Errors and Noise in Laser-Recoil Measurements

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A study of noise and error sources encountered during development of a laser-recoil test capability is reported. The laser-recoil technique is a method of evaluating the response of a burning energetic material to fluctuations of radiant heat flux, usually supplied by a laser. The technique involves measuring the extremely small recoil force imparted as the burning gases leave the surface. This technique offers the advantages of small sample size, reduced cost, and potentially improved accuracy over the existing acoustic T-burner technique but has the disadvantage of high sensitivity to noise because of the small magnitude of the recoil force to be measured. Noise sources identified include electrical ground loops, thermal drift, structural vibrations, acoustics, and low-frequency atmospheric pressure variations. Remedial changes reduced the overall noise level by a factor of five and extended the usable measurement range from 200 to 700 Hz. Tests and analyses of several potential errors are discussed, including demonstration of linear behavior at input heat-flux modulation levels up to 25%.

INTRODUCTION

The response of a burning energetic material to pressure fluctuations is the material property of primary interest in the study of oscillatory combustion in rocket motors. However, techniques to measure this property have not been entirely satisfactory because of the need to deduce the response indirectly from measurements of the acoustic behavior of the apparatus and because of the cost per data point.

Theory indicates that the desired pressure-coupled response is very closely related to the response to heat-flux fluctuations applied at the burning surface. Theory also indicates that there is a small recoil force applied at the burning surface as a result of mass efflux from the burning surface during burning. These two theoretical observations have been combined in the laser-recoil technique for combustion response measurements to offer several attractive features: more direct and potentially more accurate measurement, reduced cost per data point through small sample sizes and multiple measurements per test, and measurement of both the magnitude and phase of the response.

The laser-recoil technique measures the response of a burning energetic material to radiant heat-flux fluctuations by measuring the recoil force generated by the mass efflux from the burning surface. The measured radiation-coupled response is then later converted to pressure-coupled response by a theoretical relationship. The concept was originally proposed by Milifeith [1] in 1972 in the United States and mainly developed in the former Soviet Union [2]. At the present state of the measurement technique, a modulated source of thermal radiation, generally emitted by a laser (mainly CO₂ or Nd:YAG) or a xenon arc lamp, is applied to the burning surface [3–6]. The key element in the laser-recoil apparatus is a microforce transducer, typically a piezoelectric or capacitive, or inductive transducer. The time-modulated radiant flux incident on the propellant burning surface drives burning-rate oscillations and, consequently, recoil-thrust fluctuations. For small amplitude sinusoidal modulation, sinusoidal burning rate and thrust oscillations are obtained, but at higher amplitudes, nonlinearities may occur, causing nonsinusoidal waveforms. The principal experimental difficulty is the low signal/noise ratio due to the very small intensity of the recoil force and the influence of a variety of noise sources. This difficulty

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can be overcome by a combination of isolating the experiment from external (acoustic and structural) noises, reducing the intrinsic (instrument) noise, and increasing the radiation modulation (within the linearity bounds) to increase the recoil force. Most laser recoil experiments are performed at atmospheric pressure, but tests at slightly higher pressures have also been reported [4, 7]. Despite these difficulties, this technique appears to be a useful tool for screening new propellant formulations, for quality control of industrial propellant production, and for fundamental reasons to better understand combustion processes. The purpose of the work is to investigate the noise and error problems in laser recoil measurements, with two specific goals in mind:

- identify noise and error sources;
- minimize their effects.

In the following sections, the experimental apparatus and data-reduction technique currently used are described. The noise problems encountered in early measurements and the implemented noise-reduction techniques are discussed. The radiation-driven recoil frequency response, measured for a nonmetalized ammonium perchlorate composite propellant AP18 (80% AP, 18% hydroxyl-terminated polybutadiene, and 2% additives), is also reported to show the influence of noise on data quality. Possible error sources are also described. Finally, some conclusions and recommendations are drawn.

**DISCUSSION**

The radiation-driven recoil frequency response is defined as

\[ R_{fq} = \frac{F' \delta}{I_0 / I_s} \]  

This requires simultaneous measurement of both the steady \( F \) and \( I_0 \) and nonsteady \( F' \) and \( I_s' \) components of the recoil force and heat flux.

Although the recoil force measurement is relatively simple and straightforward, the recoil thrust is very small. The recoil force is due to the mass efflux from the burning surface and thus it depends upon the burning rate among other physical quantities. For a propellant sample burning at 2 mm/sec, the mean recoil force per unit area is of order \( 5 \times 10^{-3} \) N/cm² or 50 Pa. For the 7.8-mm sample sizes typically used, the steady recoil force component is \( \approx 2.5 \times 10^{-3} \) N and the nonsteady component is 10-20% of that (i.e., \( \approx 2.5 - 5 \times 10^{-4} \) N). These very small force levels tax the capabilities of the most sensitive force transducers available and require very close attention to minimize noise effects in the resulting data. This is especially true for materials that show a low response to heat flux, such as AP-based propellants when tested using CO₂ lasers.