FIFTH INTERNATIONAL CONGRESS ON SOUND AND VIBRATION

DECEMBER 15-18, 1997
ADELAIDE, SOUTH AUSTRALIA

Invited Paper

RANDOM VIBRATION RESPONSE OF A CANTILEVER BEAM TO ACOUSTIC FORCING BY SUPERSONIC ROCKET EXHAUSTS DURING A SPACE SHUTTLE LAUNCH

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ABSTRACT

This paper presents a brief overview of recently completed research in the area of rocket noise and resulting dynamic behavior of launch pad structures. To gain accurate insight into the vibratory behavior of these structures, dynamic tests were integrated into the design process. Aspects of the acoustic load characterization procedure and the test-analysis correlation of random vibration structural response in the low frequency range (1 to 50 hertz) are presented.

BACKGROUND

During a Space Shuttle launch (figure 1), ground support equipment and structures in close proximity of the launch pad are subjected to intense sound pressure loads generated by rocket exhausts (thrust > 6E+06 pounds). The generated sound manifests itself to payloads and pad structures in the form of transmitted acoustic excitation and structureborne vibration. Measurement of the launch environment is important for defining impact lines (the boundaries beyond which no debris from an uncontrollable rocket will impact the ground) and blast zones (areas created by acoustic and shock propagation waves). Acoustic pressure waves are of concern since they affect structures and wildlife near the pad. Therefore, continuous monitoring of systems is vital for ensuring operational safety and long-term reliability to maintain NASA Kennedy Space Center's (KSC's) role as a premier site for the preparation and launch of Space vehicles.

This paper marks the turning point of decade-long research at KSC in the areas of characterizing acoustic loads, development of random vibration prediction models, and test-analysis correlation. At launch, the pad structures are exposed to sound levels of ~180 dB generated by the supersonic (mach 3 to 4) rocket exhausts. Launch-induced structural vibration can pose a major design and safety limitation. To control vibration levels in order to ensure structural integrity, it is essential that the dynamic characteristics of the structure be fully understood. The two most-often-used tools to solve structural dynamical behavior are finite element analysis (FEA) and experimental modal analysis. Field dynamic tests were chosen for test-analysis correlation. Space Shuttle launches provide a unique platform to integrate dynamic tests in the structural design analysis process, which are often infeasible or cost prohibitive for many researchers in the field of structural dynamics.

VERIFICATION TEST ARTICLE

A cantilever beam (figure 2), representative of tall and slender ground structures and serving as a Verification Test Article (VETA) simulating complex launch pad structures, was exposed to acoustic forcing during several Space Shuttle launches. The VETA represents the first comprehensive and concerted effort to design a safe and pad representative structure and to be installed within the pad perimeter in an attempt to characterize near-field rocket noise and to assess induced vibration. Specially instrumented sensors not only provided front and back pressure loads on the VETA but yielded simultaneous vibration and strain response, which was crucial for the subsequent test-analysis correlation effort. The ability to tune VETA dynamic characteristics to simulate pad structures governed the VETA design, instrumentation, and analysis. The latter was also driven by the fact that the natural frequency of most pad structures is in the 1 to 20 hertz, and existing dynamic response models (such as Statistical Energy Analysis) cannot be used.

ACOUSTIC LOAD CHARACTERIZATION

The design of launch pad structures, particularly those having a large area-to-mass ratio, is governed by launch-induced acoustic pressures (figures 3a and 3b), which are relatively short transient (< 20 seconds) with random amplitudes and exhibiting a non-Gaussian distribution. The factors influencing acoustic excitation or forcing on any pad structure are numerous (acoustic efficiency, clustered and homogeneity of rocket engines, varying diameters, launch trajectory, pad placement of structure, atmospheric conditions, shielding, etc.).

Significant contribution has been made by KSC engineers to advance the state of the art for dynamic load (acoustic forcing) characterization. Use of traditional sound pressure levels (SPL's) and power spectral densities (PSD's), based on wideband analysis, has been enhanced. Newly developed functions such as normalized cross-PSD's (NCPSD's), coherences (COH's), pressure correlation lengths (PCL's), and correlated pressure distributions (CPD's) have been the common descriptors of the acoustic forcing function. Net effective (front-back) acoustic loads, coupled with spatial variation, were chosen to enhance test-analysis correlation accuracy.

