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Static Firing Tests of Solid Propellant Rocket Motors: Uncertainty Levels of Thrust Measurements

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ABSTRACT

Static firing tests of solid propelled rocket motors (SRMs) are important tests in aerospace industry during the development of new motors as well as to assure the quality of a motor batch. This type of test allows the operator to obtain the measured "thrust versus time of burning" graphic yielded by the motor during burning to verify whether the motor performance matches the project requirements. Laboratory Quality Certificates and good measurement practices make necessary the evaluation of the typical uncertainty of these test results, which demand a wide number of instruments, called measurement chain. This work aims to present the uncertainty levels expressed to the thrust values gathered during a SRM static firing test for two differently configured measurement chains. In order to estimate the uncertainty of a complete measurement chain, the theories of expanded and combined uncertainties are employed. It was possible to verify that in the analyzed case the use of signal amplifiers increased the measurement uncertainty of the chain.

Keywords: Thrust measurement; Uncertainty; Solid rocket motor.

INTRODUCTION

A solid propellant rocket motor can be described, in general, as a single outlet pressure vessel, internally storing a solid block composed by a mixture of a fuel and an oxidant in adequate proportion. When this set is ignited, gases are produced inside the pressure vessel due to the interaction between the propellant and the oxidizer and, at a given moment, the difference between internal pressure and atmospheric pressure causes the gas expulsion through the outlet. This mass of gas is ejected at high speed, causing a displacement of the rocket. The load exerted in the opposite direction due to the expulsion of the gases is called thrust. Thus, it is possible to state that the thrust level is linked to the mass and velocity of the gases expelled (Ribeiro 2013). The approach of this article considers a rocket motor powered by solid propellant, although there may be rocket configurations using liquid fuel or even a hybrid combination.

Figure 1 shows a typical set up for thrust measurement on a test bench for static tests (static firing) of rocket motors.

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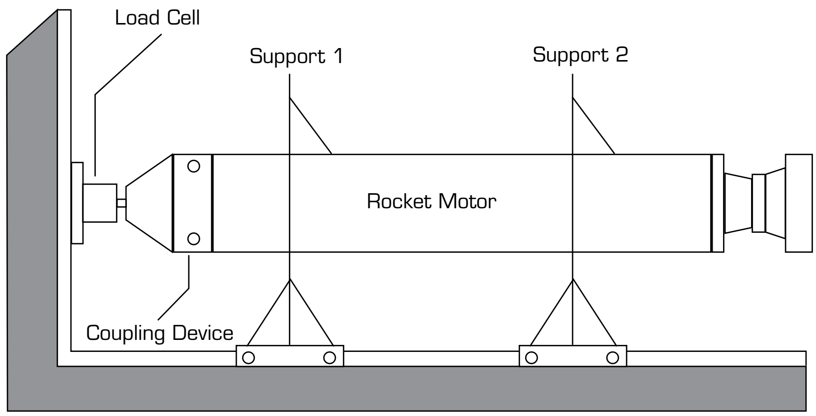


Source: Elaborated by the authors.

Figure 1. Typical set up of a SRM firing test.

Notice that a load cell is used as a sensing element to measure the thrust force. In this transducer, a model based on strain gage bridges operates only in the compression direction. A typical load cell model with 133,446.60 N full scale and two independent channels for reading output signals is shown in Fig. 2.

Source: Vishay Transducers (2005).

Figure 2. 133,446.60 N full scale load cell with two independent channels.

According to Sutton and Biblarz (2001), prior to its definitive operation, the propulsion systems are subjected to a series of tests that normally follow the sequence below:

- Manufacturing inspection and testing on individual components, including dimensional inspections, pressurization tests, X-rays, leaking checks, electrical continuity and electromechanical tests;
- Functional and operational tests on components such as ignitors, valves, controllers and structures;
- Static firing tests on complete or partial propulsion systems in test bench;
- Tests in which the propulsion system is integrated into a stage or static vehicle;
- Flight tests applied to prototype or serialized vehicles.

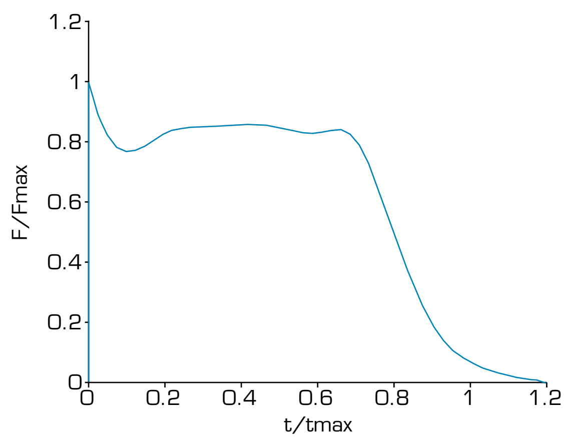
Sutton and Biblarz (2001) also describe that the purposes of carrying out each type of test are:

  - Research, development or improvement of a new propulsion system (mechanical or chemical), as well as its components and propellant formulation;
  - Assess the suitability of a new propellant (mechanical or chemical) for a specific application or approval for flight;
  - Quality assurance and the production process quality control.

