JOURNAL OF PROPULSION AND POWER
Vol. 9, No. 2, March–April 1993

Pressure Oscillations in Post-Challenger Space Shuttle Redesigned Solid Rocket Motors

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Data from the first seven solid rocket motor (SRM) static tests were used to establish upper bounds for the maximum acoustic pressure amplitudes in the latter half of firing. Those bounds have since been used as a basis for worst-case simulation scenarios by specialists in structural dynamics at NASA and Rockwell International, and to provide a basis for evaluating data from individual motors which were tested subsequent to the original seven SRMs. The purpose of this article is to compare current motor data with data from the early motors and determine whether or not the upper bounds need to be recalculated. Comparisons of chamber pressure amplitudes in redesigned solid rocket motors (RSRMs) with the predicted upper bounds, based on the original seven motors, initially suggest that the original bounds are no longer suitable descriptors for the current motor designs. However, a rigorous statistical analysis of the SRM and RSRM motor data indicates that the data are from similar statistical populations.

Introduction

SPACE Shuttle liftoff and early ascent utilizes thrust provided by a combination of the Shuttle's main engines and two solid propellant rocket booster motors (SRMs). The SRMs burn for approximately 2 min. Because of their size, the motors are manufactured in sections which are assembled prior to launch. Seal failure at a motor joint was identified as the prime cause of the Challenger accident. Booster motor seal and segment designs were revised after Challenger to provide improved reliability. Motors with redesigned joints are designated as RSRMs (redesigned SRMs) to differentiate them from earlier SRMs.

All SRMs and RSRMs exhibit low-amplitude longitudinal pressure oscillations during burning. Although the oscillations have no known deleterious effect on motor ballistics, the acoustic pressure variations cause thrust oscillations which might affect Shuttle systems or components. The acoustic mode of greatest interest is the first or fundamental mode which, in the SRM, has a nominal frequency of 15 Hz. Oscillations in the SRM are believed to be caused by coupling between large scale vortices and the acoustic modes of the motor chamber. The vortices are thought to be created in the region of the motor segment interfaces and are inherent in the design of the motor. In such a situation the usual approach is to measure the oscillations and assess their impact on any sensitive components through tests and analysis. Questionable components can be altered to survive the vibration environment. As motor firings occur, oscillations are monitored to determine whether there are changes in the nature of the oscillations.

Since the first static test, SRMs have been equipped with instrumentation especially designed to acquire chamber pressure oscillation data. Data from the first seven SRM static tests were used to establish predicted upper bounds for the maximum amplitudes in the latter half of firing. Those bounds have been used as a basis for worst-case simulation scenarios by specialists in structural dynamics at NASA and Rockwell International, and to provide a basis for evaluating data from individual motors which were tested subsequent to the original seven SRMs. Comparisons of chamber pressure amplitudes in RSRMs with the predicted upper bounds, based on the original seven motors, suggest that the original bounds may no longer be suitable descriptors for the current motor designs.

The information presented here is part of a continuing effort to monitor chamber pressure oscillations in Space Shuttle solid propellant boosters.[1] This report describes the methods of analysis and results obtained.

SRM Data: First Seven Motors

Static tests of SRM motors have included a specially instrumented channel for detecting and processing only oscillatory pressures. That channel was designated P006. Unfortunately, equipment failures prevented P006 oscillatory data from being acquired on the first two SRM tests. P006 functioned on subsequent tests and was used for detailed analysis of chamber pressure oscillations using analog techniques. Early in the test program it was necessary to provide a characterization of the first longitudinal acoustic mode pressure amplitudes. The times of interest were located in the latter half of firing. During the later half of firing, the Shuttle vehicle assembly is lighter and more sensitive to thrust oscillations. Structural dynamic specialists at Rockwell International had devised simulations of the Shuttle for specific times during SRM firings (64, 80, 100, and 112 s). Data from static tests of SRMs were grouped to bracket the Rockwell model times in the following manner: data from 60 to 75 s was to be used for the 64-s simulation, etc. The 112-s model used data based on a 10-s span which covered the 105–115-s interval. The data to be used consisted of the maximum peak-to-peak (pk-pk) amplitudes obtained from analysis of SRM test data. SRM data was grouped by time period as noted above to include each Rockwell model. From the measurements of individual motors, mean amplitudes and sample standard deviations were computed for each group of data. Data for individual motors, mean amplitudes, and sample standard deviations are shown in time groupings in Table 1. Data in Table 1 are maximum

