NASA/TM—2000-210526

IN/20

512112

2001 018 994

Vibration Testing of an Operating Stirling Convertor

William O. Hughes, Mark E. McNelis, and Thomas W. Goodnight
Glenn Research Center, Cleveland, Ohio

November 2000

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized data bases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at *http://www.sti.nasa.gov*

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA/TM—2000-210526

Vibration Testing of an Operating Stirling Convertor

William O. Hughes, Mark E. McNelis, and Thomas W. Goodnight
Glenn Research Center, Cleveland, Ohio

Prepared for the
Seventh International Congress on Sound and Vibration
sponsored by the International Institute of Acoustics and Vibration
Garmisch-Partenkirchen, Germany, July 4–7, 2000

National Aeronautics and
Space Administration

Glenn Research Center

November 2000

Acknowledgments

The authors acknowledge the support and expertise of Richard Shaltens, Jeff Schreiber, Lanny Thieme, Steve Geng, Lee Mason and Ken Mellott/NASA Glenn Research Center, the NASA Glenn Research Center SDL technical staff, Rich Furlong/DOE, Maury White and Ian Williford/STC and Kurng Chang/JPL.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076
Price Code: A03

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100
Price Code: A03

Available electronically at http://gltrs.grc.nasa.gov/GLTRS

VIBRATION TESTING OF AN OPERATING STIRLING CONVERTOR

William O. Hughes, Mark E. McNelis and Thomas W. Goodnight
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

The NASA John H. Glenn Research Center and the U.S. Department of Energy are currently developing a Stirling convertor for use as an advanced spacecraft power system for future NASA deep-space missions. As part of this development, a Stirling Technology Demonstrator Convertor (TDC) was recently tested to verify its survivability and capability of withstanding its expected launch random vibration environment.

The TDC was fully operational (producing power) during the random vibration testing. The output power of the convertor was measured during the testing, and these results are discussed in this paper. Numerous accelerometers and force gauges were also present which provided information on the dynamic characteristics of the TDC and an indication of any possible damage due to vibration. These measurements will also be discussed in this paper.

The vibration testing of the Stirling TDC was extremely successful. The TDC survived all its vibration testing with no structural damage or functional performance degradation. As a result of this testing, the Stirling convertor's capability to withstand vibration has been demonstrated, enabling its usage in future spacecraft power systems.

INTRODUCTION

NASA John H. Glenn Research Center (GRC) and the U.S. Department of Energy (DOE) are currently developing a Stirling convertor for an advanced radioisotope power system that will provide spacecraft on-board electric power for NASA deep-space missions. Stirling Technology Company (STC) of Kennewick, WA is under contract to DOE to develop a radioisotope Stirling convertor. NASA GRC is providing technical consultation for this effort based on their expertise in Stirling technologies dating back to the mid-1970's.

Stirling is being evaluated as an alternative replacement to Radioisotope Thermoelectric Generators (RTGs). Due to the Stirling system's efficiency (over 20 percent) just one-third the amount of Plutonium is required compared to the RTGs, thereby significantly reducing fuel cost.

Multiple Stirling units have demonstrated convertor power, efficiency and long life. Currently, one STC terrestrial radioisotope Stirling convertor is operating maintenance-free and without performance degradation after over 53,000 hours (6+ years). Such long lifetimes are required for deep-space missions to the outer planets where solar power is not an option.

Figure 1 illustrates the basic concepts of a Stirling convertor. Designing this convertor with long life and high reliability entails eliminating wear mechanisms and the proper selection and verification of materials. References 1 and 2 provide further insight into Stirling technology and current developmental efforts.

Before this convertor could be recommended as a viable flight power system a test program was needed to determine whether it could survive and function after exposure to the launch vibration environment. To address this issue a DOE/STC 55-We (electric watt) Stirling TDC was tested at NASA GRC's Structural Dynamics Laboratory (SDL). The TDC's heat source was electricity, not nuclear fuel. During this test program, the TDC was exposed to high random vibration levels and durations that simulated the maximum expected launch vibration.

