Therefore, this paper will present modeling analyses results, followed by test results to support the modeling analyses results.

## II. SIMULATION MODELING

A simplified block diagram of the FPSC with a fixed-frequency controller is shown in Fig. 1 (Ref. 2). In the simulation modeling, a linearized FPSC model was used[3,4] to generate a root locus plot as the tuning capacitor value changes from 840μF to 1040μF and 1240μF as shown in Fig. 2. It should be noted that the nominal tuning capacitor value for the ASC used in this study is 840μF. The root locus plot suggests that the stability of the FPSC improves as the tuning capacitor value increases.

On the other hand, the same modeling analysis also suggests that the changed tuning capacitor value does not change the electrical power output significantly as shown in Fig. 3, when the piston amplitude and other operating conditions are held constant. Furthermore, only negligible changes in power factors, back-EMF, and alternator power were observed.

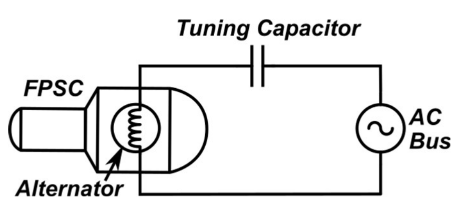


**Fig. 1.** A simplified schematic of an FPSC with a fixed-frequency controller.

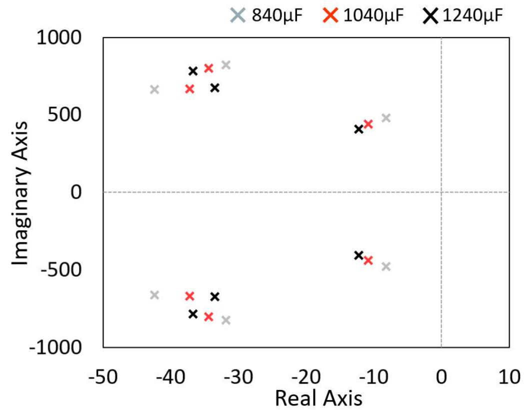


**Fig. 2.** A root locus plot of an ASC with a fixed-frequency controller (AC bus) when the tuning capacitor value changed from 840μF to 1040μF and 1240μF.

## III. TEST METHODOLOGY

An ASC article was used to study the effect of the tuning capacitor value on the stability and electrical power output[5]. In order to understand the effect of tuning capacitor value on the electrical power output, the same ASC article was operated on an AC power supply at a fixed frequency of 102.2Hz. This specific frequency was selected empirically to enable efficient operation of the ASC. As the tuning capacitor value changed, the amplitude of the AC power supply was adjusted to control the piston amplitude to 4.3mm, while maintaining hot-end temperature, cold-end temperature, and charge pressure to values $760°C$, $40°C$, and 480psig, respectively. All these operating conditions are nominal conditions for the ASC and the electrical power output, alternator power factor, alternator voltage, and alternator current were recorded.

The same test article underwent vibration testing in 2012 to demonstrate the effect of tuning capacitor value on stability. The test article was controlled by a forced oscillation controller at a fixed frequency of 102.2Hz, and

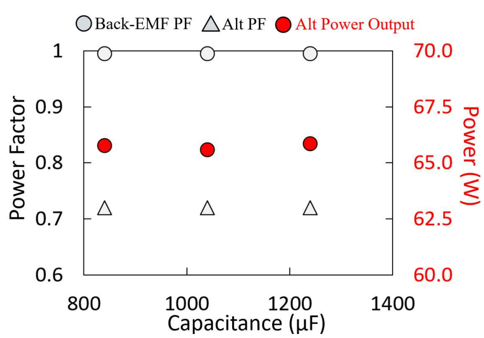


**Fig. 3.** Power factor at back-EMF, power factor at the alternator, and electrical power output with changed tuning capacitor value in the simulation model.

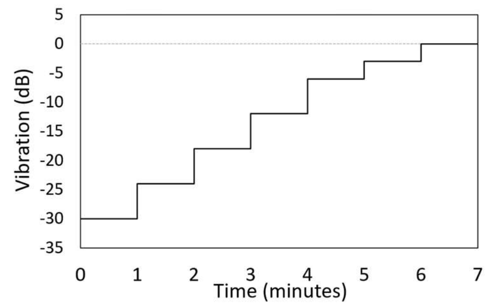


**Fig. 4.** Vibration testing profile.

all other operating conditions were held constant. During the vibration testing, the vibration acceleration was increased from $0.4g_{rms}$ (-30dB) to $7.2g_{rms}$ (-6dB) at the rate of 6dB/min and from $7.2g_{rms}$ (-6dB) to $13g_{rms}$ (0dB) at the rate of 3dB/min (Fig. 4), while the piston amplitude was controlled to 4mm throughout the testing. The vibration testing was repeated three times for each tuning capacitance and the number of events when the piston amplitude went above 5.3mm were recorded.

