Prediction of X-33 engine dynamic environments

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Abstract

Rocket engines normally have two primary sources of dynamic excitation. The first source is the injector and the combustion chambers that generate wide band random vibration. The second source is the turbopumps, which produce lower levels of wide band random vibration as well as sinusoidal vibration at frequencies related to the rotating speed and multiples thereof. Additionally, the pressure fluctuations due to flow turbulence and acoustics represent secondary sources of excitation. During the development stage, in order to design/size the rocket engine components, the local dynamic environments as well as dynamic interface loads have to be defined.

The X-33 engine is a linear aerospike rocket engine, but currently the dynamic environments database from ground hot-fire tests and flight measurements are for rocket engines with a conventional bell type nozzle only. Moreover, due to lack of geometric similarity between the aerospike and the bell type nozzle engines, instead of scaling from the existing dynamic environments, the dynamic environments for the X-33 engine components must be derived analytically. Besides lack of geometric similarities, the oscillating shocks on the ramp for the linear aerospike engines have no counterpart on the bell type nozzle engine. Therefore, this is another reason that the linear aerospike engine must be evaluated analytically. For this end, a finite element model (FEM) for the X-33 engine system has been developed. Furthermore, the sources of dynamic excitation during the engine operation were predicted analytically and then used as inputs to excite the engine system FEM in order to calculate the dynamic environments for the entire engine. In this paper, the methodology used to derive the dynamic environments at various locations on the engine will be presented, and these environment predictions will be refined based on test data obtained during future ground hot-fire testing, when these data become available.

Introduction

The linear aerospike engine is being developed by Boeing - Rocketdyne as part of a cooperative agreement between the National Aeronautics and Space Administration (NASA), Lockheed Martin, Boeing-Rocketdyne, BF Goodrich, Allied Signal, and Sverdrup companies to design and to build a subscale X-33 test vehicle that will demonstrate the key technologies and lower costs that are needed for the next generation of Reusable Launch Vehicle (RLVs) . The difference between the linear aerospike and the conventional rocket engine is the shape of the nozzle. Whereas the bell nozzle of conventional engine expands the hot gas on its inside surface, the aerospike nozzle expands the gas on its outside surface. And the linear aerospike nozzle is not a bell shape at all, but the shape of a "V" called a ramp. This unusual shape enhances performance and allows a more optimum vehicle design. Aerospike nozzles can be circular or linear with the latter being ideal for the X-33 /RLV application.

One of the many essential aspects of design is to provide structural adequacy to withstand the numerous shock and vibration loading conditions and still maintain a light, flightweight configuration. Therefore, during the development stage, in order to design/size the engine components, the local dynamic environments (zonal vibration criteria) as well as dynamic interface loads have to be defined. It is very difficult to dynamically evaluate a design without having the experience gained in the design and development of similar engines. Unfortunately, this is the case for the X-33 engine, because no linear aerospike test bed engine vibration data is available. Moreover, there are no geometric similarities between the linear aerospike engine and the conventional bell nozzle engines, e.g. the space shuttle main engine (SSME). In other words, the existing dynamic environment database for the conventional bell nozzle engines is not applicable for the X-33 engine design. Instead of scaling from the existing dynamic environments, the dynamic environments for the X-33 engine must be derived analytically. For this end, an integrated finite element model (FEM) for the X-33 engine system has been developed. Moreover, the sources of dynamic excitations during the engine operation were predicted/estimated using analytical methods, e.g. CFD models, acoustic codes, and empirical data, e.g. sub-scale thruster tests. The X-33 engine components that can produce/be subjected to excitation sources are nozzle ramps, thrusters, gas generators, nozzle end closeout, turbopumps and ducts. It is depicted graphically in Fig.1.

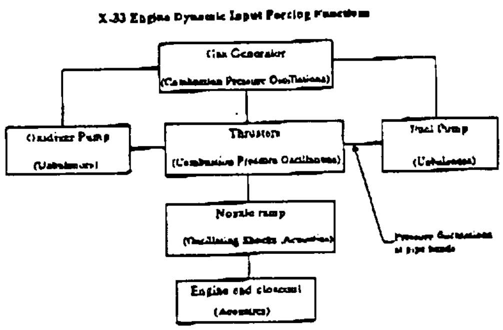

Fig.1 X-33 Engine Input Forcing Functions

In order to calculate the steady-state dynamic environments for the entire engine, random vibration analyses were performed by applying all the potential sources of excitation to the X-33 engine system FEM. The zonal vibration criteria and random vibration environments for the critical components were determined by the engine system finite element model. The predicted vibration environments were used as component initial design criteria and/or design verification test specification. This is the first time that instead of scaling from the existing vibration data base, analytically predicted dynamic environments were used as rocket engine component initial design criteria at Rocketdyne.

