ANS

NUCLEAR and EMERGING TECHNOLOGIES for SPACE

Powering the Next Era of Space Exploration

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

Dr. Max Yang, Nicholas Schifer

Dr. Tyler Steiner, and Matthew Stang

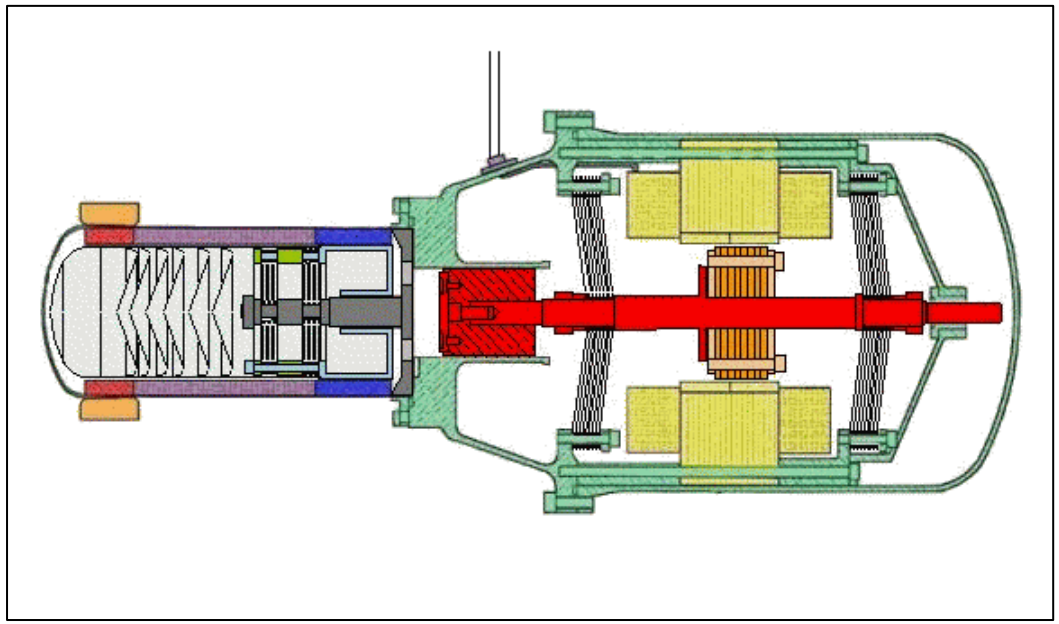
NASA Glenn Research Center

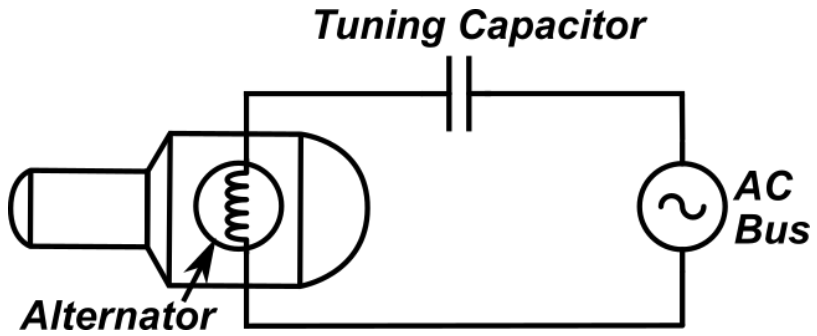
NASA

Outline

- Introduction
- Simulation Modeling Results
- Effect on Stability during Vibration
- Effect on Power Output
- Effect on Start-Up Behavior
- Conclusion

Introduction (1)





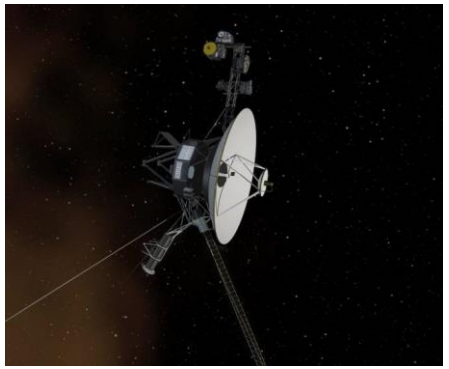
- Stirling convertors use a linear alternator to extract power from the piston motion; this requires a coil and a magnet (Faraday's law)
- The coil introduces unwanted phase shift to degrade power output as well as introduce instability; i.e., low power factor
- Tuning capacitor is added to increase power output and stability; widely accepted that tuning capacitor value will affect both the power output and stability