## IV. TEST RESULTS

Test results of the vibration testing are shown in Table I. The piston amplitude column in Table I indicates a specified range or a "bin" for piston amplitudes higher than 5.3mm, and the events columns indicate the number of events when the piston amplitude was within each bin. The test results clearly show that smaller numbers of events were observed in higher piston amplitude bins with $1040\mu F$ than those numbers with $840\mu F$, which indicates

**TABLE I.** Vibration testing results when the tuning capacitor value was nominal (840μF) and 1040μF.

| Piston Amplitude | # Events At $840\mu F$ | | | # Events At $1040\mu F$ | | |
|---|---|---|---|---|---|---|
| Test # | #1 | #2 | #3 | #1 | #2 | #3 |
| 5.3 to 5.8mm | 388 | 420 | 327 | 317 | 357 | 226 |
| 5.8 to 6.3 mm | 38 | 85 | 78 | 20 | 18 | 27 |
| 6.3 to 6.8mm | 0 | 4 | 6 | 0 | 0 | 1 |
| 6.8 to 7.3mm | 0 | 0 | 0 | 0 | 0 | 0 |

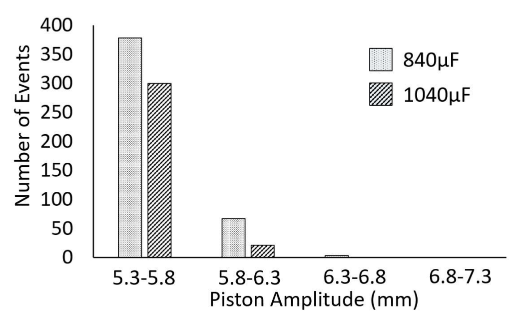


**Fig. 5.** Electrical power output and alternator power factor of the ASC at different tuning capacitor values.

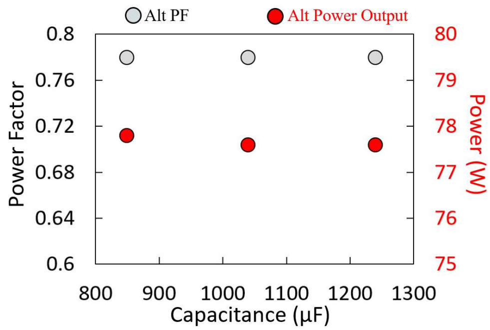


**Fig. 6.** Electrical power output and alternator power factor of the ASC at different tuning capacitor values.

that the stability was improved when the tuning capacitor value was increased.

**TABLE II.** Summarized test operating conditions and results when tuning capacitor value was changed from $840\mu F$ to $1040\mu F$ and $1240\mu F$.

| Variable | $840\mu F$ | $1040\mu F$ | $1240\mu F$ |
|---|---|---|---|
| Piston Amp | 4.31mm | 4.31mm | 4.31mm |
| Power Output | 77.8W | 77.6W | 77.6W |
| Alt PF | 0.782 | 0.781 | 0.779 |
| Hot-End Temp | $760°C$ | $760°C$ | $760°C$ |
| Cold-End Temp | $39.7°C$ | $39.9°C$ | $39.6°C$ |
| Alt Voltage | $15.8V_{rms}$ | $15.7V_{rms}$ | $15.8V_{rms}$ |
| Alt Current | $6.32A_{rms}$ | $6.31A_{rms}$ | $6.31A_{rms}$ |
| Pressure | 486psig | 486psig | 486psig |

The test results of the effect on the electrical power output are shown in Fig. 6 and Table II. Changes in the alternator power factor (PF) and electrical power output are negligible as the tuning capacitor value changes. More specifically, the electrical power output changed by approximately 0.2W and the alternator PF changed by 0.003, which are within the measurement tolerance. The reason why the power output is not affected by the tuning capacitor value may be because the operating frequency is dictated by the controller. In other words, if the operating frequency changes, the impedance of the ASC does not change and as a result, the alternator power will not change. To verify this theory, a more detailed simulation analysis was conducted to see the effect of the tuning capacitor value on the ASC performance when the operating frequency of the ASC was not fixed. This can be implemented by using a floating-frequency controller, such as the Zener diode controller[1]. As shown in Fig. 7, the power factor, which is an indicator of the power output, changes much more significantly than the change in the test data at a fixed frequency.

