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Flight Vibration Environments Defined from Mk 12 Booster Static Tests

N. Rubinstein* and W.C. Caywood†
The Johns Hopkins University Applied Physics Laboratory, Laurel, Md.

Results of a static firing test program concerning the environmental effects of rough burning of the Mk 12 rocket motor booster on the Standard Missile components are discussed. Vibration and pressure data were recorded and processed using methods of time series analyses. The test procedures, methods of data processing, and significant results are presented. The results show good agreement with flight vibration data and theoretical acoustic pressure frequencies. The methods used demonstrate the ability to determine flight environments in ground testing.

Introduction

STATIC firing tests were conducted to evaluate the burning characteristics of the Mk 12 rocket motor booster, to determine the vibration environment in the aft end of the Standard Missile-1 Extended Range (SM-1 ER), and to relate this vibration environment to the presence of rough burning. Vibration and pressure data from these tests have been correlated with flight data and theoretical predictions. The test methods and significant results are summarized in this paper.

Since a quantitative definition of rough burning did not exist, a criterion associated with the missile's steering control unit (SCU) test specification[1] was chosen. This specification covers a power spectral density (PSD) range from 2-2000 Hz. The chosen criterion defines rough burning as the occurrence of any longitudinal acceleration on the SCU with a PSD in excess of the environment defined in the SCU test specification.

A comprehensive report on this series of tests has been prepared by the authors.[2]

Test Setup and Instrumentation

The test configuration, shown in Fig. 1, included the Mk 12 booster rocket motor, the SM-1 (ER) steering control unit (SCU) with four control surfaces, and the spacer section. Two cradles provided the vertical support for the test configuration and these supports permitted freedom of motion along the thrust axis. Thrust was carried out through a load cell mounted to a heavy aluminum plate at the forward end of the spacer section.

Instrumentation consisted of accelerometers, pressure transducers, strain gages, and a load cell. The accelerometers were located on the external structure of the missile's SCU section, the missile's autopilot activate switch (APAS) module within the SCU section, and on the booster headcap. Transducers to measure both dc and ac pressure were also mounted on the headcap. Thrust was measured at the forward end. The location of the test instrumentation is schematically shown in Fig. 1. The location and installation of the APAS module accelerometers duplicates the actual flight unit installation. Data from these instruments, as well as a time code and the time of release of the missile-booster retaining clamp, were recorded on 14 channels of FM magnetic tape with a frequency bandwidth of 5000 Hz.

The manufacturing dates and conditioning temperatures of the propellant grains are identified in Table 1. The first six tests were conducted with the propellant grains in their original cases. For the remaining tests, refurbished cases were used along with the headcaps from the original six motors. In some instances more than one test was conducted with a particular motor case.

Data Processing and Analysis

Digital time series analyses techniques[3] were used to analyze the data. To assure that the analyzed data would be good to at least 5000 Hz, a digitizing rate of 20,000 points/s was chosen. After the data were digitized and stored on a seven-track tape, three separate computer programs were used for the analysis. The first of these programs transferred the data to the IBM 360/91 disk pack and then computed the time histories of the mean, rms, standard deviation, and maximum and minimums of the data. Plots of absolute values of peaks and rms were automatically made. Examinations of these plots led to subsequent choices of particular time intervals of interest and further detailed statistical analyses using the other

Table 1 Mk 12 booster hardware identification

Test no.	Test date	Grain manufacturing date	Conditioning temp., °C(°F)
1	3 Oct. 1974	June 1971	25 (77)
2	3 Dec. 1974	Feb. 1967	25 (77)
3	3 Dec. 1974	Nov. 1967	25 (77)
4	3 Dec. 1974	Sept. 1965	− 12 (10)
5	6 Dec. 1974	Dec. 1970	25 (77)
6	6 Dec. 1974	Feb. 1971	25 (77)
7	5 June 1975	Sept. 1968	25 (77)
8	5 June 1975	July 1964	− 12 (10)
9	5 June 1975	May 1971	25 (77)
10	5 June 1975	Sept. 1971	25 (77)
11	5 June 1975	April 1968	25 (77)
12	23 July 1975	Nov. 1965	25 (77)
13	23 July 1975	Jan. 1967	25 (77)
14	23 July 1975	Dec. 1965	49 (120)
15	2 Dec. 1975	Sept. 1967	25 (77)
16	2 Dec. 1975	Aug. 1966	25 (77)
17	2 Dec. 1975	Nov. 1966	49 (120)
18	4 Dec. 1975	Jan. 1966	49 (120)
19	4 Dec. 1975	Mar. 1969	25 (77)

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*Senior Staff, Structures.
†Supervisor, Structures. Member AIAA.