VIBRATION TEST DESCRIPTION

On November 29 - December 2, 1999 vibration tests were performed on the Stirling TDC. The testing followed the requirements of the test plan (Reference 3). The Stirling TDC was supported in a specially made test fixture, as shown in Figure 2. This fixture was, in turn, attached to the slip table driven by the MB Dynamics Model C210 (28,000 pound-force) horizontal electrodynamic shaker, shown in Figure 3. Testing was performed in both the lateral (X, perpendicular to the TDC's piston stroke) and axial (Y, direction of TDC's piston stroke) directions. The Stirling TDC was fully operational (producing power) during the vibration tests.

Two accelerometers located on the test fixture were used to control the vibration test input. Eleven other accelerometers, located on the fixture and TDC, were used to measure the response. The TDC was mounted in the fixture by eight force gauge-measuring bolts.

Other non-vibration measurements were recorded during the testing. This included the input voltage and current at the heater end, the output voltage and current at the alternator end, the instantaneous output electric power, and the TDC's temperature and internal dynamic pressure.

Since little was known about the TDC's capability to withstand vibration, it was decided to incrementally test it to higher random vibration levels. Thus the TDC was initially tested to a modified workmanship (NASA-STD-7001) level of 6.8 Grms. Next it was shaken to the higher Jet Propulsion Laboratory (JPL) vibration levels (-6 dB, -3 dB and 0 dB relative to the qualification level of 12.3 Grms). These test levels are shown in Figure 4. All random test durations were for one minute per axis, except for the 3 minutes per axis qualification tests.

To closely monitor the performance and structural integrity of the TDC, low-level (0.25 g) sine sweep tests were performed before and after each major random vibration test. This provided a means of observing any structural changes caused by the random testing. Functional and electrical tests and visual inspections were also performed before and after each dynamic test (random or sine sweep) to monitor the TDC's functional performance and structural integrity.

VIBRATION TEST RESULTS

Figure 5 shows the test matrix and the order in which the tests were performed. The control of the test input was excellent for all tests.

The objectives of this test program were met and exceeded. The Stirling TDC was exposed to significant (greater than expected launch) vibration test levels and durations, and successfully passed. The most severe test was to the JPL qualification test levels (12.3 Grms, 0.2 g^2/Hz from

50 to 250 Hz, 3 minutes/axis, in both the axial and lateral directions). As a comparison, the RTGs used for the Galileo/Ulysses/Cassini missions were test qualified to 7.7 Grms (laterally) and 6.1 Grms (axially).

The Stirling TDC survived all dynamic testing with no structural damage or functional performance degradation. The Stirling TDC operated at full-stroke and produced power during all its vibration testing. Dithering (reducing) the piston stroke was not necessary. The TDC produced full power at the end of each and every vibration test.

The instantaneous power produced by the Stirling TDC did vary somewhat during testing. During the lateral random vibration testing, a slow steady degradation of power output was observed as a function of increasing vibration test input, but the power immediately returned to the full and stable level when each vibration test ended. The change in power during the testing is believed to be due to the increased friction and leakage losses caused by the lateral vibration.

During the axial direction random vibration testing, the power output remained on average at full level. Instantaneous surges and dips were observed however, which were believed to be due to shaking the TDC in the direction of its piston stroke. Once again, the power immediately returned to the full and stable level when each vibration test ended.

The Stirling TDC structure was found to be dynamically well behaved and linear, with reasonable damping. The pre and post sine testing showed no significant changes in the dynamic characteristics of the TDC measurements, due to its exposure to the random environments. Figure 6 illustrates this comparison for one of the force gauge measurements.

The lateral direction sine sweep data shows a convertor casing structural resonance at 1030 Hz, with a Q (dynamic amplification) of 5 to 8. In the axial directions, the sine sweep data shows possible convertor casing/fixture structural resonances at 1492 Hz and 1730 Hz, with Q values of 2 to 5. In both directions, the structural resonances are high enough in frequency to avoid any dynamic coupling problems with the Stirling's piston stroke frequency of 79 Hz.

Figure 7 (test input control versus alternator response) shows that the TDC responds rigidly to the random test input below 350 Hz, with its casing resonance appearing around 952 Hz (for the lateral random test). A verification of the structure's linearity to random lateral excitation (qualification versus flight acceptance test input difference of 6 dB) is illustrated in Figure 8.