Presented as Paper 91-0203 at the AIAA 29th Aerospace Sciences Meeting, Reno, NV, Jan. 7–10, 1991; received Feb. 12, 1991; revision received Aug. 17, 1992; accepted for publication Sept. 3, 1992.

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Table 1 Maximum amplitude data for the first seen SRMs

Times, s		Maximum pressure amplitudes, kPa peak-to-peak[a] (1 psi = 6.895 kPa)								
Rockwell model	Motor interval	DM-1	DM-2	DM-3	DM-4	QM-1	QM-2	QM-3	Average pressure amplitude, kPa pk-pk	Sample standard deviation, s
64	60–75	[b]	8.21	9.86	10.27	9.86	9.79	8.96	9.49	0.76
80	75–90	11.65	8.34	12.34	12.07	10.96	10.55	10.27	10.88	1.36
100	90–105	11.65	9.58	11.72	9.31	10.48	7.38	11.93	10.29	1.66
112	105–115	10.62	6.90	12.82	7.72	7.58	4.69	7.52	8.26	2.65

[a]Measurements based on SRM data digitally filtered, 10–20 Hz. [b]Data not available in this time period for DM-1.

Table 2 Predicted upper bounds of maximum acoustic amplitude for the first seven SRMs

Times, s		Average pressure amplitude, kPa pk-pk	Sample standard deviation, s	Predicted upper bounds, kPa pk-pk[a]
Rockwell model	Motor interval			
64	60–75	9.49	0.76	11.84
80	75–90	10.88	1.36	15.08
100	90–105	10.29	1.66	15.42
112	105–115	8.26	2.65	16.45

[a]Based on a one-sided tolerance; populations coverage of 99.9%, and a 50% confidence level.

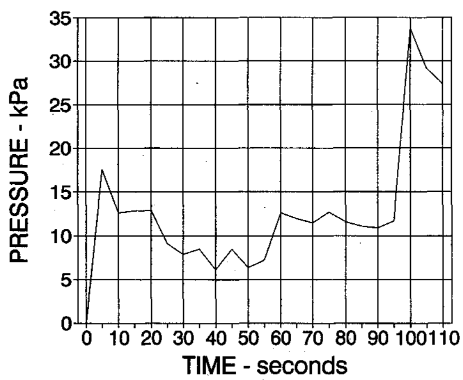

Fig. 1 Maximum pressure oscillations for QM-8 RSRM.

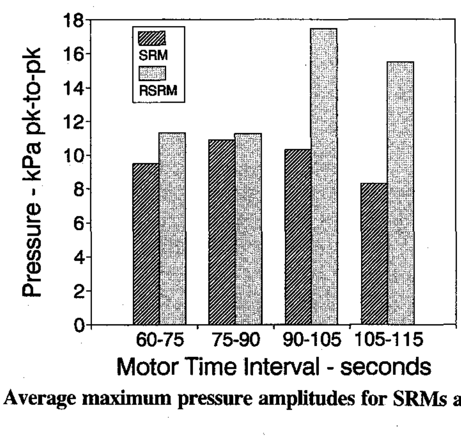

Fig. 2 Average maximum pressure amplitudes for SRMs and RSRMs.

amplitudes from digitally processed data that were reduced by data processing specialists at the Marshall Space Flight Center, Huntsville, AL, since analog oscillatory data were not available for the first two motors.

Predicted upper bounds of maximum acoustic amplitude were computed for each data group using the procedure for statistical tolerances. Details are provided in Ref. 1. A population coverage of 99.9% (approximately three standard deviations) and a single-sided confidence coefficient of 0.5 (50% confidence level) were used for the calculations. Values of the predicted upper bounds (also termed "statistical tolerance limits") based on the above criteria are presented in Table 2.