Introduction (2)

Launch

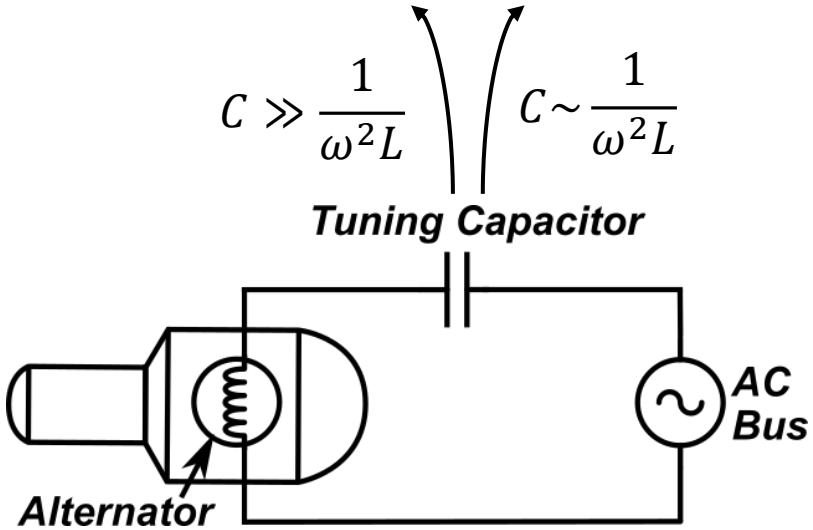
https://www.nasa.gov/feature/around-the-moon-with-nasa-s-first-launch-of-sls-with-orion

Mission



https://www.nasa.gov/mission_pages/voyager/voyager20130912.html

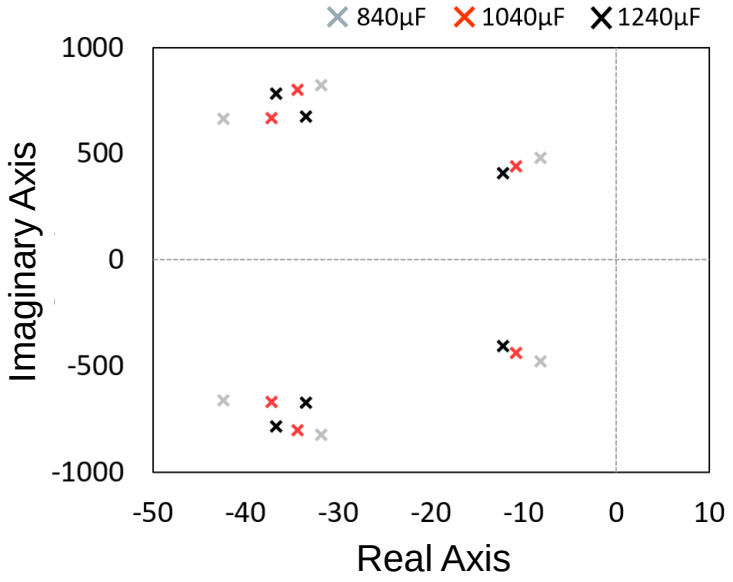
$$C \gg \frac{1}{\omega^2 L} \qquad C \sim \frac{1}{\omega^2 L}$$



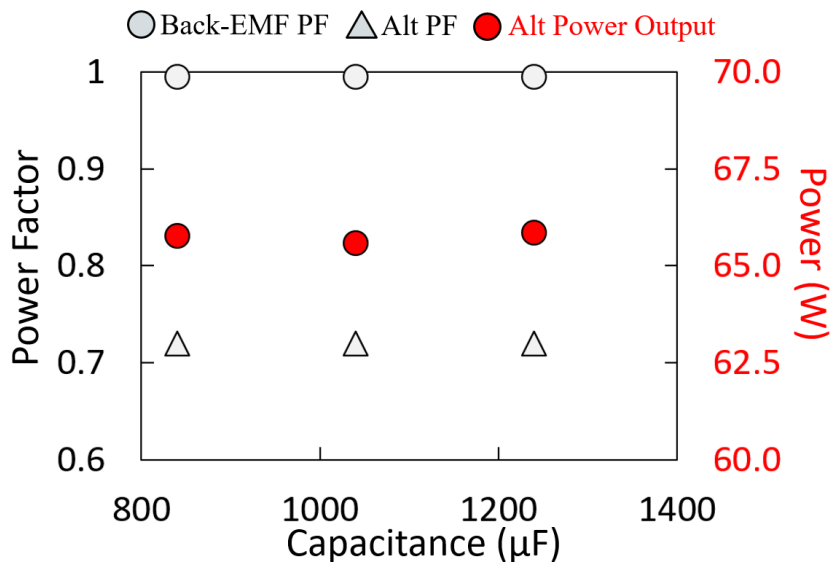
- It is widely accepted that tuning capacitor value affects both the power output and stability: “The Conventional Theory”
- Also, according to this theory, the tuning capacitor value for the maximum power output is different from that for the highest stability.
- As a result, two separate tuning capacitor values were suggested during launch and mission.
- ***However, recent modeling analysis suggested that this may not be correct.***