Figure 8 also shows the TDC's self-vibration (no external shaking). While the piston stroke frequency (79 Hz) and harmonics dominate the self-vibration, it is insignificant in the vibration test data. However, as seen in Figure 6, the force gauges react these internal forces and thus the force gauge measurements provides information on the TDC's internal dynamics.

The SDL test report (Reference 4) provides additional test data and results.

POST VIBRATION TESTING EVALUATION

Following the vibration testing at NASA GRC, the Stirling TDC was operated for an additional 10 million cycles (35 hours) to demonstrate its post-test life. On January 4, 2000 a team of STC, NASA GRC and Lockheed Martin personnel participated in the disassembly and inspection of the TDC unit at STC. This team concluded that there were no areas of concern attributable to the vibration testing (Reference 5). The bases for their conclusion were: (1) satisfactory alignment for all moving parts and properly retained clearances, (2) no broken parts found inside convertor and intact structural integrity, (3) all fasteners retained adequate tightness, and (4) all post-test electrical measurements were consistent with pre-vibration test values.

CONCLUSIONS

The Stirling convertor is a promising and viable alternative to the RTG for use as an electric on-board power source for future NASA deep-space missions. The vibration testing performed at NASA Glenn Research Center has proven that the Stirling convertor can survive and function after exposure to its expected launch random vibration environment. Both structural integrity and power performance were retained throughout and at the completion of the vibration testing.

REFERENCES

1. "Technology Demonstration of a Free-Piston Stirling Advanced Radioisotope Space Power System," M. A. White, S. Qiu, R. W. Olan and R. M. Erbeznik, *Proceedings for the Space Technology & Applications International Forum (STAIF-99)*, Albuquerque, New Mexico, 30 January-4 February 1999.
2. "Technology Development for a Stirling Radioisotope Power System for Deep Space Missions," L. G. Thieme, S. Qiu, and M. A. White, NASA Technical Memorandum-2000-209767, March 2000.
3. "Vibration Test Plan to Characterize the TDC Stirling Engine for Future Technology Development," approved by R. Furlong (DOE), M. White (STC), J. Schreiber (NASA GRC), and T. Goodnight (NASA GRC), November 23, 1999.
4. "Technology Demonstrator Convertor (TDC) Stirling Engine, Prototype Unit, Vibration Test Report," S. Samorezov, NASA GRC Test Report SDL-TR 99-37, 24 January 2000.
5. "STC Convertor Disassembly and Inspection," by L. Mason, NASA GRC memorandum, January 19, 2000.