Table 3 Comparison of first longitudinal acoustic mode data: post-Challenger RSRMs

Time interval, s	Maximum pressure amplitude, kPa peak-to-peak					
	PVM-1	DM-8	DM-9	QM-6	QM-7	QM-8
0–5	[b]	[a]	[a]	[a]	[a]	[a]
5–10	[b]	[b]	9.72	9.65	12.55	17.58
10–15	[b]	[b]	8.27	9.93	10.76	12.62
15–20	[b]	6.83	6.76	9.58	8.96	12.89
20–25	7.58	7.58	6.76	7.65	8.34	12.89
25–30	3.93	5.52	5.38	5.72	9.72	9.10
30–35	4.90	4.27	4.62	5.59	6.83	7.86
35–40	4.55	4.76	3.72	4.62	7.52	8.48
40–45	3.65	4.21	4.83	4.83	8.21	6.07
45–50	4.48	5.10	4.69	4.34	9.17	8.48
50–55	5.86	5.38	5.72	4.90	7.79	6.34
55–60	5.72	6.34	4.62	7.52	9.58	7.17
60–65	5.38	6.48	7.79	11.58	13.17	12.62
65–70	11.24	8.21	7.58	13.51	10.07	11.93
70–75	7.86	6.76	9.24	9.86	12.20	11.45
75–80	8.96	11.51	10.41	13.51	9.72	12.69
80–85	7.17	8.48	10.27	10.55	9.45	11.58
85–90	7.65	9.72	6.83	10.89	10.20	11.10
90–95	17.31	6.41	7.72	12.82	20.06	10.89
95–100	18.62	9.45	6.14	13.24	21.03	11.72
100–105	16.27	9.79	8.34	10.34	18.00	33.72
105–110	12.14	8.62	13.10	18.13	11.72	29.10
110–115	12.07	6.83	6.76	12.48	11.86	27.30

[a]Data not reduced due to ignition transient.
[b]Data missing in all or part of this interval.

Post-Challenger Motor Data

An improved motor segment design was adopted following the Challenger mishap. Static test data from motors using the new design have been made available, and the oscillatory chamber pressure data has been analyzed. The data presented here were produced by analog techniques. Data from six of those motors are shown in Table 3. By convention, motor data time intervals are 5 s for initial reduction. Also, the convention is to reduce all 5-s intervals except the first, which contains some spurious information caused by chamber pressure transients generated by motor ignition. A plot of the maximum pressure oscillations is shown for motor QM-8 in Fig. 1.

The data in Table 3 provides the basis for constructing a table of maximum amplitudes of the post-Challenger motors similar to Table 1. That has been done as shown in Table 4, which includes average maximum amplitudes and sample standard deviations for each of the time intervals.

A comparison of data from post-Challenger motors (Table 4) with data from the first seven SRMs (Table 1) reveals an apparent upward shift of amplitudes in post-Challenger motor data. Figure 2 compares the average maximum pressure amplitude for the pre- and post-Challenger motors for each time zone. An evaluation of the presumed differences between the two groups of data is provided below.

Table 4 Maximum amplitude data for post-Challenger RSRMs

Times, s		Maximum amplitude, kPa peak-to-peak							
Rockwell model	Motor interval	PVM-1	DM-8	DM-9	QM-6	QM-7	QM-8	Average pressure amplitude, kPa pk-pk	Sample standard deviation, s
64	60–75	11.24	8.21	9.24	13.51	13.17	12.62	11.33	2.19
80	75–90	8.96	11.52	10.41	13.51	10.20	12.69	11.24	1.69
100	90–105	18.62	9.79	8.34	13.24	21.03	33.72	17.46	9.36
112	105–115	12.14	8.62	13.10	18.13	11.86	29.10	15.49	7.34

Table 5 *F*-Test results

Time interval, s	SRM data[a]				RSRM data[b]				*F*-test	95% confidence	
	Mean	s	s_2^2	DOF[c]	Mean	s	s_1^2	DOF	s_1^2/s_2^2	level[d]	Results
60–75	9.49	0.76	0.58	5	11.33	2.19	4.80	5	8.28	5.05	Rejected
75–90	10.88	1.36	1.85	6	11.24	1.69	2.86	5	1.55	4.39	Accepted
90–105	10.29	1.66	2.76	6	17.46	9.36	87.61	5	31.74	4.39	Rejected
105–115	8.26	2.65	7.02	6	15.49	7.34	53.88	5	7.68	4.39	Rejected

[a]Data from Table 1. [b]Data from Table 4. [c]Degrees of freedom. [d]Reference 2, Table 5, 95% confidence level.

