Application of Combustion Instability Technology to Solid-Propellant Rocket Motor Problems

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Theme

PRESSURE oscillations in the combustion cavity of rocket motors can impose severe vibrating loads on motor components and associated equipment, especially at or near the resonant structural frequencies. The subject of this paper is the reduction to practice of methods for prediction of combustion instability behavior responsible for these problems.

Analysis and experimental data are combined in a computer program to evaluate the various contributions to the growth of oscillations in combustion cavities. Actual calculations are for a 500 Hz oscillation in the Minuteman II Stage III (M-57A1) motor.

Content

The program for stability analysis applied herein follows the method suggested by Hart and McClure.[1] The linear acoustic gains and losses are determined individually by the most suitable method and combined algebraically to determine the net growth or decay of pressure oscillations.

The principal sources of acoustic gains are considered to be the coupling between combustion and flow oscillations and coupling between flow oscillation and mean flow. Combustion response to both pressure and velocity oscillations are considered. An assumption of low amplitudes is made, which limits velocity oscillations to the extent that flow reversal does not occur. Contributions from higher mean flow velocities from slots were approximated by treating the slot region as a surface with the average efflux velocity.

The equations used to calculate the contributions of combustion and mean flow driving to the growth rate of the mode were derived[2,3] using perturbation expansions of the acoustic field equations.

Data required for calculations are 1) geometry of the acoustic cavity, 2) the acoustic pressure distribution, 3) admittance of the propellant, and 4) gas velocity leaving the burning surface. Geometry is given by selecting a motor and time during burning. The acoustic field is obtained by selecting the acoustic mode and determining the mode structure by acoustic experiments on inert models or by a finite-element analysis.[4] Admittances of the propellant are obtained from T-Burner experiments. Gas velocity is obtained from propellant density and measured propellant burning rates.

Sources of damping include droplet damping of waves by condensed phase products, nozzle acoustic losses, and structural damping. The droplet damping was calculated on the basis of the Epstein–Carhart theory,[5] extended to incorporate particle size distributions, with the particle size distributions based on the frequency function of Fein.[6] Damping due to nozzles was calculated as acoustic decay rates, determined by either the theory of Crocco and Cheng[9] or by experimentally determined functions of Buffum et al.[10,11] Structural damping was determined from the rate of energy dissipation in the motor case and propellant grain using a numerical steady-state vibration solution.[7,8]

Choosing the 500 Hz oscillation in the M-57A1 motor, stability calculations were made to correlate motor oscillatory behavior, analysis, and laboratory measurements on CYH propellant. Laboratory measurements of combustion response were available from tests in a modified T-Burner,[12] and the resulting parameters used in the present paper are shown in Table 1 for various powder lots.

Figures 1–3 show the contributions to oscillation growth, contributions to damping, and the net effect of both contributions, respectively. The figures show these effects as functions of time during burning and propellant lot number based on the M-57A1 motor configuration. Figure 1 indicates that the driving processes decrease rapidly early in burning, that combustion driving differs appreciably according to lot number, and that the contribution due to pressure coupling with combustion is around three times the combined contributions of velocity coupling and mean flow driving (this last

Table 1 Combustion response parameters for CYH propellant

CYH powder lot	Pressure-coupled admittance $A^{(r)}$ (dimensionless)	Velocity-coupled response parameter $\widetilde{CK}^{(i)}$ (dimensionless)
1–3	3.2	
1–9	2.5	2.1
1–13	1.5	
1–14	2.0	
1–15	4.1	0.01
1–16	4.6	
1–20	3.4	0.61

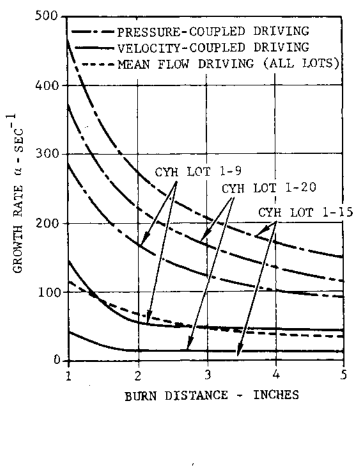

Fig. 1 Acoustic gains predicted for the M-57A1 motor.

