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ROCKET NOISE PREDICTION PROGRAM

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ABSTRACT

A comprehensive, automated, and user-friendly software program was developed to predict the noise and ignition over-pressure environment generated during the launch of a rocket. The software allows for interactive modification of various parameters affecting the generated noise environment. Predictions can be made for different launch scenarios and a variety of vehicle and launch mount configurations. Moreover, predictions can be made for both near-field and far-field locations on the ground and any position on the vehicle. Multiple engine and fuel combinations can be addressed, and duct geometry can be incorporated efficiently. Applications in structural design are addressed.

INTRODUCTION

Acoustic noise is an unavoidable byproduct of rocket thrust. It is particularly important in large vehicles (such as the Saturn V and Space Shuttle) and is a primary structural design consideration for ground support equipment and payloads. Besides being an operational hazard to personnel in and around the launch pad, acoustic noise can be a severe annoyance to communities near rocket launch sites. Over the last three decades, NASA's John F. Kennedy Space Center (KSC) has lead the way in the development of analytical tools for the prediction of rocket noise and launch-induced vibration of structures. Such tools are a vital part of NASA's "better, faster, cheaper" philosophy and facilitate a proactive engineering function for newer launch vehicles such as the X-33 and Sea Launch. This is especially important since full-scale acoustic and vibration testing on launch vehicles or payloads is often difficult, time consuming, and cost prohibitive. Often, analytical predictive tools provide the framework necessary for subsequent acceptance and qualification testing.

BACKGROUND

During a rocket launch, structures in the proximity of the launch pad are subjected to an intense acoustic environment generated by the rocket exhausts. The launch acoustic levels (> 160 decibels) represent a significant load on the spacecraft, ground facilities, and equipment. The design of some structures, particularly those having a large area-to-mass ratio, is governed by launch-induced acoustics that lead to harmful vibration behavior. It also manifests itself to the spacecraft and payload in the form of transmitted acoustic excitation and as structureborne random vibration.

The ground facilities are exposed to severe fluctuating external-pressure loading by the rocket propulsion system during holddown and up to a few seconds after liftoff. The acoustic environment (airborne noise) is severe in the near-field (within 500 to 1,000 feet of the launch pad). Accurate knowledge of near-field acoustic and ignition over-pressure loading is necessary to develop acoustic and vibration test criteria for qualification and acceptance testing of many types of ground support and launch equipment.

KSC has been involved in the measurement of launch acoustic loads and the development and verification of random vibration response models over the last 30 years. A significant launch acoustic and vibration database exists primarily for ground support equipment. Additionally, we have focused on developing deterministic models to predict the vibroacoustic response of structures, especially accurate in the low frequency range (1 to 20 hertz) of launch transients. Lastly, these theories have been validated via physical measurement of launch acoustic loads and simultaneous structural response (vibration and strain) on structures mounted in close proximity (within 300 feet) of the Space Shuttle launch pad.

The purpose of the present project was to develop a comprehensive, automated, and user-friendly software program to predict the noise and ignition over-pressure environment and to complement the vibroacoustic prediction effort for existing rockets. More importantly, it serves a crucial role in the prediction of acoustic loads on such rockets as the X-33 (using new aerospike engines), sea-launched rockets (where the plume impinges in water), and the new generation launch vehicles with a variety of configurations.

Software represents enormous cost savings since a multitude of sensitivity checks pertaining to the design of launch and spacecraft infrastructure may be determined in the early budgetary and design phase. Software with modifications may be used to predict environments for future rockets that will be deployed in the Martian atmosphere.

PREDICTION METHODOLOGY

This paper briefly summarizes the analysis methodology used for predicting holddown and liftoff acoustic environments and ignition over-pressure values generated by launch vehicles. These predictions are necessary for the evaluation of the impact of the generated acoustic load environment on spacecraft, nearby buildings, and facilities.

Acoustic Environment

The predictions can be made for single-engine (light) and multiple-engine (heavy) configurations. Acoustic environment predictions are also made for three unique external locations on the vehicle – close proximity of the vehicle mount and two locations in the proximity of the payload. The predictions cover two unique launch scenarios. The first scenario occurs when the vehicle is on the launch mount, which is typical of flight readiness firing (FRF) conditions. The second scenario addresses the supersonic core tip at the launch mount interface, signifying the vehicle nozzle exit plane (NEP) is several hundred feet off the launch pad surface. Predictions are made for varying launch scenarios, mount positions, vehicle configurations, and vehicle locations for a variety of rocket engine configurations and for both open-duct and closed-duct scenarios.