Simulation Results

Stability: Agreed!

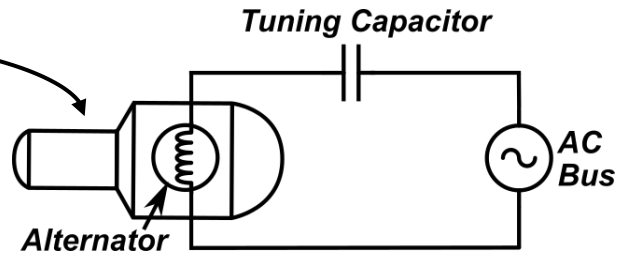


Power Output: ???



<Linearized Stirling Model>

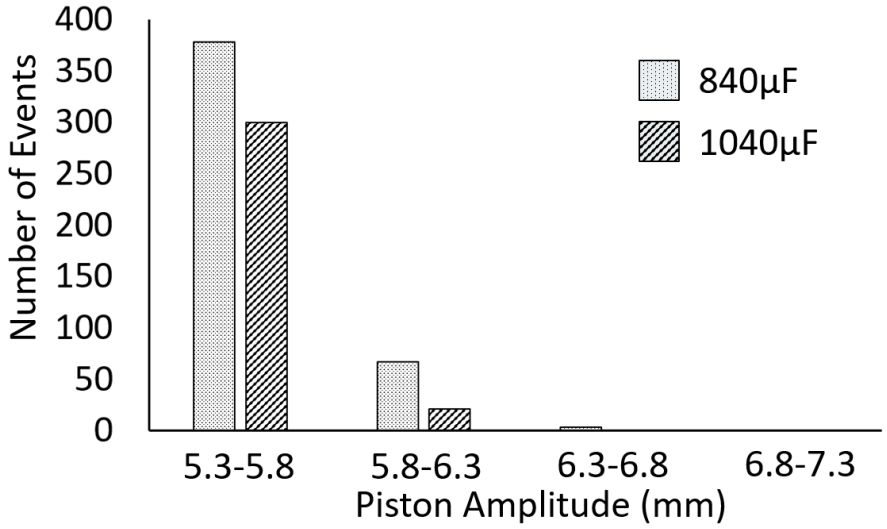
$$\begin{bmatrix} \dot{X}_d \\ \ddot{X}_d \\ \dot{X}_p \\ \ddot{X}_p \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\frac{K_d + A_r P_d}{M_d} & \frac{A_d \Delta P_d}{M_d} & -\frac{A_r P_p}{M_d} & \frac{A_d \Delta P_p}{M_d} \\ 0 & 0 & 0 & 1 \\ -\frac{A_p P_d}{M_p} & 0 & -\frac{K_p + A_p P_p}{M_p} & -\frac{C_p}{M_p} \end{bmatrix} \begin{bmatrix} X_d \\ \dot{X}_d \\ X_p \\ \dot{X}_p \end{bmatrix}$$



- Simulation Conditions
  - A linearized Stirling model on AC Bus
  - Hot-end ~ 760°C / Cold-end ~ 40°C
  - Piston amp ~ 4.0mm
  - Operating frequency ~102Hz
  - Tuning cap value: 840μF, 1040μF, 1240μF
- The stability results agree with the conventional theory; however, the power output results do NOT agree with it.
- Therefore, test setups were designed to check the simulation results.

