T-Burner Data and Combustion Instability in Solid Propellant Rockets

F. E. C. CULICK* AND E. H. PERRY‡
California Institute of Technology, Pasadena, Calif.

Nomenclature

$\bar{a}$ = average speed of sound
A_b = admittance function
D_p = port diameter
K_n = ratio of burning surface to throat area
L = length of chamber
m' = fluctuation of mass flux at the burning surface
$\bar{m}$ = mean mass flux
m_l = constant identifying acoustic modes
M_b = Mach number of mean flow at the surface
p' = pressure fluctuation
$\bar{p}$ = mean pressure
u' = velocity fluctuation at the surface
γ = ratio of specific heats

Received January 2, 1969; revision received February 6, 1969. Work supported by the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, Calif. The authors are indebted to W. Dowler and other members of the Solid Propellant Section of the Jet Propulsion Laboratory for their advice and help.

* Associate Professor of Engineering, Daniel and Florence Guggenheim Jet Propulsion Center. Member AIAA.
† Graduate Student, Mechanical Engineering, Daniel and Florence Guggenheim Jet Propulsion Center.

Reprinted from AIAA JOURNAL, Vol. 7, No 6, June 1969, pp. 1204-1205

Γ = function of γ, $\Gamma = [(\gamma - 1)/2]^{(\gamma+1)/(\gamma-1)}$
ρ' = density fluctuation
$\bar{\rho}$ = mean density

It has long been a cherished hope of some people that measurements of unsteady burning in the laboratory should be applicable to the very important practical problem of instabilities in a rocket chamber. In this Note, we wish to describe what appears to be the first experimental verification of this idea.

The T-burner is a simple device intended to provide information about the response of a burning solid to oscillatory pressure changes. By suitable interpretation of the pressure in such a burner, it is possible to infer a quantity called the admittance function, the ratio of the change in the gas velocity at the flame to a small fluctuation of pressure. In normalized form, this function is

$$A_b = (\gamma\bar{p}/\bar{a})(u'/p') = \gamma M_b[(m'/\bar{m})/(p'/\bar{p}) - (\rho'/\bar{\rho})/(p'/\bar{p})] \quad (1)$$

The first ratio in the brackets is usually called the response function. For the computation of stability boundaries in a rocket, one needs the complex function A_b, and fortunately the T-burner provides this directly. (On the other hand, data taken in an L*-burner will give the response function.)

By far the most thorough experimental study of the stability characteristics of a solid propellant rocket was reported by Brownlee and Marble.[1] The measurements were taken in cylindrical rockets of different lengths (17–44 in.) and having port diameters in the range 1.5–5.5 in. In virtually all cases of instability, the same acoustic mode was found, namely the first tangential, having the form $\cos\theta J_1(r)$, with no axial variations to first order.

Somewhat later, an analysis was devised[2] to compute the stability of waves in a combustion chamber, and applied to the stability boundary observed in Ref. 1. It was found that much of the behavior could be explained in terms of a linear theory accounting for the influence of the mean flow, viscous damping at the head end of the chamber, and the driving associated with the interaction between pressure changes and combustion at the solid surface. The formula deduced for the stability boundary is Eq. (26) of Ref. 2:

$$K_n = 0.0935[\Gamma\bar{a}\, L/(\gamma D_p)^{1/2}][(A_b^{(r)}/M_b) + m_1^2] \quad (2)$$

Here, the definition of A_b is M_b times the definition used in Ref. 2. For the mode observed, $m_1 = 1/(1.84)^2 = 0.295$. Note that only the real part $A_b^{(r)}$ of the response function affects the stability boundary. The imaginary part causes a small shift in the frequency of a mode, which cannot be distinguished experimentally.

The formula (2) represented quite well the shift of the stability boundary with length, a consequence of including the viscous damping at the head end. In addition, the data gave the stability boundary as a straight line for K_n vs D_p: if $L = 31$ in., $K_n = 66.1\ D_p$ with D_p in inches. Equivalently, since the frequency of the mode observed depends principally on the diameter of the chamber, one has experimentally K_n vs f, the frequency in cycles/sec.