RESPONSE ANALYSIS METHODOLOGY

Random vibration response methodology involves characterization of acoustic load spectra, definition of spatial variation using PCL's and CPD's, and the modal parameters. The determinisitic method is based on the knowledge of modal parameters (natural frequency, mode shape, and damping from a modal test), response spectra to acoustic pressures (response spectra plots), and a definition of the acoustic field by means of PCL's. A PCL was a way of defining the distribution pressure field along the length of the beam and required the knowledge of

COH and phase (PHA) between two sensors or points on the VETA. PCL's significantly longer than the length of the structure implied a uniformly distributed pressure field. Correlated pressure distributions were in turn derived from PCL's.

The time history of acoustic pressure, p(t), was assumed to be known from the measurements taken in the acoustic field where the structure was located. Response load spectra computations were then made for all available multiple launch/sensor combinations. Generally, a multitude of measurements is required for a proper definition of all basic parameters in an acoustic field that is highly uncorrelated or nonuniform. The deterministic analysis facilitates the computation of a generalized modal load defined by G(t), where G(t) = AJ * p(t). The product, AJ, defines the vibroacoustic coupling between the structural response and the acoustic field, where A is the surface area of a large structure and J represents the joint acceptance factor. AJ is computed from PCL's, CPD's, and modal displacements or individual mode shapes of the structure. Response spectra and PCL's were assumed available for the frequency containing at least the first four normal modes. The calculation of generalized modal loads was then reduced to the problem of estimating AJ coefficients for each normal mode and peak response modal coordinates, which are computed from response spectra. Utilization of response spectra, $Y = q \bullet \omega_1^2 / (AJM)$, to acoustic pressures, p(t), is in the application of peak structural responses.

DYNAMIC TEST RESULTS

While many vibration modes are excited in a wideband acoustic field, stress-strain extremes governing a design occurred mainly in a single fundamental mode of the VETA. Typically, the first three or four modes are considered for design, assuming the structures respond to them. For the VETA located in the near-field (below 300 feet from the launch centerline) and exposed to the acoustic field during the first 17 seconds after liftoff, the number of acoustic load cycles were not significant enough to induce full or near-full resonance at fundamental mode and its harmonics. Front and back acoustic pressures, along with strain response are included in figure 3. Based on the measurements, it was observed that acoustic loading was uniform on the VETA and that the strain response was found to be governed by the first mode only. VETA responses were significant after the Space Shuttle cleared the tower when low frequencies of the rocket exhausts dominate. Table 1 summarizes the first four modes, both computed and measured.

TEST-ANALYSIS CORRELATION

The primary purpose of the test-analysis correlation involved: (1) establishment of the validity of the deterministic method for predicting dynamic behavior of structures, especially in the low-frequency range (0 to 20 hertz) and (2) development of a simplified concept of the equivalent static load (ESL) to account for dynamic loads (figure 4). The correlation procedure focused on the computation of the net effective load on the VETA, followed by ESL definition and evaluation of pressure correlations. This was followed by an assessment of joint acceptance factors for the first flexure mode (higher modes were not excited). Predicted strains were then compared to those measured on the VETA. Strategic test planning for simultaneous load and response measurements on the VETA provided excellent results.

Computation of the ESL established valuable benchmarks for design evaluation and testing of a variety of launch pad structures. Generated acoustic excitation is input as a forcing function into a nonstationary transient vibroacoustic structural response prediction model. The results indicate excellent correlation between the analytical model and measured responses from the dynamic tests. The deterministic method overestimated the measured response by about 10 percent. For complex studies such as this, the variation seems reasonable.

KEY FINDINGS

The following key findings were made during the analysis test program:

a. The acoustic load environment experienced by the VETA was indicative of a uniformly distributed load with no significant phase shifts.

b. Launch-to-launch variability of acoustic load data was dictated by launch inclination. Higher inclinations (51 to 57 degrees) resulted in higher loads.

c. The VETA was subjected primarily to flexural vibration. The torsional load on the structure was insignificant.

d. Higher acoustic loads were observed on the VETA front face during liftoff phase (T-0 to T+7 seconds), with lower loads being observed during the Shuttle roll maneuver (T-10 to T+17 seconds).

e. Acoustic loads on the back face of the VETA indicated the opposite, with loads during the roll maneuver being almost twice those observed on the front. This regime has been dubbed as the "plume impingment zone."

f. The orientation of the VETA along the plume direction (vertical) also affected correlation. Typically, horizontal structures yielded longer PCL's than those oriented vertically.

g. PCL computations were found acceptable below 20 hertz. PCL's that were based on sensors placed at 3- and 6-foot distances were used in the analysis.

h. The actual load-carrying capacity of the VETA is higher than the design. This is due to the cancellation of the front and back pressures. Net effective acoustic load rather than front or back pressure alone is of consequence.

i. Only the first fundamental frequency was significantly excited. Test, analysis, and modal models were in reasonable agreement.

j. No significant modal coupling was observed during the test. The VETA design is governed by the first mode.

