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STARS Missile - Modal Analysis of First-Flight Data Using the Natural Excitation Technique, NExT

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ABSTRACT

The Natural Excitation Technique (NExT) was used to analyze STARS launch data during first and second stage flight using telemetered acceleration data. A continuous track of modal frequencies and modal damping was acquired for the first and second elastic modes of the system during first stage flight and for the first mode during second stage flight. The results from this modal analysis of launch data allowed a final quantification of the inherent bias errors which result from ground-based modal tests. Also, NExT is shown to be an important new tool for analyzing structural dynamics data during launch.

INTRODUCTION

The Strategic Targeting System (STARS) missile successfully completed its first flight in February 1993. The missile guidance and control system design relied heavily on the predictions of test-verified finite element models. The modal tests which were used to verify these models were performed on the ground and were subject to several inherent bias errors. First, to approximate free-free boundary conditions the vehicle was suspended from the top of its shroud using a structural support scheme which introduced additional structural dynamics. Second, the missile flies under a large compressive load due to the thrust of the rockets, however it was tested under a 1g tensile load. Third, the vehicle's powered stage is pressurized during flight, while the ground tests were in an unpressurized configuration. Fourth, it was only possible to test in a few discrete missile configurations, consequently it was not possible to continuously track the modal parameters as the fuel was expended. And finally, the launch environment includes aeroelastic and high amplitude vibration excitations which can cause nonlinear effects. Therefore, it was desirable to use actual flight data to perform a further verification of the predictive models.

A technique to determine modal parameters from systems which experience some type of in-situ

excitation has been under development at Sandia National Laboratories for several years [1]. This technique is called the Natural Excitation Technique (NExT). NExT utilizes a time domain modal parameter identification scheme to analyze cross-correlation functions for modal frequency and modal damping information. Reference [1] contains a theoretical derivation, an analytical verification, and comparisons to experiment for NExT.

A separate development project has entailed using time domain modal parameter identification schemes to track changing frequencies during such events as high force level impact tests [2]. This technique entails analyzing windows of data which are successively displaced from the starting point of the data set, which allows the frequency to be tracked. This sliding window technique allows the nonlinearity of the system to be assessed as the amplitude dependence of frequency and damping can be quantified.

A recent proposal has suggested that these two techniques can be combined to analyze the changing natural frequencies of a rocket during launch [3]. This allowed the results of ground-based modal tests, finite element analysis, real-time control algorithms, and actual flight data to be compared in a companion paper [4]. Additionally, estimates of damping during flight can be provided. This work provides the first results from this procedure as applied to the first launch of the STARS Missile.¹

APPROACH

The sensors used in this analysis include a set of three accelerometers in orthogonal directions situated on the Inertial Measurement Unit (IMU) of the missile. The IMU is placed at the top of the third stage of the three stage rocket. The specific analysis performed herein was not envisioned during the design of the on-board

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signal conditioning and telemetry, therefore it was far from an optimal data set to work with. The signals were filtered at 50 Hz and sampled at 50 Hz, which aliased all information above 25 Hz. Fortunately, there were no indications of aliased modes in the vicinity of the expected modes of the missile. The damping ratios of the extracted modes were also reasonable, which gave further evidence that they were not aliased modes.

Also, the signals were telemetered to earth at 64 Hz and some data points were repeated. However, each data point was time-tagged and the extraneous data points could be removed. And finally, several data drop-outs occurred and had to be handled by a linear interpolation between the surrounding data points. One important point to note is that the IMU accelerometers were configured for floating point measurements and did not suffer resolution problems. In spite of the problems, this data set yielded meaningful information.

The data reported herein were analyzed using windows of 1024 samples (approximately 20 seconds per window). The reported results therefore represent an average over 20 seconds of flight time. Smaller windows produced adequate frequency information, however the damping estimation was much improved using the longer data sets. This window was slid forward in time in 20 sample increments (.4 seconds per increment). This small increment size allowed the trends in the data to be shown with greater clarity, since a more continuous graph resulted.