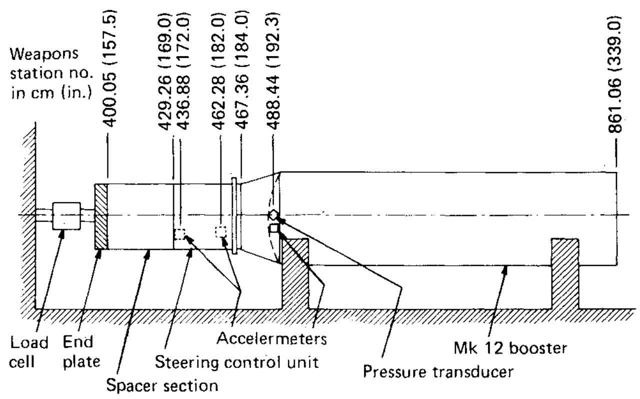

Fig. 1 Mk 12 booster static firing test configuration schematic.

two computer programs. In one, the power spectral density (PSD), mean squared power, and one-third-octave rms-frequency spectrum were determined, and plots of these functions were automatically made. In the other, the autocorrelation function, the probability density, and cumulative probability of the data were found. This program also makes plots of the time-history of the data, the autocorrelation function, the probability density along with the Gaussian (normal) for comparison, and, finally, plots the cumulative probability on computer-constructed probability paper for easy comparison with the Gaussian.

Results

Review of Accelerometer Data

Digital processing was performed on the accelerometer data from tests 5-7, 11-14, 17, and 18. Data on the remaining tests were analyzed for peak and rms accelerations only.

An examination of the time-history data indicated the presence of discrete shocks associated with booster ignition and missile-booster clamp release. The magnitudes of the peak accelerations measured on the APAS module during ignition, clamp release, and burning are summarized in Table 2. These data indicate that on most of the tests the APAS accelerations induced by ignition and clamp release are of the order of 50-120 g.

The rms accelerations on the APAS module and the steering control unit during booster burning are presented in Table 3. In this presentation, the data are shown for several time durations, since rms values are inherently dependent on the time interval over which the data are taken.

An example of the acceleration power spectral density (PSD) for the steering control unit is given in Fig. 2. Here the longitudinal PSD's from tests 11 and 13 are compared with the steering control unit test specification.[1]

Based on an examination of the data, a criterion was selected for judging whether the boosters exhibited rough burning characteristics. Rough burning has been defined as the occurrence of any resulting longitudinal accelerations on the SCU which produce a PSD in excess of the environment defined in the SCU test specification. This test specification covers frequencies to only 2000 Hz; whereas, static firing test data to 5000 Hz has been recorded and analyzed. The data from tests 5-7, 11, and 14 met this criterion and the boosters of these tests have been classified as rough burning. In all other tests, the PSD of the SCU is within the specification values.

Detailed examination of the static firing test results showed a marked correlation between the APAS acceleration levels and the SCU PSD levels. In every case where rough burning (based on SCU PSD criterion) has been observed, the APAS radial or longitudinal accelerations exceeded 20 g rms for at least 0.60 s (see Table 3). Accelerations measured during quiet motor tests were less than 14 g rms for the 0.60-s time period. Also, an examination of the data on the APAS longitudinal

Table 2 APAS module peak accelerations, g

Test no.	Ignition Radial	Ignition Long.	Latch release Radial	Latch release Long.	Burning Radial	Burning Long.
1			60	60	These values manually scaled from oscillograph data.	
2			50	35		
3			70	65		
4			50	50		
5[a]	129	112	99	120	99	120
6[a]	37	38	66	55	72	84
7[a]	32	46	72	75	59	83
8	113	115	71	77	40	40
9	77	116	61	57	31	46
10	91	115	74	64	32	32
11[a]	54	74	71	59	67	107
12	33	49	54	53	23	22
13	121	119	74	52	43	30
14[a]	121	119	54	48	65	113
15	19	26	49	49	30	46
16	37	52	43	43	26	26
17	27	26	35	35	36	37
18	...	...	...	...	...	...
19	39	62	28	28	26	26

[a] Tests exceeding rough burning criterion.