CONCLUSION

There are a number of critical structures (such as bridges, off-shore structures, aircraft, rocket engines, and launch pad structures) for which structural integrity is of the utmost importance. Integration of field dynamic testing in some of these cases is paramount for ensuring safety and operational reliability. Significance of accurately characterizing complex acoustic loading is of great consequence towards accurate understanding of structural dynamic behavior.

Many architectural and engineering firms are familiar with the concept of equivalent static load as an avenue for accommodating dynamic loads (aerodynamic, earthquake, water waves, acoustic pressures, etc.). Therefore, for the preliminary design process, the KSC-developed concept of equivalent static load, based on the deterministic method of analysis, would suffice. A more detailed and exhaustive analysis is in order, however, for critical launch pad structures. The type of structure, launch pad placement, and acoustic exposure duration all equally contribute to dynamic behavior. Additionally, net effective loads rather than frontal incident loads alone must be considered for analysis purposes. Past ground structure design was primarily based on the liftoff peak acoustic loads. The VETA dynamic testing clearly demonstrated that the plume impingement portion of the Space Shuttle acoustic signature is by far more damaging than the liftoff peak acoustic loads.

ACKNOWLEDGMENT

This ongoing research was sponsored by the John F. Kennedy Space Center, NASA. The authors wish to extend their sincere appreciation to the KSC Engineering Development Directorate for their continued support toward advancement of the state of the art in the area of low-frequency (0 to 20 hertz) nonstationary random vibration analysis.

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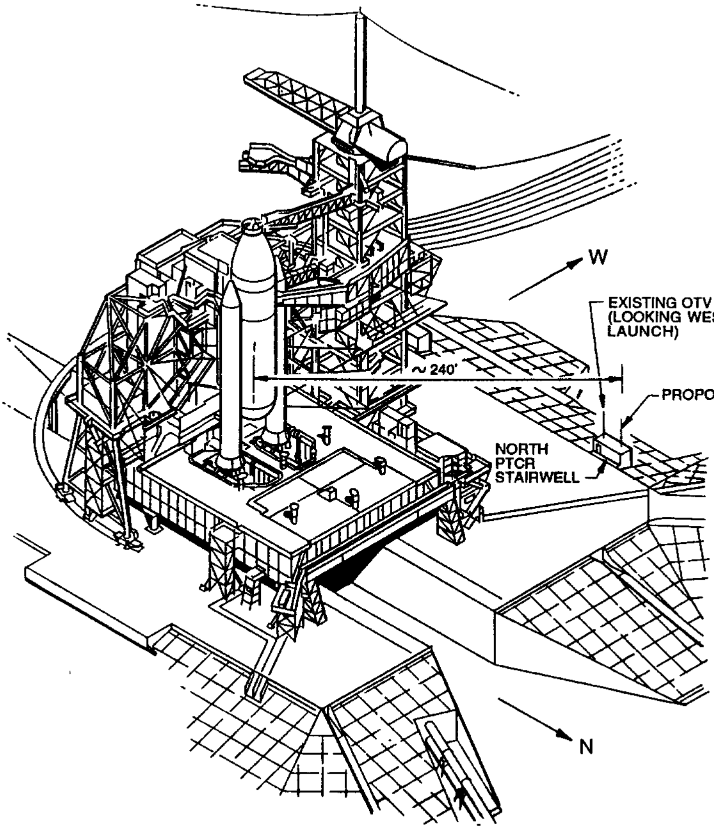