In the case of a) and b), the focus is on testing and measuring new concepts and physical phenomena arising from modifications or innovations applied to experimental rockets. Testing a new propellant grain and measuring the thermal expansion of a nozzle during propellant firing are examples of these applications (Sutton and Biblarz 2001).

In the case of serialized rocket motors (scale production), it is important to make sure that:

- The internal ballistic parameters need to be in compliance with the design requirements so that the vehicle can be launched safely. Figure 3 depicts a curve of thrust versus time, from which the propulsive characteristics of the rocket motor, necessary for the validation of the propulsion system, are extracted.
- A given batch of rocket motors does not show significant changes in their propulsive characteristics over time. One must consider the storage environment of the propellants in terms of humidity and temperature, for example. To this end, at each predetermined time interval, motor samples are statically tested and their ballistic parameters undergo to analysis that attests (or not) the reliability of the integration of this batch of thrusters in aerospace vehicles.



Source: Elaborated by the authors.

Figure 3. Typical thrust curve versus time.

In SRMs, the propulsive parameters experience variations arise from the production process, which results in changes of the thrust curves obtained in the burning of each propellant. However, the establishment of approval ranges (minimum and maximum values) for each parameter yields a tolerance in relation to these variations, allowing the validation of the motor batch.

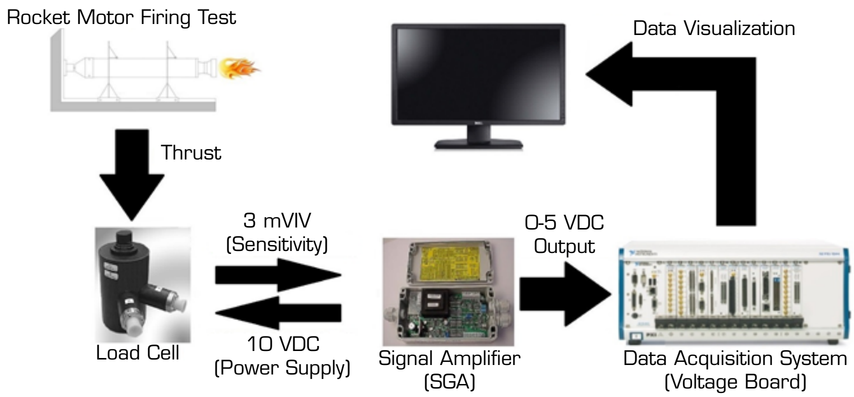
In Di Salvo and Frederick (1998), the characterization of the propellant through the test of reduced-scale motors (also called test motors) is addressed. The main objective of these tests is to determine the propellant burn rate and respective propulsive characteristics of the solid gran, of which at least five different samples were tested.

Thus, it is possible to state that an assertive evaluation concerning both the associated errors and the thrust measurements uncertainty, directly influences the results of ballistic parameters calculation. As a consequence, this issue may affect the impact point of rockets, missiles or launchers.

METHODOLOGY

Thrust Measurement Chains

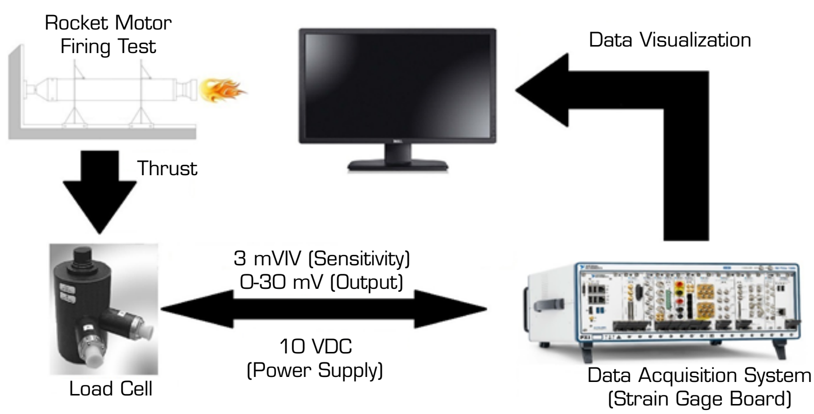
A thrust measurement chain basically consists of a force sensor (load cell) and a data acquisition and processing module. Two different thrust measurement chains can be used to determine the curve thrust versus time of a propellant, during burning tests. Figure 4 illustrates an amplified data acquisition system by mean of a strain gage amplifier, which provides an output signal of 0 to 5 direct current voltage (DCV) read by a data conditioning board in electrical voltage.