Data Comparisons

As noted above, the amplitudes seen in post-Challenger motors appear to be greater than in the early motors. The question as to whether the observed differences between the two sets of motor data are due to a real shift in oscillatory pressure behavior or due to chance variations in the data can be addressed quantitatively by applying several statistical tests.[2–4] There are two applicable statistical tests to determine if the means between the pre- and post-Challenger RSRM tests are different. Both tests are referred to as "t" tests. One test assumes the standard deviations are equal, and one assumes they are not equal. In order to determine which test is more applicable, the Fisher "F" test was applied to the data to determine whether the observed differences between the standard deviations are due to chance or are real. Ideally, with all of the following statistical tests, many data points are necessary. Most statistic books recommend 30 or more samples.[2–4] However, real world constraints in testing Shuttle booster motors makes this prohibitive. When dealing with small data sets, additional subjectivity is required in interpreting the statistical results.

Fisher *F* Test

The common statistical procedure for comparing two population variances, s_1 and s_2, is the Fisher F-test. It is given by

$$F = (s_1^2/s_2^2) \tag{1}$$

In this expression, s_1 and s_2 are the standard deviations for the two data populations. F is computed so that the ratio of the standard deviations is greater than one. This ratio is then compared to tabulated values depending on the number of degrees of freedom (DOF) for each group of data at a given confidence level. The DOF is the number of observations minus one. The confidence level is the percent confidence at statistical inference will have. If the calculated value is greater than the tabulated value, then the assumption of equal standard deviations is rejected at that confidence level, i.e., the standard deviations are not statistically the same. It is the null hypothesis (H_0) which is rejected (i.e., the assumption), under the predetermined constraints of the test, that the standard deviations of the two groups of data differ only by chance. Table 5 shows the results of the F-test on the pre- and post-Challenger RSRM data.

The results are mixed as one of the four pairs of standard deviations, the 75–90-s interval, is accepted by the F-test, i.e., the SRM and RSRM data have similar standard deviations. The other three pairs, 60–75-, 90–105-, and 105–115-s intervals, are rejected by the F-test and do not have statistically similar standard deviations. The choice of a 95% confidence level is fairly standard in statistics when there is no basis for a different level, and for that reason that level was used here. Because of the different F-test results, both statistical t tests will be performed.

t Test Assuming Equal Standard Deviations

The first t test assumes equal standard deviations. This t test will be applied to the 75–90-s motor interval. The SRM and RSRM data for this interval was found to have equal standard deviations. The t-test for equal standard deviations is given by the following equations:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{s_0\left(\dfrac{1}{n_1} + \dfrac{1}{n_2}\right)^{1/2}} \tag{2}$$

where s_0 is the pooled standard deviation of both populations of measurements. It is defined as

$$s_0^2 = \frac{\sum_{j=1}^{n_1} (x_{1j} - \bar{x}_1)^2 + \sum_{j=1}^{n_2} (x_{2j} - \bar{x}_2)^2}{n_1 + n_2 - 2} = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2} \tag{3}$$

In these equations, x is the amplitude of the pressure oscillations, $\bar{x}$ is the mean pressure amplitude of the oscillations, and n is the number of data points. The subscripts 1 and 2 refer to the pre- and post-Challenger data, respectively. A summary of the calculations is shown in Table 6.