Furthermore, another interesting phenomenon was observed during startup of the ASC. While the rate of the change of the piston amplitude with respect to the hot-end temperature was almost constant as the temperature increases, the rate itself changed when the tuning capacitor value was changed as shown in Fig. 8. The AC bus amplitude was held constant until it was adjusted to control the piston amplitude within a reasonable range. The moments when the AC bus amplitude was adjusted are the steep and positive slopes in Fig. 8. Also, when the average slope was plotted over the tuning capacitor value and equivalent series resistance (ESR), as shown in Fig. 9, the x-intercepts can be found at $880\mu F$ and $35.5m\Omega$. This might be because different tuning capacitor values introduce different voltage drops across the capacitors and different power factor of the AC bus. Further research is needed in the future.

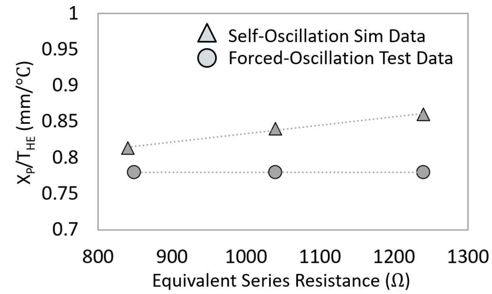


**Fig. 7.** Comparison between the floating-frequency simulation data and fixed-frequency test data.

## V. CONCLUSION

In this paper, it was empirically proved that the tuning cap value does not affect the ASC performance when the ASC is controlled by a fixed-frequency controller, such as an AC Bus. An increased tuning capacitor value also improved the stability of the ASC during vibration testing. We first began with a nominal tuning capacitor value, $840\mu F$, after which the tuning capacitance value was changed to $1040\mu F$ and then $1240\mu F$, while all convertor operating conditions including the hot-end temperature, cold-end temperature, pressure, and piston amplitude were held constant. The experimental results verified the simulation results that that the change in the power out was

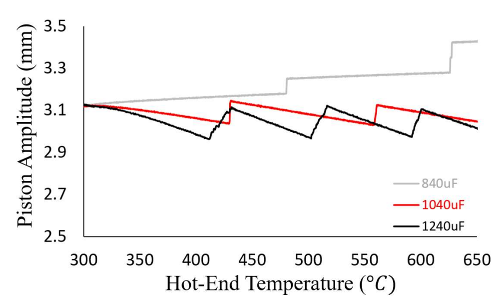


**Fig. 8.** Piston amplitude during start-up. It should be noted that a steep increase in the piston amplitude indicates adjusted AC power supply amplitude to maintain piston amplitude within a reasonable range.

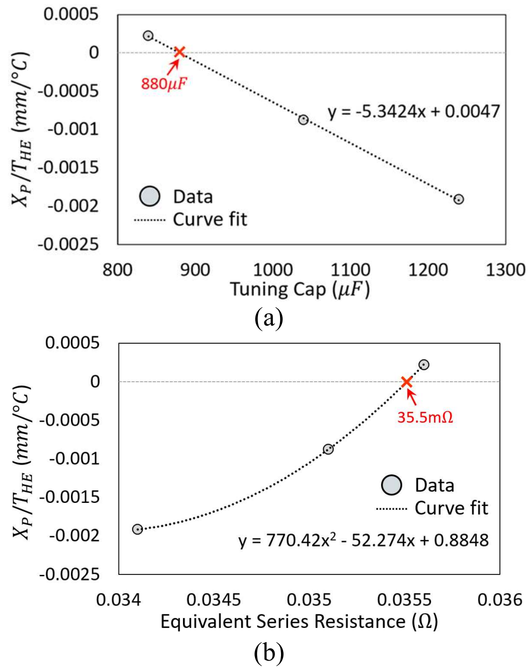


**Fig. 9.** The average rate of the change of the piston amplitude ($X_P$) due to hot-end temperature ($T_{HE}$) over (a) the tuning capacitor value and (b) equivalent series resistance (ESR). The rate becomes nearly zero when the tuning capacitor value is approximately 880$\mu F$ and ESR is 35.5mΩ.

negligible when the ASC was controlled by a fixed-frequency controller. On the other hand, the simulation results with a floating-frequency controller showed that the changed tuning capacitor value affected the power output significantly. Furthermore, an increased tuning capacitor value also improved the stability of the ASC during vibration testing up to 13$g_{rms}$. Therefore, this suggests that the tuning capacitor value should be selected such that the FPSC becomes the most stable when a fixed-frequency controller is used and the tuning capacitor value does not need to be changed back and forth during launch, which would simplify the controller design. Finally, it was found that the tuning capacitor value changed the piston behavior as the hot-end temperature increased during startup. A further study will be needed in the future.

## ACKNOWLEDGMENTS

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