JOURNAL OF PROPULSION AND POWER
Vol. 9, No. 4, July–Aug. 1993

Development of a Dual-Frequency Microwave Burn-Rate Measurement System for Solid Rocket Propellant

David T. Foss,* Richard J. Roby,† and Walter F. O'Brien‡
Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061

Abstract

A DUAL-FREQUENCY microwave burn-rate measurement system for solid rocket motors has been developed. The system operates in the X-band (8.2–12.4 GHz) and uses two independent frequencies operating simultaneously to measure the instantaneous burn rate in a solid rocket motor. Computer simulation and limited laboratory testing of the system were performed to determine its ability to limit errors caused by secondary reflections and by uncertainties in material properties, particularly the microwave wavelength in the propellant. Simulations showed that the frequency ratio and the initial motor geometry determined the effectiveness of the system in reducing secondary reflections. Overall, the simulations showed that a dual frequency system can provide up to a 75% reduction in burn-rate error over that returned by a single-frequency system. The hardware and software for dual-frequency measurements was developed and tested; however, further instrumentation work is required to increase the data acquisition rate so its full potential can be realized.

Contents

In 1987, Waesche and O'Brien[1] concluded that measurement errors of less than 1% are necessary for a system to examine relevant phenomena in the rocket motor environment. Using this criteria, they examined three nonintrusive measurement techniques: 1) x-ray video, 2) ultrasonics, and 3) microwave, and found that only the microwave technique has a theoretical measurement error of much less than 1%. However, the major obstacle to achieving such accuracy is the uncertainties in material properties. Therefore, they concluded that elimination or suppression of material property errors should be the major focus of further microwave measurement system development.

As Fig. 1 shows, a typical rocket motor cross section has two material layers beginning with the structural casing/insulating layer, then the propellant. At each material interface, incident microwave energy is both reflected and transmitted. The reflection of interest is the reflection from the propellant burning surface. Reflections from the casing are fixed in phase and can easily be eliminated. Reflections off the far wall of the combustion chamber and multiorder reflections which travel several times through the propellant between the burning surface and casing before being picked up can induce large measurement errors. Unfortunately, all reflected radiation is combined into a single signal which is then received by the measurement equipment.

Elimination of the requirement to estimate individual reflection vectors would greatly improve the practicality and accuracy of the microwave measurement system. The rationale behind the simultaneous use of two frequencies is that unwanted reflections associated with each frequency can be eliminated due to their ratios being related to the ratio of the frequencies used. There is also the fact that the measurement of burn rate from one frequency signal must equal the measurement from the second frequency signal.

Three relationships can be developed between the two frequencies used in the dual frequency system based on the fact that both signals measure the same burn rate, and the assumption that the ratio of the microwave wavelengths in the propellant is equal to the frequency ratio of the two signals used. They are

$$r = \kappa \phi_{b1}(t) \lambda_{p1} \tag{1}$$

$$r = \kappa \phi_{b2}(t) \lambda_{p2} \tag{2}$$

$$\phi_{b1}(t)/\phi_{b2}(t) = \lambda_{p2}/\lambda_{p1} = f_1/f_2 \tag{3}$$

where κ is $\frac{1}{4}\pi$, $\phi_{b1}(t)$, and $\phi_{b2}(t)$ are the time rate of phase change of the burning surface vector for frequencies 1 and 2, and the unknowns are λ_{p1}, λ_{p2}, and r.

By iterating through values of the wavelength until the two burn rates match, errors in the measurement of λ and the rate of phase change can be reduced, resulting in a more accurate measure of the burn rate. A schematic of the measurement system (minus the data acquisition system) is shown in Fig. 2.

Microwave radiation is generated by the two Gunn diode microwave oscillators. These are modified C-2070 units made by MPD, Inc. Both oscillators produce approximately 100 mW of microwave energy with a 10-V dc input and draw 300 mA of current. The oscillators are set for 9.15 and 10.45 GHz and can be varied by ±0.5 GHz.