Figure 1. VETA Location on Launch Pad 39A

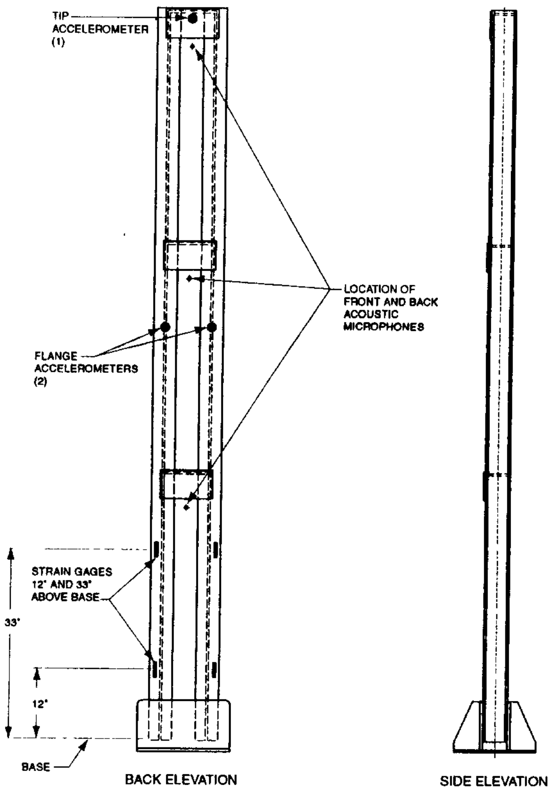

Figure 2. Test Article (Elevations)