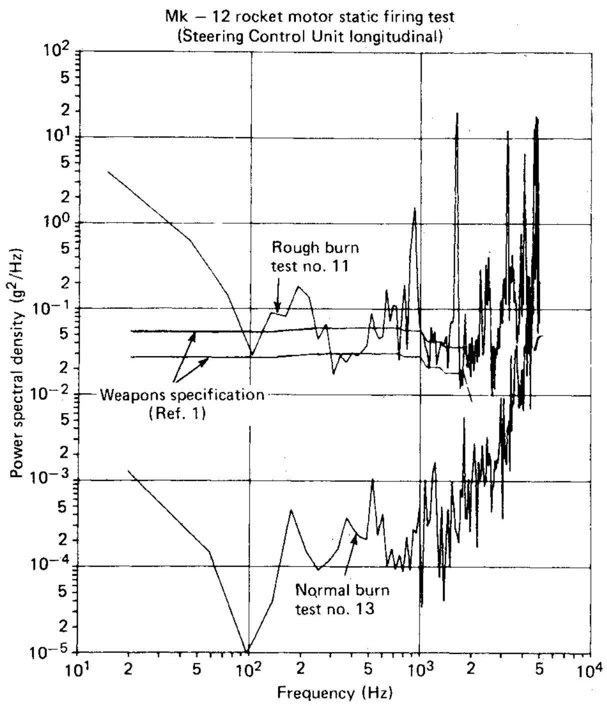

Fig. 2 Comparison of static firing results and steering control unit specification values.

peak accelerations, Table 2, showed that accelerations during burning were greatest in those tests which met the rough-burning criterion. These accelerations ranged from 83-120 g during the period of rough burning. These results are significant, since they imply that a rough burning criterion based on APAS module acceleration levels may lead to the same conclusion as that derived from the use of the SCU PSD criterion.

An examination of the booster data showed that in all cases, high accelerations (greater than 350 g peak for more then ½ s) were present prior to clamp release, but only in those tests with 49°C (120°F) conditioned boosters was there evidence of rough burning on the missile before clamp release. However, for the 49°C (120°F) conditioned boosters, only in test 14 was the PSD criterion of rough burning met. In only four of the tests were high accelerations (greater than 350 g