Effect on Stability during Vibration

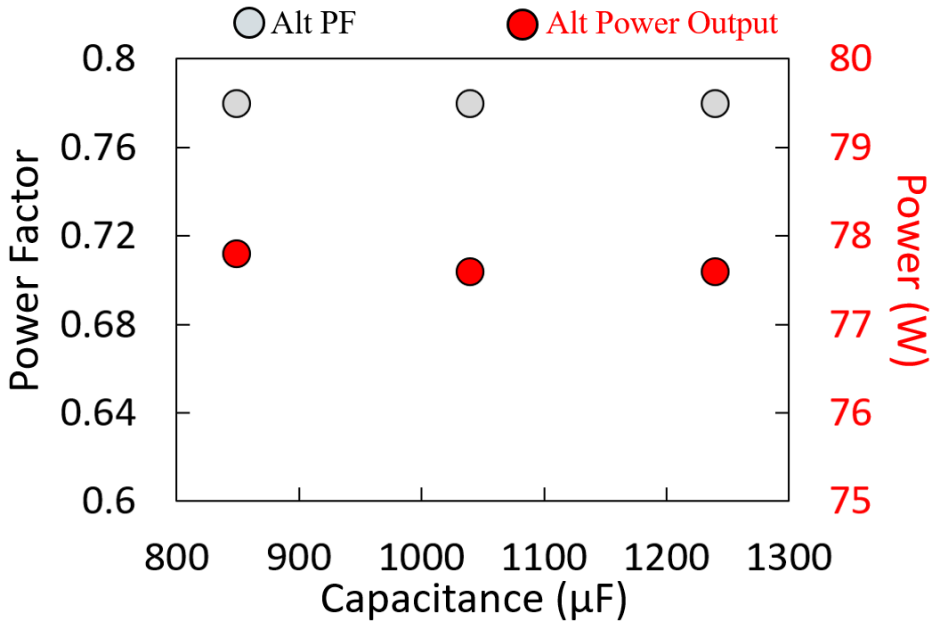
Vibration Test Setup



Piston Amplitude	# Events At 840μF			# Events At 1040μF		
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

- Vibration test was conducted back in 2012 (up to 13g_{rms}).
- The vibration test was conducted with 840μF (nominal) and 1040μF.
- The results suggest that 1040μF (higher cap) is more stable under vibration.
- Vibe test results in agreement with the simulation results **AND** with the conventional theory

Effect on Power Output



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

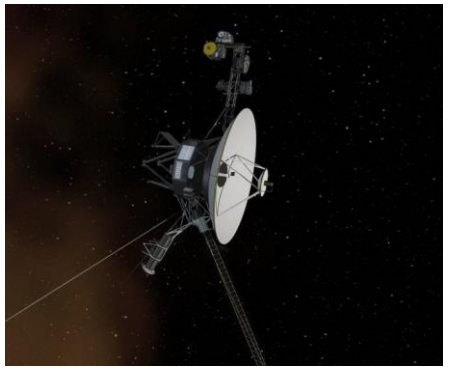
- This test was conducted in 2022 to understand the effect of tuning capacitor value on the power output.
- Same convertor used in the vibration test was tested.
- Test Conditions
  - Hot-end ~ 760°C / Cold-end ~ 40°C
  - Pressure ~ 490psig
  - Piston amp ~ 4.3mm
  - Operating frequency ~102Hz
  - Tuning cap value: $840\mu F$, $1040\mu F$, $1240\mu F$
- Test results show that the effect of the tuning capacitor value on the power output is negligible.
- Power output results also in agreement with the simulation results but **NOT** with the conventional theory.

What Does This Mean?

Launch

https://www.nasa.gov/feature/around-the-moon-with-nasa-s-first-launch-of-sls-with-orion