The computed t, which is derived from the data, is compared to a tabulated value, designated here as "T". The tabulated value of T is based on the number of DOF and a 95% confidence level. If the calculated value of t exceeds the tabulated value of T, the test statistic is rejected, i.e., the assumption of equal means is invalid, and the two statistical data sets do have different levels of maximum pressure oscillations. Again, it is the H_0 which is rejected. If rejected, under the predetermined constraints of the test, we cannot accept that the two means differ by chance. Here, "chance" refers to the random variations always present when comparing two groups of data. If H_0 is accepted, it is implicitly assumed that the two groups of data represent samples from a single larger (hypothetical) population. If H_0 is rejected, it is implicitly assumed *but not proven* that the two groups of data represent samples drawn from two distinct populations. The results of this test (Table 6) indicate that there is no statistical difference between the means for the 75–90-s time interval at a 95% confidence level.

t Test Assuming Nonequal Standard Deviations

The second *t* test assumes that the standard deviations are different. This *t* test will be applied to the 60–75-, 90–105-, and 105–115-s motor intervals. The SRM and RSRM data for these intervals was found to have nonequal standard deviations. This test only works best when the two populations of data are of roughly equal numbers. That criteria is met since there are six or seven samples in all populations considered for all four time intervals. This *t* test is given by the following equations. First it is necessary to define

$$n_1 \leq n_2 \tag{4}$$

$$u_i = x_{1i} - x_{2i}\sqrt{(n_1/n_2)} \tag{5}$$

$$\bar{u} = \frac{1}{n_1}\sum_{i=1}^{n_1} u_i \tag{6}$$

$$Q = n_1 \sum_{i=1}^{n_1} (u_i - \bar{u})^2 \tag{7}$$

Where x_{1i} and x_{2i} are the observations of the two populations, and n_1 and n_2 are the number of observations. Then the *t* test for nonequal standard deviations is defined below:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\dfrac{Q}{n_1^2(n_1 - 1)}}} \tag{8}$$

A summary of the calculations is shown in Table 7. As before, the computed *t* is compared to a tabulated value, designated here as *T*. The tabulated value of *T* is based on the number of DOF at a 95% confidence level. If the calculated value of *t* exceeds the tabulated value of *T*, the test statistic is rejected, i.e., the assumption of equal means is invalid and the two statistical data sets do have different levels of maximum pressure oscillations. These results agree with the previous *t* test and indicate that there is no statistical difference between the means for these three motor time intervals at a 95% confidence level.

Post-Challenger RSRM Upper Bounds

Although the statistical test results indicate that RSRM amplitudes are not significantly different from SRM results, it should be recognized that RSRM amplitudes are consistently higher (compare the mean amplitude values in Table 8). Therefore, two conclusions can be suggested: 1) to be conservative, treat RSRM data as indicative of an upward shift of oscillatory amplitudes, and compute new upper bounds based solely on RSRM data; and 2) accept the 95% significance tests, pool SRM and RSRM data, and calculate new upper bounds which are based on all 13 motors. The predicted upper bounds based on RSRM motors alone, and based on both SRM and RSRM motors, along with the original predicted upper bounds for the SRM motors, are shown in Table 8. The differences between the predicted upper bounds are shown graphically in Fig. 3.

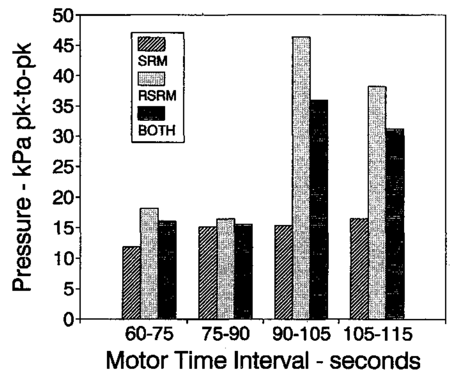

Fig. 3 Predicted acoustic pressure oscillation upper bound comparison between SRMs and RSRMs.

Table 6 Summary of *t* test results assuming similar standard deviations in the data (95% confidence level)

Time interval, s	SRM data[a] Mean	*s*	No. tests	RSRM data[b] Mean	*s*	No. tests	*t* test data s_0	*t*	DOF[c]	T^d	Results
75–90	10.88	1.36	7	11.24	1.69	6	1.52	0.430	11	1.796	Accept

[a]Data from Table 1. [b]Data from Table 4. [c]Degrees of freedom equals total observations minus 2. [d]Reference 2, Table 3, 95% confidence level.