The methodology used for the acoustic environment predictions is outlined in NASA-SP-8072 [1], a space vehicle design criteria document. Section 4.2 of this document addresses the acoustic load prediction methodology using two empirical models. For the present effort, the second source allocation model (method 2) is used as opposed to the first model (method 1). The second model recognizes that rocket noise in each of the frequency bands is generated throughout the flow rather than each frequency band being generated at a unique location along the flow axis [1]. Measurements performed on the Space Shuttle launch pad over the last 15 years provide a necessary framework for the applicability of the former model for external acoustic environment predictions.

Significant effort was expended to develop a new, dedicated computer code running on MATLAB, a commercially available code to predict the acoustic environment. The code was checked via manual calculations to ensure programming accuracy. The program uses the following methodology as outlined in reference [1]:

1. Determine the flow axis relative to the vehicle and stand.
2. Estimate the overall acoustic power in watts from engine thrust, number of nozzles, fully expanded exit velocity, and acoustic efficiency values.
3. Convert the overall acoustic power level from watts to decibels.
4. Calculate the effective nozzle exit diameter for rockets with multiple nozzles.
5. Compute the core length of the plume or normalized plume core length (normalized to effective nozzle exit diameter).

6. Estimate the number of identical slices of the plume for analysis.
7. Determine the normalized acoustic power per unit of the plume core length for each identical slice along the plume.
8. Calculate the overall acoustic power for each of the plume slices.
9. Convert the normalized spectrum for rockets to a conventional acoustic bandwidth (i.e., the power spectrum per hertz, per 1/3 octave band, as desired) for each slice of the plume.
10. Compute the sound pressure level at any given position on the vehicle for each plume slice and for each 1/3 octave band, inclusive of the effects of directivity.
11. Calculate the sound pressure level at any given position on the vehicle for all plume slices by logarithmic summation of contributions from each slice.
12. Finally, compute the overall sound pressure level (OASPL) by logarithmic summation for all plume slices and all 1/3 octave bands.

The program output shows the input parameters, computed outputs showing 1/3 octave band number, frequency band center, and frequency band width and the sound pressure level in that band is included. A plot of sound pressure level for each 1/3 octave band number is output also for developing qualification test specifications [3].

Ignition Over-Pressure

The ignition over-pressure values are predicted using the methodology outlined in a technical paper entitled "Transient Pressures Caused by Rocket Start and Shutdown in Ducted Launchers" [2]. Solutions for ignition over-pressure computations are outlined in equations (1) and (2), respectively. The former is considered appropriate for determining over-pressure values downstream of the exhaust duct. Since the effect of over-pressure on the launch support structures above the NEP was of interest, equation (2) was used.

$$p_1'/p_0 = \dot{m}_e / 2A \{\gamma/a_0\rho_{eo} + u_e/p_0 \} \tag{1}$$

$$p_1'/p_0 = \dot{m}_e / 2A \{\gamma/a_0\rho_{eo} - u_e/p_0 \} \tag{2}$$

where:

p_1 = exhaust pressure
p_0 = ambient pressure
$\dot{m}_e$ = engine mass flow rate in lbm/sec
A = cross-sectional area of the duct in ft^2
γ = ratio of air specific heats = 1.4
a_0 = ambient speed of sound, ft/sec
ρ_{eo} = density, engine exhaust
u_e = velocity of the exhaust

( )′ = perturbation from ambient conditions

The ratio p_1/p_0 represents the pressure perturbations or the ignition over-pressure peak, incorporating necessary corrections for the effects of combustion and jet momentum loss due to the ducted launcher.

Equations outlined in reference [2] were verified via manual calculations before coding them on the MATLAB platform. The code was exercised several times to evaluate the variability of various parameters associated with equation (2).

APPLICATIONS IN STRUCTURAL DESIGN

Standard structural design practice treats dynamic loads as equivalent static loads (ESL's). Acoustic and over-pressure load predictions can be expressed as ESL's on structures of interest with the following simplifying assumptions:

1. Acoustic pressures are uniform and correlated over the loaded surface.
2. The transient nature of the loading can be accounted for by applying a correction factor, C_f, to the low frequency end of the spectrum.
3. The first dynamic bending mode shape of the structure is the principal contributor to the response.
4. The system may be idealized as a linear single degree of freedom (SDOF) system.
5. Damping values are typically between 0.5 to 2 percent.
6. The statically deformed shape under "uniform loading" is essentially the same as the first bending mode shape of the structure.