But at the time when the work of Ref. 2 was performed, information on the response function was even more uncertain than at the present time; hence, formula (2) was used with the experimental result $K_n = 66.1\ D_p$ to determine what the admittance function would have to be to produce the stability boundary observed. The result appeared in Fig. 4 of Ref. 2 and is reproduced here as the dashed line in Fig. 1. It was recognized at that time that the response found in that way was unusually flat and significantly smaller than available measurements of the response function for other propellants.

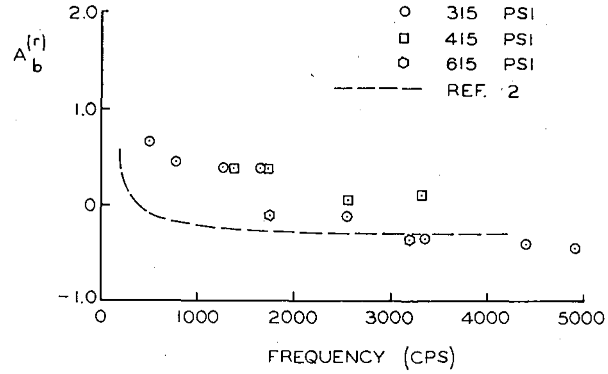

Fig. 1 Comparison of measured values of the admittance function with values inferred from a stability boundary for a tubular rocket.

When the work of Ref. 1 was carried out, the use of the T-burner was just beginning; when Ref. 2 was completed, no measurements of the response function for the propellant (T-17) used in Ref. 1 had been taken. Recently, however, in connection with an extensive study of the T-burner,[3] it has been possible to measure the response of T-17. Some of the results are shown in Fig. 1 for three different mean pressures, 315, 415, and 615 psia. This covers the range of the data reported by Brownlee and Marble; the stability boundary is really for the initial part of a firing when the mean pressure was 300–400 psia.

The qualitative agreement between the data and the result found in Ref. 2 is very satisfactory; quantitatively, the agreement is substantially better than one could reasonably have expected. Owing to experimental errors, the uncertainty in the data is around 5%. The general shape of the admittance function implied by these results is similar to that of other propellants, although the peak appears to be at an unusually low frequency. Also, the response may be atypically flat at higher frequencies.

Thus, it appears that the T-burner may indeed provide quite reliably the crucial information required for assessment of the stability of small amplitude pressure oscillations in a solid rocket. One cannot, of course, exclude the possibility of compensating errors or omissions in both the analysis of Ref. 2 and the measurements cited here, but this question cannot be refuted or resolved at the present time.

Moreover, if the favorable comparison exhibited here is correct, it lends support to the main conclusions of Ref. 4. In that work, data obtained in both T-burner and L*-burner tests of several different propellants were compared with the existing theory of the response. Substantial qualitative differences were discovered, of such a character that the theoretical models rather than the experimental techniques seemed likely to be in error. The evidence shown in Fig. 1 does not involve any theory of the response function itself and thus bears only on the experimental results obtained from the T-burner.

References

[1] Brownlee, W. G. and Marble, F. E., "An Experimental Investigation of Unstable Combustion in Solid Propellant Rocket Motors," *ARS Progress in Astronautics and Rocketry: Solid Propellant Rocket Research*, Vol. 1, edited by M. Summerfield, Academic Press, New York, 1960, pp. 455–494.

[2] Culick, F. E. C., "Acoustic Oscillations in Solid Propellant Rocket Chambers," *Astronautica Acta*, Vol. 12, No. 2, March-April 1966, pp. 113–126.

[3] Perry, E. H., work in progress.

[4] Beckstead, M. W. and Culick, F. E. C., "A Comparison of Analysis and Experiment for Solid Propellant Combustion Instability," NWC TP 4531, May 1968, Naval Weapons Center, China Lake, Calif.