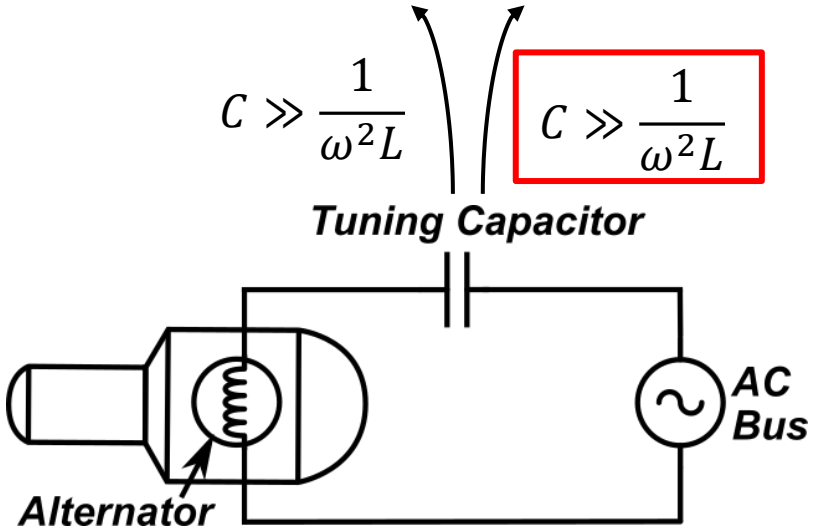
Mission



https://www.nasa.gov/mission_pages/voyager/voyager20130912.html

$$C \gg \frac{1}{\omega^2 L}$$

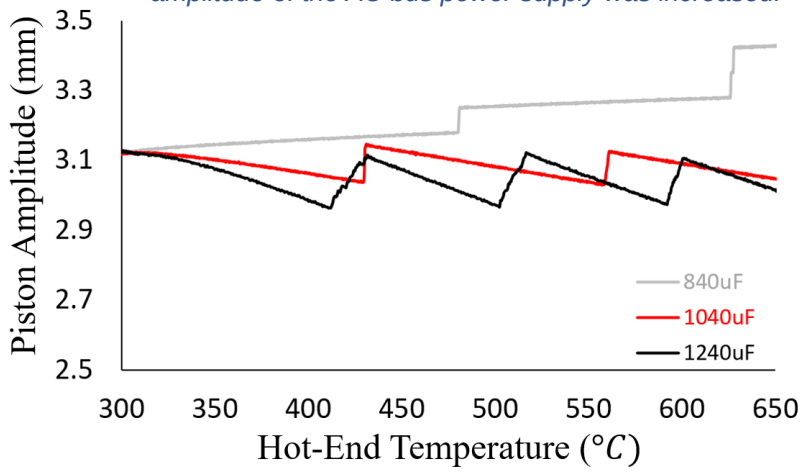
$$C \gg \frac{1}{\omega^2 L}$$

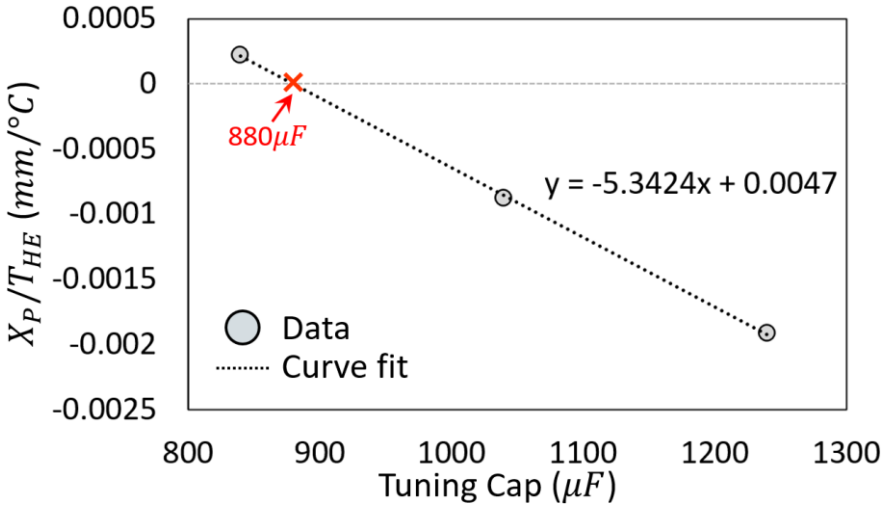


- Previously, two separate tuning capacitor values were suggested during launch and mission.
- However, according to this study, this is not necessary; we can use a single tuning capacitor value that maximizes the stability.
- Therefore, no need for additional communication and control.

Effect on Start-Up Behavior

**Note that a sharp change in piston happened when the amplitude of the AC bus power supply was increased.*





- During the power output testing, we observed that the rate of the change of the piston amplitude over hot-end temperature changed with the tuning capacitor value.
- Assuming the rate of the change of the piston amplitude over hot-end temperature is constant, the rate is inversely proportional to the tuning capacitor value.
- We believe this is related to the impedance of the tuning capacitor. Further study needed.

Conclusion

- According to the conventional theory, different tuning capacitor values are required during launch (requiring higher stability) and mission (requiring higher power output); this complicates communication and control system.
- According to the new theory presented in this paper, however, the effect of the tuning capacitor value on the power output is negligible; therefore, no need for additional communication and control.
- Also, tuning capacitor value affects the start-up behavior of the Stirling convertor; this may require a different controller design. Further study needed.

Thank you!