Source: Elaborated by the authors.

Figure 4. Thrust measurement chain with amplified signal acquisition.

In Fig. 5, it is possible to observe an arrangement for non-amplified recording signals, that is, acquired directly from the load cell output (0 to 30 mV) by a strain gage conditioning module.



Source: Elaborated by the authors.

Figure 5. Thrust measurement chain with non-amplified signal acquisition.

It may be noticed that the use of both chains is only possible because the load cell has two output channels (here called A and B). In this way, the signal coming from channel A is amplified and read by the voltage conditioning board. On the other side, the strain gage conditioning module supplies and acquires data from channel B.

In the case of the amplified chain (Fig. 4), the transformation of the so-called *raw data* (in electrical voltage) to data in engineering units takes place through a conversion factor calculated by a software dedicated to this purpose. This factor can be expressed in N/V. For the non-amplified chain (Fig. 5), the full scale of the load cell to be used, the supply voltage, as well as its sensitivity in $mV \cdot V^{-1}$ may be informed. Thus, the test data is immediately provided in N (as well as in another load unit selected via software). Once treated, this information is processed in order to determine the performance parameters of the tested rocket motor.

Pretest Verification Procedure

Before installing the force sensor on the test bench, it is important to assess the calibration certificate validity of the load cell to be used. This procedure aims to ensure the correct function of the referred sensor as well as to acquire highly accurate measured data.

As illustrated in Fig. 6, two load cells (standard and assessed) are coupled by mean of a threaded adapter and then, with the use of a hydraulic clamp, undergo a mechanical compression effort. The data acquisition system performs the conversion of the standard load cell output signal to engineering unit (N). In this way, it is possible to monitor in real time the value of the force applied to the set. Since the sensor has two independent output data acquisition channels, it is possible to obtain the data redundancy (the voltage conditioning board reads the results from channel A, while the signals generated by channel B are acquired by the *strain gage* conditioner module). The program then compares the responses of the standard load cell and the sensor to be used in the test. This test load cell is approved for use in the rocket motor firing test if both sensors show similar responses. It is considered that the difference between the readings shall not exceed 2.5%, a value defined as a safety factor obtained through the history of previous verifications.

Source: Elaborated by the authors.

Figure 6. Arrangement for Pre-Test Load Cell Verification.

Thus, in the case of the amplified chain, the thrust values are given in N (or Newton) after the firing. These values are obtained by multiplying the electrical voltage signals (recorded in the data acquisition system) by the conversion factor generated in the pre-test verification in N/V. The non-amplified chain data is exported directly in engineering unit.

Definition of Measurement Uncertainty

The uncertainty of a measurement is defined as "a parameter associated with the measurement result, which characterizes the dispersion of the values attributed to a measurand" (Silveira 2016, p. 37). Also according to Silveira (2016), uncertainty is inherent to a given measurement value that is the result of the measurement itself, differing from the *true value* of the measurand. Thus, the measurement result consists only of the best estimate of the so-called true value and, in the absence of systematic effects, it is usually obtained by the arithmetic mean of repeated measurements of the same measurand.

Another important definition provided by the JCGM (2008) is that uncertainty is characterized by a range or dispersion interval, and is therefore not punctual (as is the error, whose correction could be eliminated by applying a correction factor). Confusion between these concepts was eliminated only after the publication of the *Guide to the Expression of Uncertainty in Measurement* (GUM) (JCGM 2008), which clarifies that error is an unknown quantity on the measurand, while measurement uncertainty is a parameter that quantifies knowledge of the nature of the phenomenon to be measured.

Finally, it is noteworthy that uncertainty corresponds to a range of values that can be expressed exclusively to the measurement, in a reasoned and realistic way, and should not be understood as a safety range.

Importance of Measurement Uncertainty

According to Silveira (2016), the expression of uncertainty is essential in several occasions, as in the interpretation of measurement results and verification of compliance as well as in the fields of testing and calibration. Furthermore, it can be characterized by a differential, since a customer is induced to engage the services of a laboratory to present best quality in its measurements (therefore smaller uncertainty).