Table 3 Maximum rough burning accelerations, g rms

	APAS module								Steering control unit							
	Radial				Longitudinal				Radial				Longitudinal			
	Time interval, s				Time interval, s				Time interval, s				Time interval, s			
	0.05	0.20	0.40	0.60	0.05	0.20	0.40	0.60	0.05	0.20	0.40	0.60	0.05	0.20	0.40	0.60
5[a]	44.5	31.1	29.8	27.0	47.3	40.4	36.3	31.6	66.8	49.9	42.1	35.1	70.7	50.1	42.6	36.3
6[a]	35.2	24.8	24.6	21.3	41.4	30.3	30.1	25.8	(101.2	61.3	48.5	40.5)[b]	85.7	73.1	71.8	64.2
									(68.0	47.2	39.9	33.6)	43.5	35.9	35.2	30.5
									– Limiting –							
7[a]	21.1	19.8	16.4	14.2	47.0	37.4	36.0	30.2	40.2	30.5	23.1	19.5	(104.6	83.0	68.7	60.6)
													(76.3	66.9	59.1	53.5)
													– Limiting –			
8	10.8	9.1	7.9	7.2	9.7	9.3	8.9	8.6	9.2	8.8	8.4	7.9	27.9	21.1	19.4	18.8
9	10.4	8.2	7.6	7.1	20.3	18.1	15.5	13.4	15.0	11.4	10.7	10.6	36.5	32.6	30.4	27.8
10	11.3	10.4	9.7	9.1	9.3	8.5	7.8	7.7	22.1	17.0	14.8	13.5	32.9	31.2	27.8	25.5
11[a]	25.0	19.8	17.4	16.5	61.2	54.7	42.0	38.1	(55.3	45.3	37.8	32.8)	(85.7	73.1	71.8	64.2)
									(55.3	45.3	37.8	32.8)	(84.3	72.6	70.1	62.9)
									– Limiting				– Limiting –			
12	7.1	6.4	5.8	5.3	6.6	6.0	5.6	5.4	11.5	9.0	8.0	7.8	39.9	35.3	32.5	30.0
13	14.3	11.5	10.5	9.8	9.8	8.2	7.8	7.6	38.8	29.8	27.6	25.8	68.5	45.1	44.7	40.4
14[a]	24.2	19.1	17.0	15.7	56.8	44.0	43.7	39.2	76.7	65.4	60.4	55.8	– Erratic data –			
15	12.0	10.5	9.1	8.4	8.5	7.8	7.0	6.6	14.0	12.4	11.8	10.9	36.8	28.8	25.3	24.0
16	10.7	9.0	8.2	7.4	8.6	7.3	6.5	6.2	10.8	8.7	7.6	7.1	23.5	20.8	18.7	16.7
17	12.8	11.1	10.5	9.7	14.8	12.9	12.1	11.1	41.8	35.4	34.5	30.7	71.1	63.9	57.5	55.2
18	– Erratic data –				– Erratic data –				50.8	38.1	32.2	30.7	62.5	54.5	51.2	48.7
19	9.0	7.2	6.6	6.2	7.8	6.8	6.1	5.6	29.3	21.9	20.1	17.3	34.5	32.2	29.7	25.0

[a] Tests with evidence of rough burning effects.
[b] Data on limiting values for reference only; upper values are rms, lower values are 1σ.

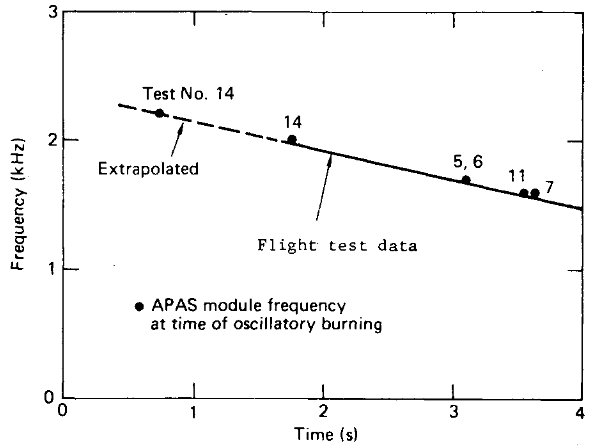

Fig. 3 Correlation of ground and flight test frequencies.

peak for more than ½ s) seen after clamp release, and all four exhibited rough burning characteristics. The boosters for these four tests were conditioned at 25°C(77°F). Two boosters, on tests 4 and 8, were conditioned at −12°C(10°F), and neither of these exhibited rough burning characteristics.

Comparison of Static Firing and Flight Test Accelerometer Data

Vibration levels and characteristic resonant frequencies during periods of rough burning have been measured on Standard and Terrier missiles during flight. These frequencies usually occurred 2-4 s into the flight and were in the 1200-1700 Hz range. Typically, the characteristic frequency starts at the higher value and decreases with time as the propellant is burned. Similar characteristic frequencies were also derived from the accelerometer data of the static firing tests. The static tests have also shown that when rough burning occurs early, characteristic frequencies of the data can reach 2200 Hz. Furthermore, these predominant frequencies are present on the booster, SCU, and APAS module. When frequencies greater than 2200 Hz are predominant or when no predominant frequencies exist, the criterion for rough burning is not exceeded. Correlation of the frequency data determined from static and flight tests is shown in Fig. 3. In this figure, the solid line represents the average of data reported on six flight tests and the dots indicate data recorded in the static firing tests during periods of rough burning. The correlation is excellent.

Most of the flight test acceleration measurements were taken at the forward end of the missile, but in one of the flights, data were taken on the APAS module at the same location as measured in static firing tests. A comparison of the peak acceleration levels on the APAS from flight and static firing tests are presented in Table 4. Also presented in this table is a comparison of the rms acceleration levels. To draw definitive conclusions from this comparison would be highly improper, since only one flight test data point exists and scatter exists in both the static and flight test measurements. However, the data comparison is encouraging in that the magnitudes are of the same order.