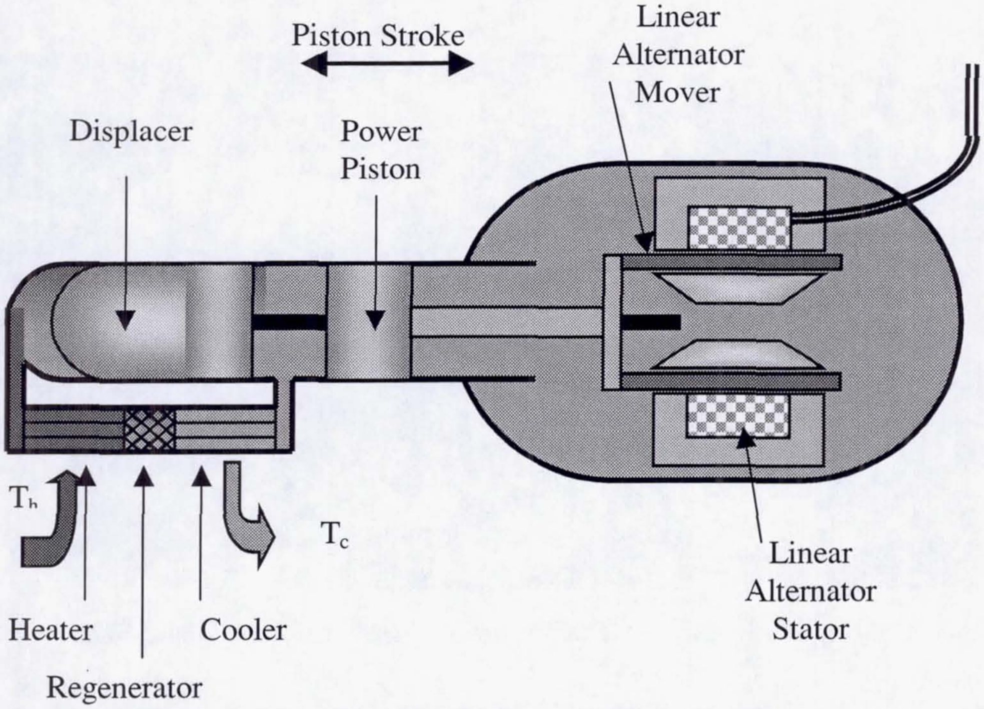

Figure 1. General Free-Piston Stirling Convertor Schematic

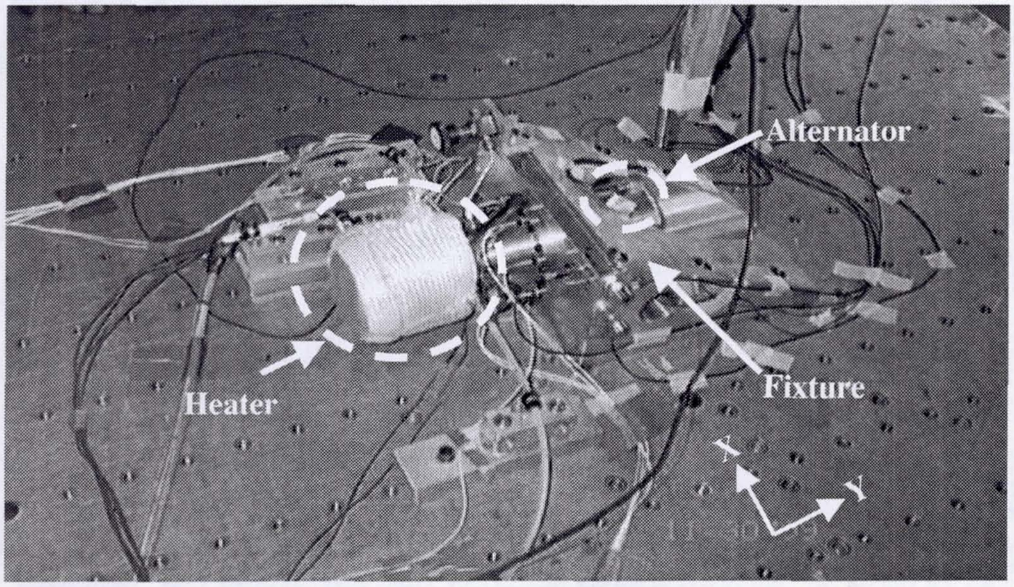

Figure 2. Stirling TDC and Vibration Test Fixture

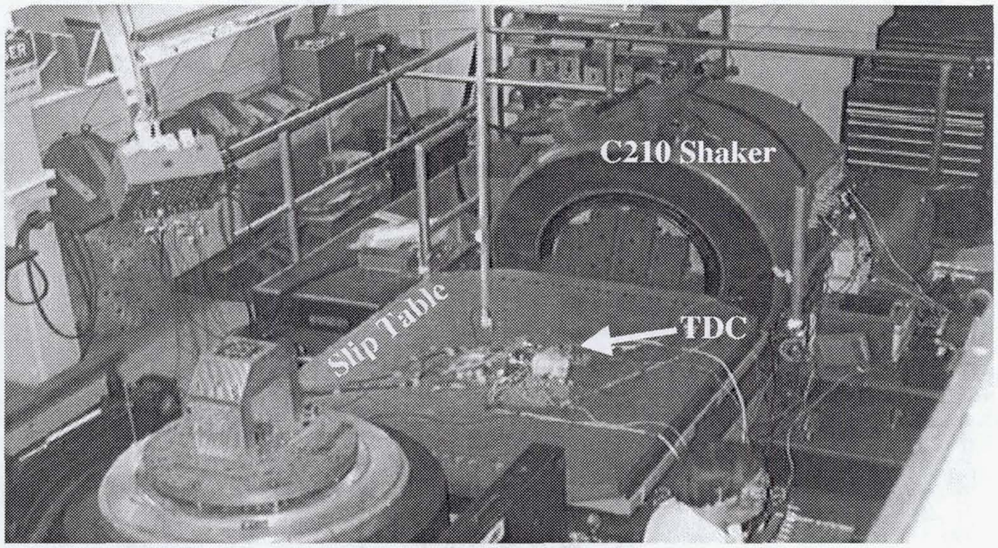

Figure 3. Stirling TDC Vibration Test at NASA Glenn SDL

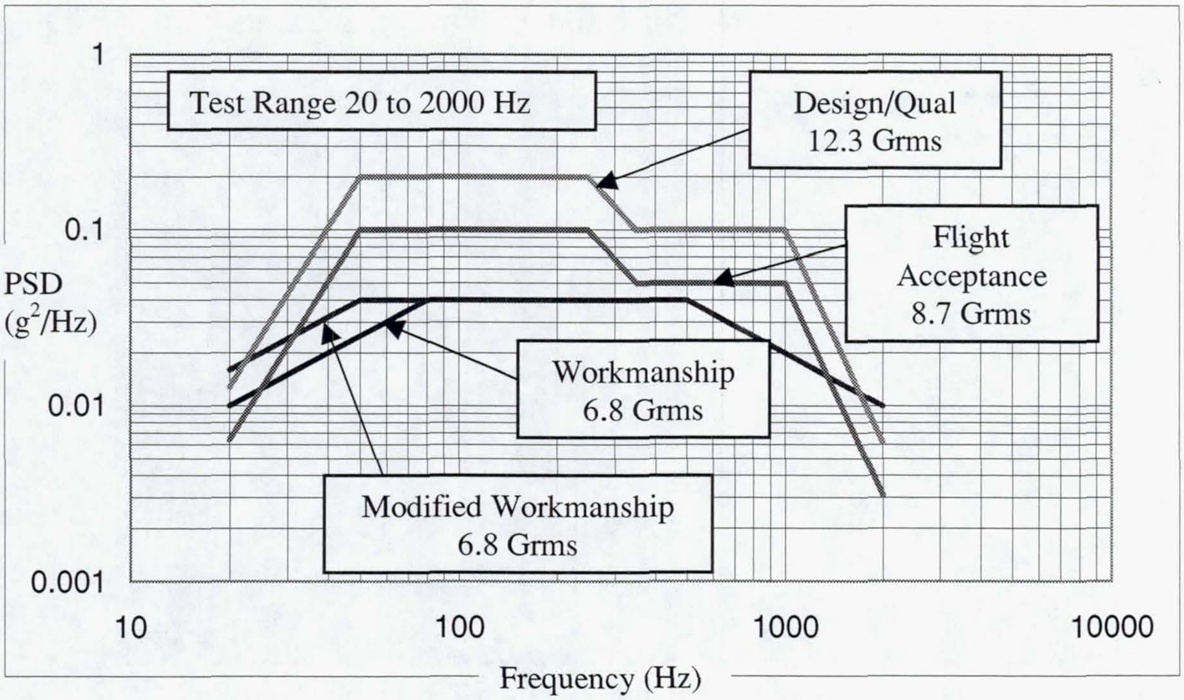

Figure 4. Stirling TDC Random Vibration Test Levels

Test Description	Test Magnitude	Test Duration	Axial * Direction	Lateral* Direction
Pre Sine Sweep	0.25 g	4 octaves/min	6	1
Workmanship Random Vibration	6.8 Grms	1 min/axes	7	2
Post Sine Sweep	0.25 g	4 octaves/min	8	3
Sine Sweep	0.375 g	4 octaves/min	9	4
Sine Sweep	0.50 g	4 octaves/min	10	5
Pre Sine Sweep	0.25 g	4 octaves/min	11	16
JPL Random Vibration Qualification - 6 dB	6.2 Grms	1 min/axes	12	17
JPL Random Vibration Qualification - 3 dB = Flight	8.7 Grms	1 min/axes	13	18
JPL Random Vibration Qualification	12.3 Grms	3 min/axes	14	19
Post Sine Sweep	0.25 g	4 octaves/min	15	20

Figure 5. Stirling TDC Vibration Test Matrix (* Order of testing; Random tests from 20 to 2000 Hz; Sine tests from 5 to 2000 Hz)