Two reference signals are extracted from the main signals at the oscillator outputs through two 20-dB waveguide couplers. A 3-dB coupler is used to couple the two main signals, allowing use of common waveguide sections and one micro-

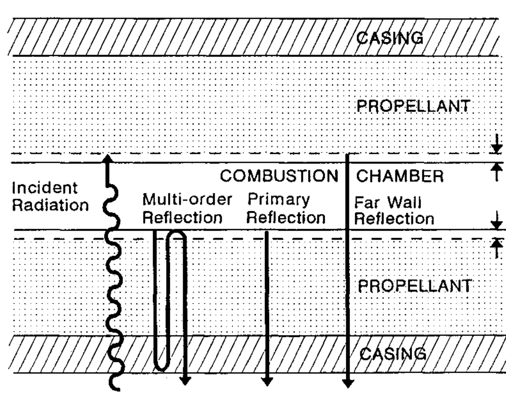

Fig. 1 Rocket motor cross section with microwave reflections.

Presented as Paper 89-2530 at the AIAA/ASME/SAE/ASEE 25th Joint Propulsion Conference, Monterey, CA, July 10–12, 1989; received Oct. 31, 1990; synoptic received Feb. 26, 1993; accepted for publication March 9, 1993. Full paper available from AIAA Library, 555 West 57th St., New York, NY 10019.

*Graduate Student, Mechanical Engineering; currently Engineer, Combustion Turbine Engineering, Westinghouse Electric Co., Orlando, FL 32826. Student Member AIAA.

†Adjunct Professor, Mechanical Engineering. Member AIAA.

‡Professor, Mechanical Engineering. Member AIAA.

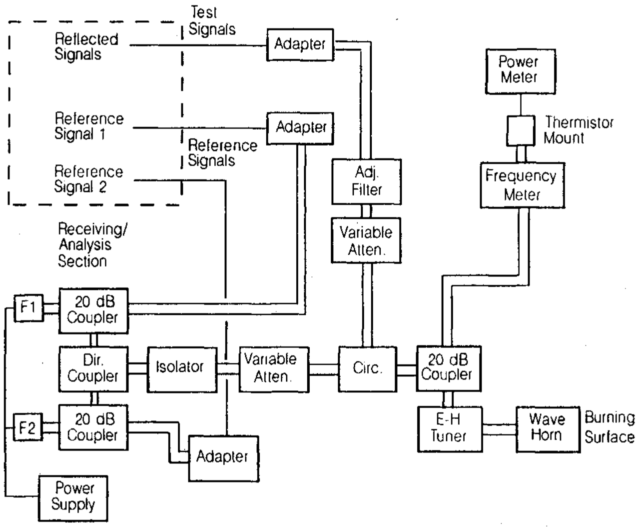

Fig. 2 Schematic of dual-frequency microwave measurement system.

wave horn. After exiting the 3-dB coupler, the combined signal passes through an isolator (to prevent unwanted reflections from reaching the preceding section) and a precision variable attenuator which allows control of the microwave power level leaving the horn. Radiation through the horn is reflected off the combustion chamber/propellant interface after passing through the rocket motor casing and insulation.

The circulator is used to route the combined reflected signals into the receiving section of the measurement system. The combined signal is passed through a variable attenuator, an isolator, and an adjustable waveguide short section to the coaxial cable adapter. The adjustable short is used to vary the power of the individual frequencies by acting as an adjustable filter. This is to ensure that one frequency does not dominate the system.

The two reference signals and the test signal carry the relevant information to a 20-GHz oscilloscope connected to a PC acting as controller and data acquisition device. The combined test signal is used as the oscilloscope trigger.

Although full-scale tests of the system were not performed due to limitations in the data acquisition system speed, limited testing with laboratory equipment was performed to determine the viability of dual-frequency operation. The test apparatus consisted of a motorized reflector placed in front of the microwave horn to simulate propellant regression during burning. Tests were done for the same conditions using one frequency at a time, then with both frequencies operating simultaneously. The frequencies used for this testing were 9.15 GHz (F1) and 10.33 GHz (F2).