This section provides a brief overview of the steps required to assess design loads versus acoustic and over-pressure load predictions. The ESL's derived from this method are rough estimates since much of the detailed information required for this kind of analysis is assumed to be known. For particularly sensitive structures, the references provide detailed methods for conducting this type of analysis. In practice, most structures will not require detailed methods to assess their loading.

The first step is to determine the first bending natural frequency and mode shape of the structure or equipment in question. This can be accomplished by the use of handbook equations for simple structures and finite element models for complex structures. The first bending mode shape of the structure is of prime interest due to assumption number 3. This information is needed to determine the FRF for the structure being evaluated. The FRF is an equation that relates the dynamic load on a structure to the response (displacement, velocity, acceleration, etc.) of the structure. The FRF's for SDOF systems are included in most basic vibration text books.

Next, the predicted sound pressure levels (SPL's) are converted into power spectral densities (PSD's). This is a relatively straightforward conversion as outlined in reference [9]. In the case of over-pressure, the SPL may be scaled assuming that the shape of the predicted SPL spectrum remains the same. The scaling is accomplished

by multiplying the predicted SPL spectrum by a factor to bring the overall SPL up to a level equal to the predicted over-pressure.

The PSD resulting from the above step is first multiplied by the exposed area of the structure squared to convert the PSD from a squared pressure per hertz to a squared load (pounds squared) per hertz. This spectrum is subsequently scaled by the following correction factor:

$$C_f = 1 - e^{-2\pi ft/(2Q)} \tag{3}$$

where:

f = frequency (Hz)
t = estimated time duration of transient (seconds)
Q = magnification factor = $1/(2\zeta)$
ζ = damping ratio

This correction factor reduces the low-frequency end of the pressure spectrum. The purpose of this step is to account for the transient nature of launch acoustics. The acoustic levels will exhibit two periods where the levels increase and then decrease to a lower steadier level. The first period is during engine start; this is typically known as the ignition over-pressure. The second period occurs when the rocket's plume emerges from the exhaust trench; this is often called the liftoff peak. These short-duration periods of high-level pressures are insufficient to excite the full response of the structure in the low frequency due to the limited number for pressure cycles. Thus, this correction factor reduces the final calculated response of the structure by reducing the predicted loading.

The system's displacement is calculated by multiplying the squared FRF by the corrected PSD. The result is a response PSD spectrum in units of displacement squared per hertz. Since the method presented here assumes SDOF response, the response PSD should exhibit a peak around the first natural frequency of the structure. The response PSD is integrated over the frequency range. The resulting number is the overall mean square displacement of the structure. The square root of this number gives the root mean square displacement of the structure. Under the Gaussian assumption, this value may be multiplied by 3 to get an estimate of the peak displacement.

Finally, an equation is required that results in the static uniform distributed loading for a given maximum displacement. The correct equation is chosen by making sure the deformed shape of the structures under uniform distributed static loading conforms to assumption 6 above. Those equations are tabulated in many strengths of materials and reference texts for simple beams and plates. A finite element model may be required to obtain this equation for a complex structure. The only difference is that the equations are solved for the maximum displacement due to a uniform

distributed static load; so these equations must be rearranged to result in the uniform distributed static load given a maximum displacement.

The displacement calculated from the PSD is used as the maximum displacement in the equation from assumption 6. The uniform distributed static load that results is the "equivalent static load." This calculated ESL may be compared against the actual static loads used in the design to assess the appropriateness of the applied design loads.

CONCLUSION

This paper summarizes the effort to develop dedicated software to predict the liftoff acoustic environments generated by the launch of a rocket and how to apply the data in structural design. Predictions are based on the methodology outlined in NASA-SP-8072 [1]. Additionally, ignition over-pressure calculations are provided to evaluate the impact of generated loads on the launch supporting structure.

Prediction of acoustic loads on space vehicles that are generated by the propulsion system requires the use of analytical techniques and must often be corroborated by field tests. Analytical methods developed in reference [1] are based on test data compiled almost 30 years ago. It is necessary to assess the direct applicability of this data to modern-day rockets and techniques refined to enhance overall prediction accuracy.

The primary purpose of acoustic predictions or measurements is their eventual application to vibration response analyses and environmental testing. In addition several references [4 through 9] are included that use actual launch measurements on the Shuttle and their use in structural response calculations [4 and 7] using the concept of equivalent static load.

Recent research focused on validating the analytical methods presented here with field dynamic tests, which is a dream come true for anyone working in the area of structural dynamics. Simultaneous measurement of launch-induced acoustic loads and subsequent response on a pretuned cantilever beam placed in close proximity (within 250 feet) of the Space Shuttle facilitated in the test analysis correlation effort [10].

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