Decision-making in cases where there are maximum or minimum limits for the measurements also makes it essential to calculate the uncertainty in order to assess the probability of error or success. In the case of laboratories, the measurement uncertainty enables the identification of the main sources of influence on the test or calibration result, which allows the implementation of adequate controls for quality assurance and continuous improvement (Silveira 2016).

Calculation of Measurement Uncertainty

In this work, the calculation of the uncertainty involved in obtaining the conversion factors of raw data from thrust (voltage in VCD) to engineering unit (N) will be addressed. As described in the subsection "Pre-Test Verification Procedure," these factors are obtained through a pretest verification.

The various instruments and equipment used in this activity present uncertainties inherent to characteristics such as variation with temperature, nonlinearity, gain, among others; thus, the conversion factors must be assigned uncertainties related to the measurement chain under study. The importance of this investigation comes from the fact that the errors arising from the conversion coefficient directly affect the thrust results presented after the burning tests.

Therefore, the concepts of combined uncertainty and expanded uncertainty will be used to determine the uncertainty that concerns the aforementioned conversion factor.

Determining the Uncertainty of Conversion in an Amplified Signal Measurement Chain

In JCGM (2008), the uncertainties associated with the input quantities are classified as Type A and Type B. Type A uncertainty assessment is a method that applies a statistical analysis of a series of measurements repeated at the time of testing. Generally, Type B uncertainty is expressed by the experimental standard deviation of the measurement chain. The experimental standard deviation of the measurement chain is, in this case, a measure of uncertainty associated with the mean value, indicating the repeatability of the measurement, as expressed by Eq. 1, where $S\bar{x}$ is the standard deviation for the average, S is the standard deviation and n is the number of samples.

$$S\bar{x} = \frac{S}{\sqrt{n}} \tag{1}$$

Table 1 describes five conversion factor values, calculated in different pretest verification procedures using the same 44,482.22 N (standard) and 133,446.60 N (assessed) capacity load cells.

Table 1. Conversion factors for engineering unit.

Test Number	Conversion Factor (N/V)
1	26,575.14
2	26,343.90
3	26,808.14
4	27,186.09
5	26,892.68

Source: Elaborated by the authors.

Table 2 presents the Type A uncertainty of the conversion factors for the amplified measurement chain, according to the application of Eq. 1 on the data shown in Table 1.

Table 2. Type A Uncertainty for Conversion Factors – Amplified Measurement Chain.

Conversion Factor (N/V)	Standard Deviation	Mean	Type A Uncertainty (Mean Standard Deviation)	Type A Uncertainty (%)
26,575.14	319.68	26,761.19	142.97	0.53
26,343.90				
26,808.14				
27,186.09				
26,892.68				

Source: Elaborated by the authors.

On the other hand, the Type B uncertainty assessment employs different methods from the statistical analysis of a series of measurements repeated at the time of testing (Silveira 2016). According to the GUM (JCGM 2008), in this case, the Type B uncertainty assessment (Strain Gage Amplifier – SGA) nonlinearity, standard load cell repeatability, test load cell uncertainty and conditioning board calibration) is based on other knowledge, such as historical data of measurement method performance, equipment calibration uncertainties and standards, manufacturers' technical specifications and environmental conditions.

Table 3 lists the sources of uncertainty involved in determining the conversion factor.

Table 3. Conversion uncertainties: amplified measurement chain.

Uncertainty Source	Type of Distribution	(%)
Type A uncertainty	t-Student	0.530
SGA nonlinearity	Rectangular	0.150
Standard load cell repeatability	Rectangular	0.070
Test load cell repeatability	Rectangular	0.070
Conditioning board calibration	Normal	0.031

Source: Elaborated by the authors.

The combined uncertainty is calculated as expressed in Eq. 2.

$$u_c(y) = \sqrt{\Sigma u_i(y)^2} = \sqrt{\Sigma \left[\frac{\partial Y}{\partial x_i} u(x_i)\right]^2} \tag{2}$$

where $u_c(y)$ is the combined uncertainty, $\frac{\partial Y}{\partial x_i}$ is the sensitivity coefficient and $u(x_i)$is the standard uncertainty. Thus, the combined uncertainty for the conversion is as shown below:

$$u_c = \sqrt{X_1^2 + X_2^2 + X_3^2 + X_4^2 + X_5^2} = 0.56\%$$

where X_1, X_2, X_3, X_4 and X_5 are, respectively, the combined uncertainties due to the type A experimental data, SGA nonlinearity, standard load cell repeatability, test load cell repeatability and conditioning board calibration. To obtain the effective degree of freedom (v_{eff}), the GUM (JCGM 2008) recommends using Eq. 3, known as the Wellch–Satterthwhite formula, where v_i is the degree of freedom for each source of uncertainty.

$$v_{eff} = \frac{u_c^4(y)}{\sum_{i=1}^{N} \frac{u_i^4(y)}{v_i}} \tag{3}$$

Thus:

$$v_{eff} = \frac{u_c^4}{\frac{X_1^4}{4} + \frac{X_2^4}{\infty} + \frac{X_3^4}{\infty} + \frac{X_4^4}{\infty} + \frac{X_5^4}{2}} = 319.01$$

Depending on the calculated degree of freedom and by consulting the table in JCGM (2008), it is possible to establish the coverage factor k = 2.