Figure 3 shows the regression rate curves for both frequencies during single- and dual-frequency operation. Large errors are present and are caused principally due to equipment limitations. No significant differences in measurement between the two types of operation were observed. The advantage of the dual-frequency operation is shown in Fig. 4 where the dual-frequency measurements were averaged to give a final regression rate. Though the errors are still large they have been reduced by more than 75% throughout the figure.

The dual-frequency measurement system shows promise in its ability to reduce measurement errors due to various factors.

In all cases investigated, a significant reduction in error could be observed. This compares with no error reduction when using a single frequency. In cases where secondary reflections are offset by about 180 deg, the error reduction is substantial. In other cases it provides limited suppression of secondary reflection errors.

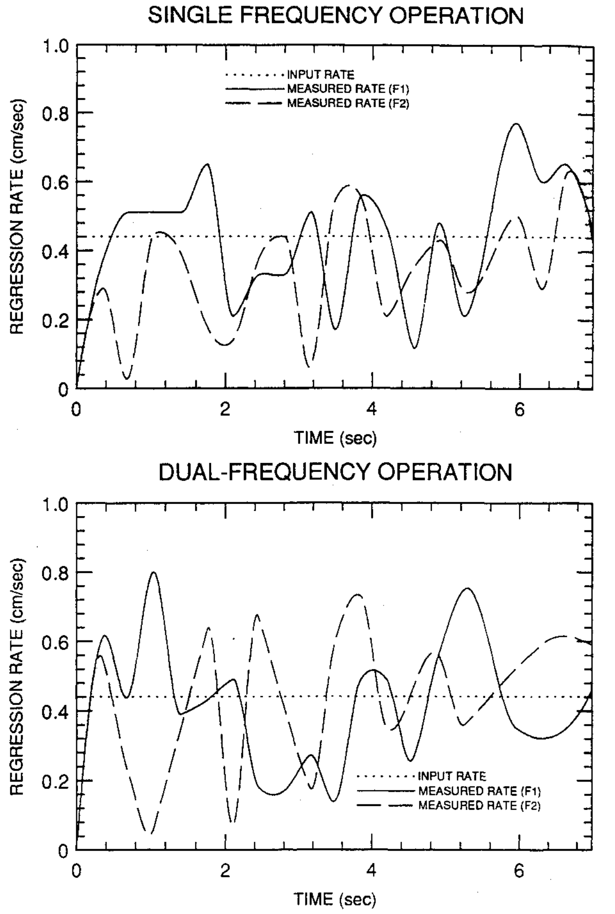

Fig. 3 Regression rate measurements in single- and dual-frequency mode.

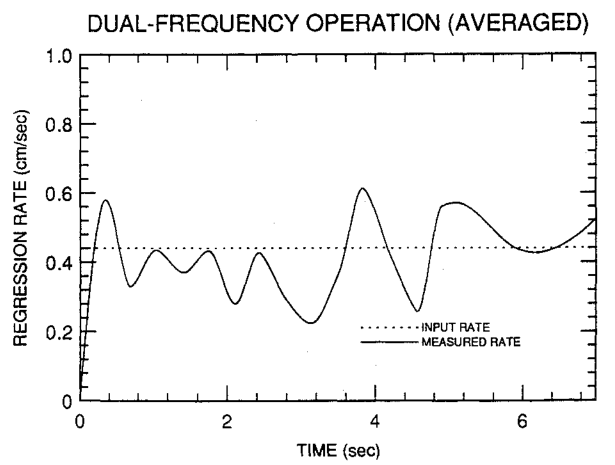

Fig. 4 Averaged regression rate for dual-frequency operation.

Continuing research should focus in parallel on the areas of hardware improvements and enhanced data reduction to enable high data rate sampling. The crude data reduction method used in the simulations did not take full advantage of the dual-frequency system.

Reference

[1]Waesche, R. H. W., and O'Brien, W. F., "Evaluation of Techniques for Direct Measurement of Burning Rates in Nozzleless Motors," NASA Ames Research Center Rept., Atlantic Research Corp., Gainesville, VA, Sept. 1987.