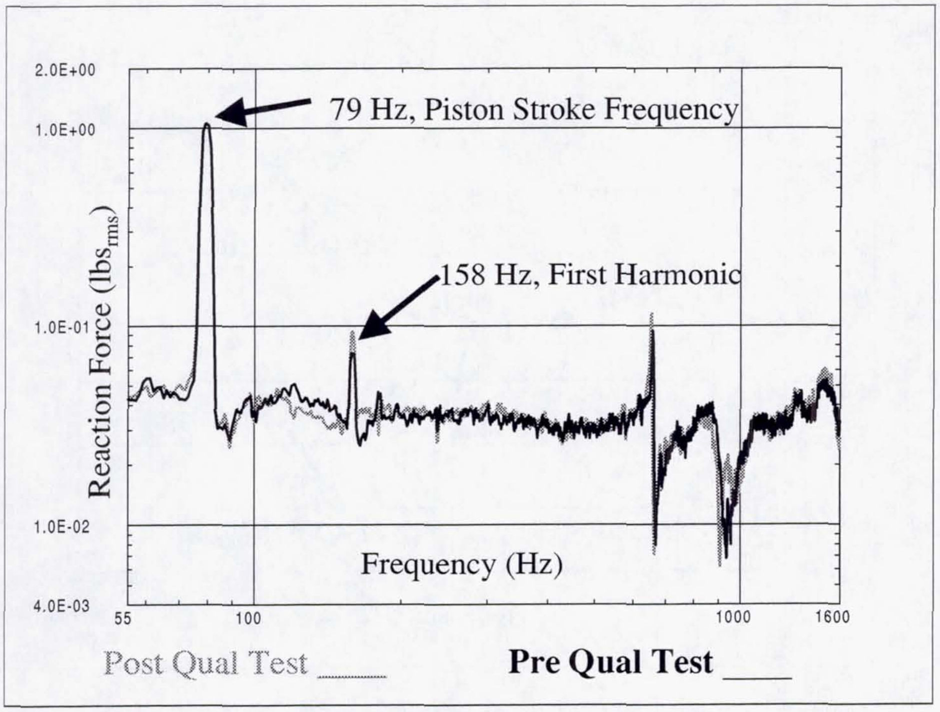

Figure 6. Comparison of Force Gauge (105Y) Data from Axial Pre and Post Qual Sine Sweep Tests

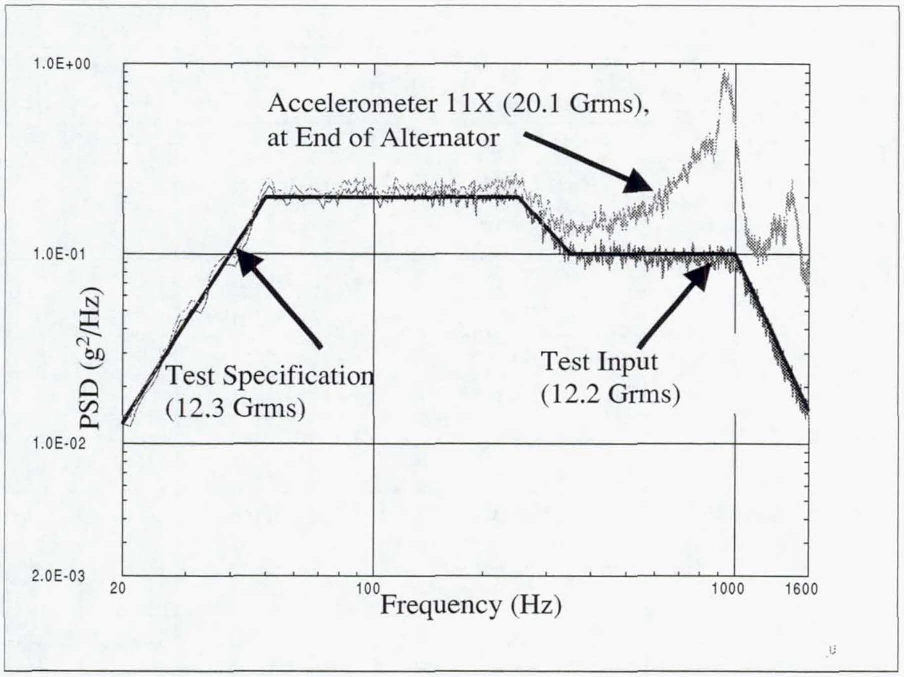

Figure 7. Comparison of Test Input versus TDC Response for Lateral Random Vibration Qualification Test