Review of Acoustic Pressure Data

The standard surveillance test dc pressure measurement was made during all test runs. This transducer was mounted to the end of a long grease-filled tube; hence, it was not sensitive to the booster pressure perturbations. On tests 15-19, a high-frequency ac pressure transducer (Kistler 601) was also mounted at the end of the long-coupled grease-filled tube, and it too was insensitive to the pressure perturbations. Another Kistler 601 high-frequency ac pressure transducer with a special close-coupled mounting was used to measure the pressure perturbations on tests 7-19. The location of the tap on the booster headcap is schematically shown in Fig. 4. Also illustrated in this figure is a cross section of the propellant grain showing the orientation of the grain protrusions in the vertical plane.

Frequency and statistical analyses of the ac pressure data were performed for tests 7, 12-14, 17, and 18. From the PSD of the pressure data, the characteristic frequencies of acoustic excitation were obtained and compared to the theoretical acoustic frequencies reported by the Naval Weapons Center/China Lake (NWC) Aerothermochemistry Division.[4] NWC reports the predominant mode of acoustic excitation is

Table 4 Comparison of APAS flight and static firing acceleration data during rough burning

	Mk 12 static firing program			Flight test	
	Test no.	Radial $\Delta t = 0.6$ s	Longitudinal $\Delta t = 0.6$ s	Radial $\Delta t = 0.7$ s	Longitudinal $\Delta t = 0.7$ s
Broadband peak amplitude, g	5	99.0	120.0	74.0	112.0
	6	72.0	84.0		
	7	59.0	83.0		
	11	67.0	107.0		
	14	65.0	113.0		
	Av.	72.4	101.4		
Broadband rms level, g rms	5	27.0	31.6	21.0	31.0
	6	21.3	25.8		
	7	14.2	30.2		
	11	16.5	38.1		
	14	15.7	39.2		
	Av.	18.9	33.0		

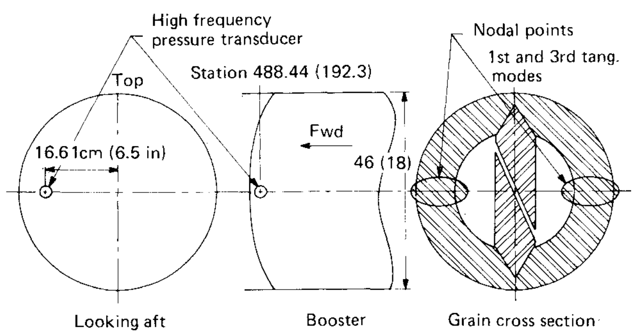

Fig. 4 Location of ac pressure transducer with respect to booster grain geometry.

the first tangential with radial modes not likely to be present. NWC has also suggested that the pressure tap may be at a poor location (see Fig. 4) to detect the principal source of pressure perturbations, since it is at a nodal point of the odd-numbered modes of the tangential wave acoustic pressure. In this location, the transducer is relatively insensitive to the odd-numbered modes. A better location to detect the first tangential mode pressure perturbations would be 90 deg from its existing location.

An examination of the measured and theoretical data indicated that the observed pressure frequencies may indeed be the result of tangential mode excitation. The predominant power appeared to be associated with the even modes, with lesser power associated with the odd tangential modes. Had the pressure transducer been located at an antinodal point (90 deg from its actual position), it is reasonable to assume that the predominant PSD of the pressure would have been associated with the first tangential mode of acoustic excitation.

Conclusions

An examination of the evidence from static firing and flight tests has led to the following conclusions:

1) Rough burning appears to be associated with the first tangential mode of acoustic pressure perturbations at frequencies between 1200-1700 Hz.

2) Rough burning appears to be triggered by either ignition or clamp release shock.

3) The characteristic frequencies measured in the static firing tests during rough burning were in excellent agreement with those observed on the missile during flight tests.

4) The technique of measuring vibration with instrumented missile hardware attached to the booster for development and surveillance testing was found to be a valid method for determining rough burning effects on the missile.

Acknowledgments

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