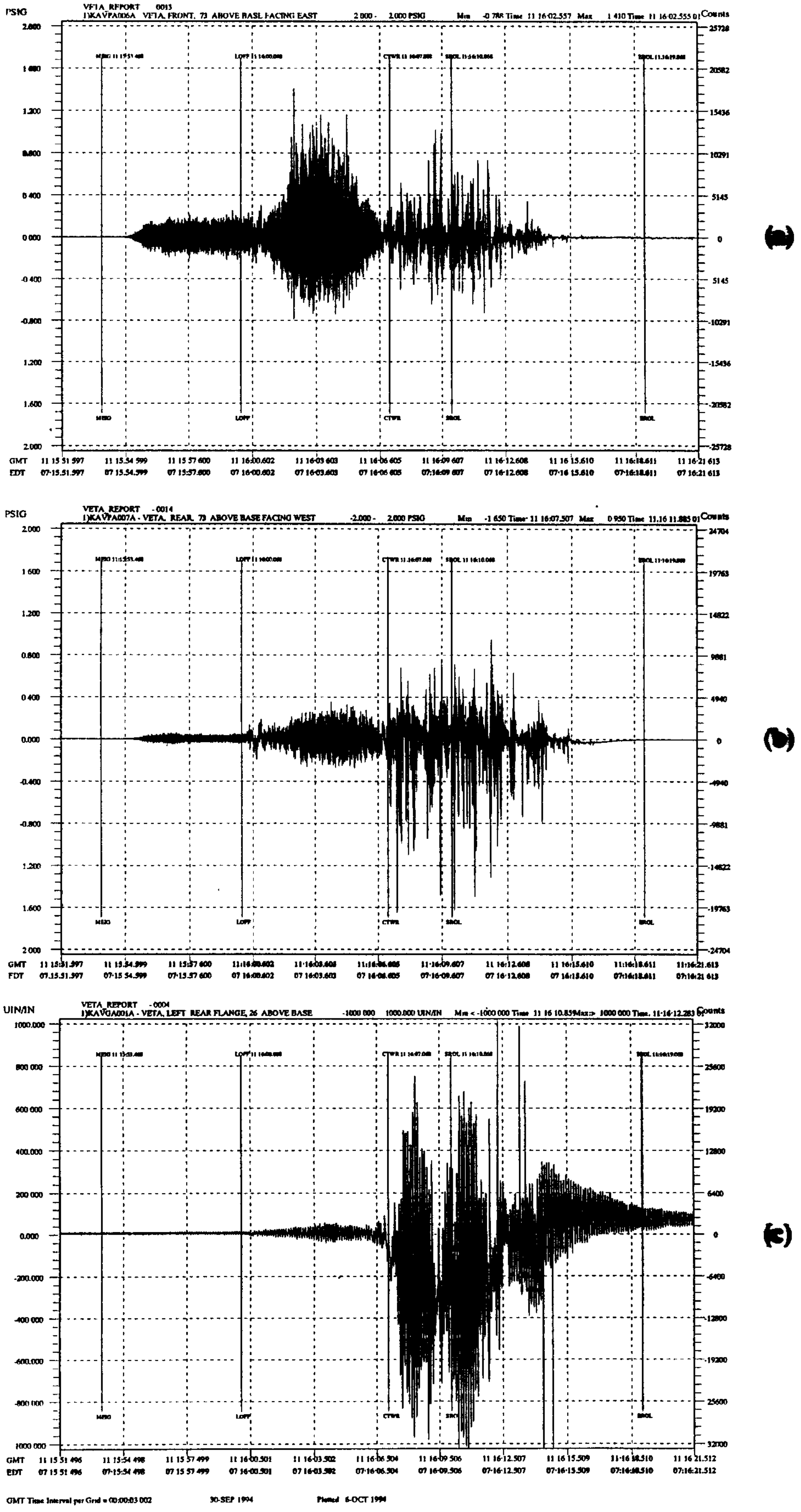

Figure 3. Front and Back Acoustic Pressure and Strain Response

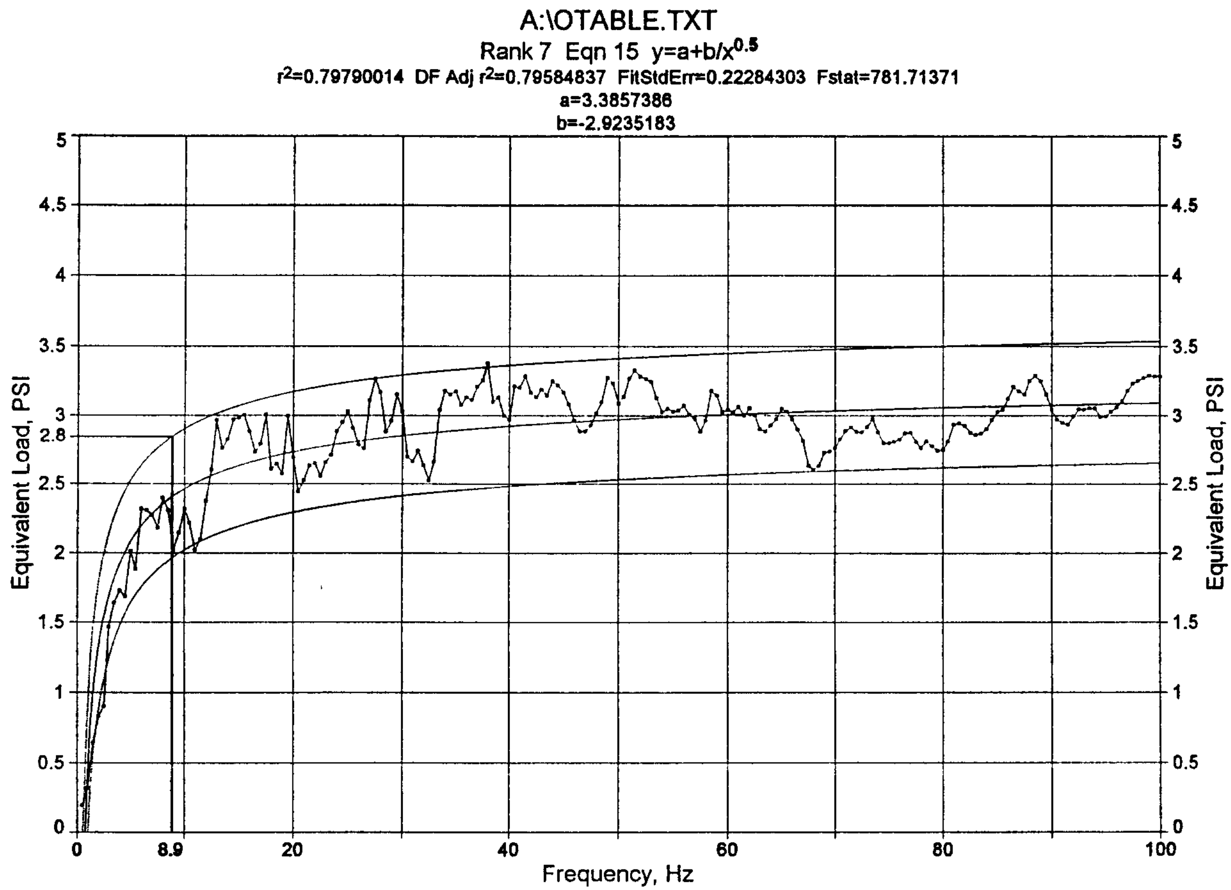

Figure 4. Response Spectra to Input Pressures (1 Percent Damping)

Table 1. Comparison of Flexural Natural Frequencies [Theoretical (C-BEAM) Versus Modal and Dynamic Tests]

Bending Mode No.	C-BEAM Frequency (Hz)	Modal Test Frequency (Hz)	Dynamic Test	Modal Test Damping (%)
1	8.902	8.836	8.789	0.45
2	55.787	54.309	53.710	0.17
3	156.207	144.004	146.484	0.17
4	306.104	Not available	Not available	Not available