Sixth order Butterworth filters were used on the full data set to remove all frequency information except that of the mode of interest. The first mode data during first stage flight was band pass filtered between 8 and 15 Hz. The second mode data during first stage flight was high pass filtered at 15 Hz. And during second stage flight, the first mode data was high pass filtered at 10 Hz. The Eigensystem Realization Algorithm (ERA) was used to extract frequency and damping information. In most cases, only two singular values were allowed since the mode of interest dominated the filtered data.

RESULTS

Table 1 provides a timeline for the STARS 1 flight. Many of these events correspond to anomalies seen in the data set. Figure 1 shows the frequency of the first mode during first stage flight. The variations in the data are probably more indicative of errors in the extraction process and not actual dynamics of the physical system. A linear fit to the data is provided to give the reader a reference to assess these potential

errors. Based on the linear fit, an increase from 11.5 Hz to 12.3 Hz over the course of the flight is seen as the first stage fuel is expended. The associated damping ratio is seen in Figure 2. Many of the oscillations are due to the errors inherent in estimating damping. However, the large rise in damping around 20 seconds corresponds to the missile entering transonic flight and could be indicative of changes to the aerodynamic input to the missile. Except for this large rise the damping appears to drop from 1% to about .7% during the flight.

Table 1. STARS FTU-1 Timeline

EVENT	TIME (sec)
1st Stage Ignition	0.0
Transonic	21.0
Max Q	33.5
1st Stage Separation	59.1
2nd Stage Dog Leg	79.0
2nd Stage Separation	137.0

Fig. 1: Modal Frequency #1 as a Function of First Stage Flight Time

Figure 3 provides the estimation of the second mode as a function of first stage flight. Based on the linear fit, the frequency tends to rise from 18.3 Hz to 22 Hz during first stage flight. Figure 4 shows that the damping associated with this mode drops from around .8% to about .6% during the course of the flight. This damping drop could be due to less fuel available for

internal damping or a less dense atmosphere for external damping.

Fig. 2: Modal Damping for Frequency #1 as a Function of First Stage Flight Time

Fig. 3: Modal Frequency #2 as a Function of First Stage Flight Time

Figure 5 contains the frequency information for the first mode during second stage flight. The extracted frequency is seen to deviate more from the linear fit. The excitation levels are much lower during second stage flight and would cause the extraction process to be more error prone. However, at 79 seconds into the flight, a dog leg maneuver is performed which changes

the thrust and gravity vectors on the missile. This mode would be very susceptible to such changes due to the importance of the 2nd/3rd stage joint. Overall, the mode rises from less than 17.8 Hz to 19.8 Hz during second stage flight. Figure 6 provides the damping estimation for this mode. As with the associated frequency plot, more deviations from the straight line fit are seen. The average value appears to be about .5%.

Fig. 4: Modal Damping for Frequency #2 as a Function of First Stage Flight Time

Fig. 5: Modal Frequency #1 as a Function of Second Stage Flight Time

Fig. 6: Modal Damping for Frequency #1 as a Function of Second Stage Flight Time

The modes analyzed above were bending modes of the entire missile and an orthogonal mode was expected as well. There were often indications of the existence of these orthogonal modes, however they were not excited well enough to be extracted at this time.

RECOMMENDATIONS

A set of sensors tailored for this type of analysis, e.g. floating point sensors with appropriate anti-aliasing filters, would be useful. Further, selection of a sampling rate which corresponds to the telemetry rate would be useful. Redundant telemetry channels or increasing the telemetry rate by an integer amount might reduce the data drop-out problem. These channels could be low sample rate channels which would be easier to obtain on future flights.

A more automated set of analysis software should be produced. It is difficult and time-consuming for the engineer to scrutinize the analysis of each window of data. There are regions of time where an orthogonal mode is present which could be analyzed if the tools were available. Also, some operating shape information could be obtained if more sensors were available.

CONCLUSIONS

A capability to analyze in-flight data from rockets during launch has been shown. This technique can

provide information to validate ground-based tests and finite element models as well as assisting in the post-flight analysis of control system operation. A sensor set tailored to this type of analysis is strongly recommended for future flights.

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