Table 7 Summary of *t* test results assuming different standard deviations in the data (95% confidence level)

Time interval, s	SRM[a] mean, kPa pk-pk	RSRM[b] mean, kPa pk-pk	u_i and $\bar{u}$[c]: u_1	u_2	u_3	u_4	u_5	u_6	n_1	$\bar{u}$	*t* test data: *Q*	*t*	DOF	T^d	Results
60–75	9.49	11.33	3.03	−1.65	−1.03	3.65	3.38	3.65	6	1.84	185	1.815	5	2.015	Accept
90–105	10.27	17.46	7.83	0.92	−2.51	4.62	11.33	26.88	6	8.18	3237	1.695	5	2.015	Accept
105–115	8.26	15.49	2.30	2.23	1.23	10.98	4.84	24.75	6	7.72	2464	1.954	5	2.015	Accept

[a]Data from Table 1. [b]Data from Table 4. [c]Computed from data in Tables 1 and 4. [d]Reference 2, Table 3, 95% confidence level.

Table 8 Predicted upper bounds of maximum acoustic amplitude for both the SRMs and RSRMs

Time interval, s	SRM data: Mean	*s*	Predicted upper bounds, kPa pk-pk[a]	RSRM data: Mean	*s*	Predicted upper bounds, kPa pk-pk[a]	SRM and RSRM data combined[b]: Mean	*s*	Predicted upper bounds, kPa pk-pk[a]
60–75	9.49	0.76	11.84	11.33	2.19	18.10	10.41	1.833	16.07
75–90	10.88	1.36	15.08	11.24	1.69	16.46	11.04	1.464	15.56
90–105	10.29	1.66	15.42	17.46	9.36	46.38	13.60	7.192	35.82
105–115	8.26	2.65	16.45	15.49	7.34	38.17	11.60	6.328	31.15

[a]Based on a one-sided tolerance: populations coverage of 99.9%, and a 50% confidence level. [b]Computed from Tables 1 and 4.

Summary and Conclusions

Monitoring of chamber pressure oscillations in Shuttle booster motors has been performed since the first motor tests. With recent design changes in the motor, an apparent increase in oscillatory amplitudes has been seen. Comparisons were made between early motor data and data from post-Challenger (redesigned) motors. Two types of statistical tests were performed to determine if a change in mean maximum pressure oscillations was due to a change in the data or chance. Both tests for the appropriate motor time interval indicated that no statistical change had taken place in the oscillatory pressure amplitudes for the four time intervals. It is important to note that this conclusion is based on a 95% confidence level. The use of a more relaxed confidence level could lead to different conclusions. With these factors in mind, predicted upper bounds were determined for both the RSRM motor data and the pooled data of both SRM and RSRM data. A conservative approach is to use the RSRM predicted upper bounds. These results, if used prudently, can be used to evaluate the effects of an increased oscillatory load from booster motors in future Shuttle flights.

The methodology presented in this article may seem overly complicated to show that the RSRM motors have different oscillatory levels of pressure fluctuations. However, it is very important to point out that looking at the oscillation pressure levels alone is not sufficient to make that claim. Changes in the data variances can confuse the test results. This is easily demonstrated by examining Fig. 2 for the 90–105-, and 105–115-s motor time intervals. From Fig. 2 it could be easily concluded that during these time intervals there is a significant change in the mean pressure oscillations. However, both these time intervals passed the t test for nonequal standard deviations at the 95% confidence level. This indicates that, statistically, the means had not significantly changed. Ideally, many more data points would be necessary to accurately apply the statistical tests used in this article. Unfortunately, it is not possible to obtain unlimited Shuttle Booster acoustic data. Because of this, the conclusions reached in this paper must be treated with caution and a firm understanding of how they were obtained.

Acknowledgments

The authors wish to thank Jose Matienzo and Tom Nesman of NASA, Marshall Space Flight Center for their financial and scientific support of this work.

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