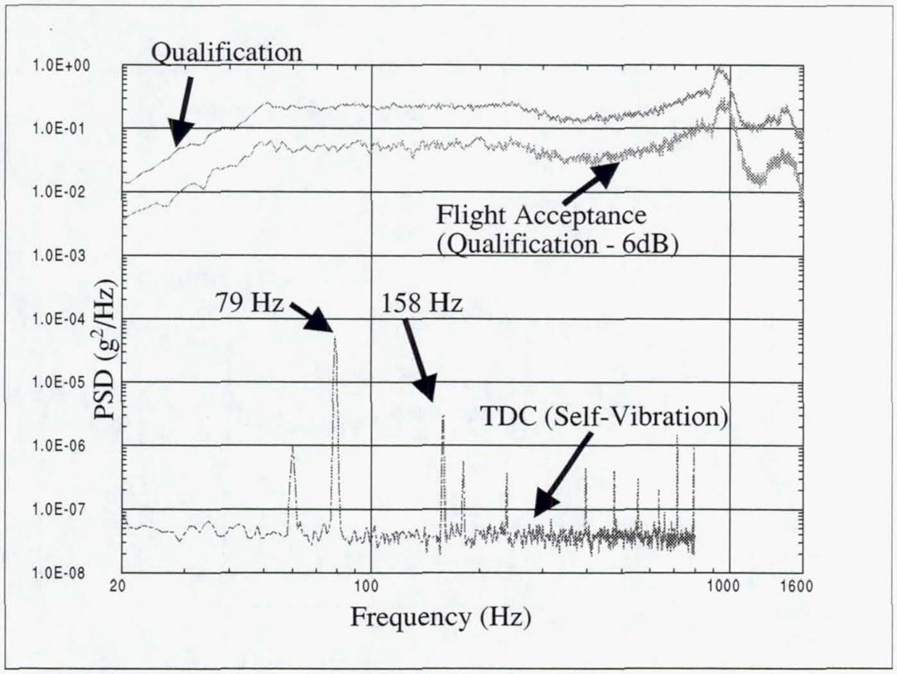

Figure 8. Lateral Random Vibration Linearity Check (Accelerometer 11X at End of Alternator) and TDC Self-Vibration

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
November 2000

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Vibration Testing of an Operating Stirling Convertor

5. FUNDING NUMBERS
WU–839–20–00–00

6. AUTHOR(S)
William O. Hughes, Mark E. McNelis, and Thomas W. Goodnight

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–12502

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM—2000-210526

11. SUPPLEMENTARY NOTES

Prepared for the Seventh International Congress on Sound and Vibration sponsored by the International Institute of Acoustics and Vibration, Garmisch-Partenkirchen, Germany, July 4–7, 2000. Responsible person, William O. Hughes, organization code 7735, 216–433–2597.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Categories: 18, 20, and 44 Distribution: Nonstandard
Available electronically at http://gltrs.grc.nasa.gov/GLTRS
This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

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

The NASA John H. Glenn Research Center and the U.S. Department of Energy are currently developing a Stirling convertor for use as an advanced spacecraft power system for future NASA deep-space missions. As part of this development, a Stirling Technology Demonstrator Convertor (TDC) was recently tested to verify its survivability and capability of withstanding its expected launch random vibration environment. The TDC was fully operational (producing power) during the random vibration testing. The output power of the convertor was measured during the testing, and these results are discussed in this paper. Numerous accelerometers and force gauges were also present which provided information on the dynamic characteristics of the TDC and an indication of any possible damage due to vibration. These measurements will also be discussed in this paper. The vibration testing of the Stirling TDC was extremely successful. The TDC survived all its vibration testing with no structural damage or functional performance degradation. As a result of this testing, the Stirling convertor's capability to withstand vibration has been demonstrated, enabling its usage in future spacecraft power systems.

14. SUBJECT TERMS
Vibration testing; Spacecraft power systems

15. NUMBER OF PAGES
14

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102