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Index category: Combustion Stability, Ignition, and Detonation.

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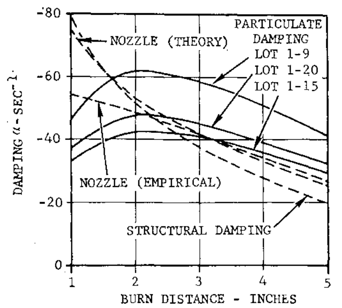

Fig. 2 Damping rate contributions M-57A1 motor.

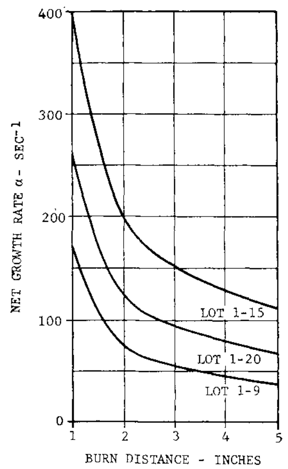

Fig. 3 Net acoustic growth rate, M-57A1 motor.

point indicates the importance of carrying out T-Burner tests on propellant lots). Figure 2 indicates that the three sources of damping (particulate, nozzle and structural) are of about equal importance, with the particulate damping being appreciably dependent on propellant lots. The net effects shown in Fig. 3 indicate large positive growth rates of oscillations early in burning, dropping rapidly but remaining positive for the maximum web burning distance calculated (5 in.) for all three powder lots. This is consistent with results from motor firings, where oscillatory behavior persisted to a web burning distance of 7 in.

A detailed analysis[13] was made of oscillations measured in M-57A1 static firings, and a condensation of results is shown in Table 2 for the tests involving the propellant lots considered in Figs. 1–3. Comparison of the results in Table 2 with Fig. 3 shows that the amplitude and duration of oscillations are qualitatively consistent (lot for lot) with the calculated net growth rates in Fig. 3. While this consistency is gratifying, it is the comparison with initial growth rates that would be expected to be most consistent with the linear analysis, and consistency was not achieved with respect to initial growth rate. More detailed consideration of the test records showed that the tests on Lots 1–9 gave high initial growth rates which quickly leveled off at low, steady amplitude, while the other lots exhibited a continued slow growth to larger amplitude after their initial moderate growth rate. While the significance of this behavior relative to the present stability analyses remains undetermined, it may contain some important clues and suggests the importance of nonlinear contributions not contained in the analysis.

Table 2 Pressure oscillation growth rates and amplitudes for the M-57A1 motor

Motor no.	powder[a] lot no.	Initial growth rate, $\alpha(\sec^{-1})$	Maximum amplitude (pk to pk, psi)	duration (in.)
QA-56	1–9	140	3.4	1.2–7.0
QA-57	1–9	170	2.3	1.2–7.0
QA-58	1–9	104	3.5	1.2–6.5
QA-72	1–15	64	24	0.3–10.0
QA-74	1–15	12	29	1.0–9.7
7-10-5	1–20	20–40	21	0.5–9.5

[a] Motors from powder lot 1-9 are classed as non-oscillatory; all others are oscillatory.

On the basis of comparisons with motor firing data, results of the linear procedures now available for acoustic analysis of rocket motors appear to over-predict growth rates even in their range of applicability. The apparent lack of agreement between experiment and analysis could be a result of several causes, including inaccuracies in T-Burner data, weaknesses in any or all of the expressions from which damping and driving are calculated, or difficulties in obtaining growth rates from conventional motor firing instrumentation. These are all considered as strong possibilities and are under investigation.

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