The combined uncertainty, therefore, is multiplied by the coverage factor k and the estimated expanded uncertainty (U_{exp}) for a measurement chain with amplified signal is obtained.

$$U_{exp} = 0.56 \cdot 2 = 1.12\%$$

Determining the Uncertainty of Conversion in a Non-Amplified Signal Measurement Chain

Since for the non-amplified measurement chain, there is no need to obtain factors by practical means (just inform the characteristic data acquisition program such as the full scale of the load cell to be used in the test, its sensitivity in $mV \cdot V^{-1}$ and the supply voltage in volts), it is considered that, in this arrangement, there are only Type B uncertainties involved in the conversion of the voltage data to engineering unit. Table 4 presents the sources of uncertainty involved in such a measurement chain.

Table 4. Conversion factor uncertainties: non-amplified chain.

Uncertainty Source	Type of Distribution	(%)
Standard load cell repeatability	Rectangular	0.070
Test load cell repeatability	Rectangular	0.070
Conditioning board calibration	Normal	0.076

Source: Elaborated by the authors.

Then, the calculation below determines the combined uncertainty (u_c) for the conversion into a measurement chain without signal amplification.

$$u_c = \sqrt{X_1^2 + X_2^2 + X_3^2} = 0.12\%$$

Thus, the effective degree of freedom (v_{eff}) is calculated as follows:

$$v_{eff} = \frac{u_c^4}{\frac{X_1^4}{2} + \frac{X_2^4}{\infty} + \frac{X_3^4}{\infty}} = 12.43$$

Considering the calculated degree of freedom and by consulting the table contained in Silveira (2016), it is possible to establish, by approximation, the coverage factor k = 2.28 (valid for an effective degree of freedom equal to 10).

Then, the combined uncertainty is multiplied by the coverage factor k, obtaining the estimated expanded uncertainty (U_{exp}) for a non-amplified measurement chain.

$$U_{exp} = 0.12 \cdot 2.28 = 0.27\%$$

RESULTS AND DISCUSSION

In this work, using data obtained through the preparation procedure for static rocket motors firing tests, it was sought to establish an analysis between the conversions of electrical signals (volts) to engineering unit (N) in two different configurations of electrical chains measured (with amplified and non-amplified signal). The evaluation of uncertainties for this procedure in its different arrangements allowed to determine the most assertive way to obtain thrust data in engineering unit.

Since in the amplified signal configuration it is necessary to obtain a numerical conversion factor (by applying a load with a hydraulic press), the combined uncertainty incorporates a Type A source that represents the largest component of the expanded uncertainty in this arrangement.

In the configuration with non-amplified signal, since for the conversion of electrical signals into thrust data it is only necessary to inform the data acquisition system about characteristics of the measurement chain, such as sensitivity ($mV \cdot V^{-1}$) and full scale (N), as well as the sensor excitation voltage, the combined uncertainty incorporates only Type B sources; thus, the expanded uncertainty for data conversion in this arrangement experiences a 76% reduction compared to the amplified configuration.

Then, it is recommended that all measurement chains with amplified signal (consisting of the load cell, a signal amplifier and a module for voltage signal acquisition) be replaced by non-amplified systems (formed solely by the load cell and its strain gage sensor conditioner card). Thus, the arrangement constituted by the hydraulic press would be used only for the validation of the sensor to be used in the test (by mean of a simple comparison between its response and the value indicated by the standard load cell).

AUTHORS' CONTRIBUTIONS

Conceptualization: Fernandes FAC; **Methodology:** Fernandes FAC; **Software:** Fernandes FAC; **Validation:** Fernandes FAC; **Formal analysis:** Fernandes FAC; **Investigation:** Fernandes FAC; **Resources:** Fernandes FAC; **Data Curation:** Fernandes FAC; **Writing - Original Draft:** Fernandes FAC; **Writing - Review & Editing:** Souto CA and Pirk R; **Visualization:** Fernandes FAC; **Supervision:** Souto CA and Pirk R; **Project administration:** Fernandes FAC; **Funding acquisition:** Souto CA.

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Data sharing is not applicable.

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