Four X-33 linear aerospike engines will be produced by Rocketdyne. Two engines will be used for ground hot-fire tests. Two will be installed in the subscale X-33 vehicle for suborbital flight tests at speeds up to about Mach 10. During both ground and flight tests, special instrumentation will be installed at critical locations. The predicted dynamic environments will be validated/revised based on the test measurements. In this paper, the comparisons between the tests and the analysis will not be presented, because test data is not yet available.

Finite Element Model

In the process of developing the X-33 engine system FEM, both structural and non-structural components were modeled, because in formulating the structural dynamic model both elastic and inertia properties must be considered. For those components identified as the critical load carrying structural components both elastic and inertia properties were modeled in detail. For the non-structural components only inertia properties were considered, and these components were modeled as lumped masses. Therefore, the engine system was treated as linear discrete dynamic system. Ideally, a complete representation of a linear discrete dynamic system should have three parameters defined, i.e. mass, stiffness and damping. However, due to technical difficulty in discretizing the damping parameter, no attempt has ever been made to discretize the damping properties for the engine components. This will not create any problem, because in general the engine is a lightly damped system. For a lightly damped system the damping will have almost no effect on the natural frequencies and the corresponding mode shapes [1]. Therefore, it is sufficient to model the elastic and the inertia properties of the engine system. The damping parameter will be introduced as modal damping factors later when response analysis will be performed.

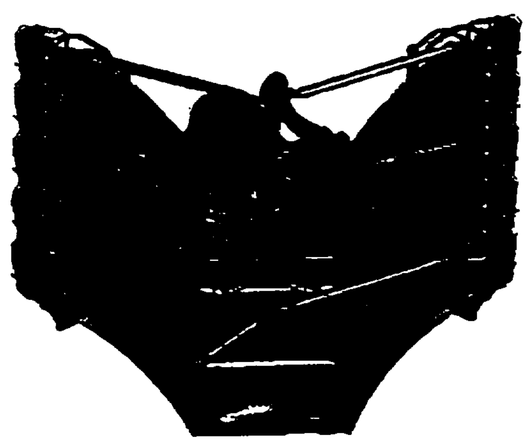

Fig.2 X-33 engine layout

The X-33 engine is a complex structural system with complicated geometry as shown in Fig. 2. A general purpose finite element code, the STARDYNE code, was employed to develop the model. Moreover, since each X-33 vehicle will have an assembly of two engines attached to the aft end of the vehicle, the finite element model will consist of two engines. The plot for the engine model is shown in Fig. 3. The types of elements used to model the engine system are simple beams, pipes, elbows, isotropic plates, orthotropic plates, distributed masses and lumped masses. The full model has about 13,400 dynamic degrees of freedom (DDOF's), i.e. ~ 4,500 nodes. By using the Sturm sequence check, it was estimated to have about 3000 modes below 2000 Hz. In order to perform the analysis economically, i.e. especially to eliminate insignificant local modes, it was necessary to reduce the model. The Guyan reduction method [2] was used to reduce the model. The master degrees of freedom chosen are the degrees of freedom with large inertias, e.g. heavy components modeled as lumped masses, as well as those with significant motions, e.g. mid-point of a duct. A total of 276 nodes which were equivalent to 828 DDOF's were selected. In order to check the accuracy of the reduction, the Lanczo's method was used to extract 100 modes from the full model. The differences in natural frequencies are <1 % for the first 40 modes. The mode shapes are also matched closely. The model has been thoroughly checked before it was used to perform structural dynamics analyses.

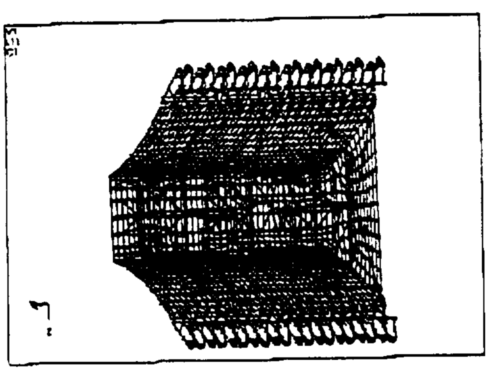

Fig.3 X-33 engine finite element model

Input Forcing Functions

Basically a rocket engine will be subjected to two kinds of dynamic environments, i.e. engine self-generated and induced. The former is caused by the operation of the rocket engines (the propulsion system), while the latter are the environments that will be imposed on the engine by the vehicle and the surroundings. During a mission depending on the mission phase, the rocket engine will be subjected to both environments. How to predict those environments is very critical to the success of the rocket engine development program as well as the mission, because the rocket engine will not be subjected to the actual flight environment prior to its first flight. Based on past experiences on various rocket engine programs, the engine self-generated environments usually dominate over the induced ones. Therefore, it is normally sufficient to use the engine self-generated environments to design the engine structures and components.

In order to design/size the X-33 engine components, the local dynamic environments (zonal vibration criteria) in terms of acceleration PSD's as well as dynamic interface loads must be defined. Since the local dynamic environments are related to the responses of the engine at various locations, it is acceptable to scale the existing environments for a new engine, if the new engine and the old engines have similar design. As mentioned in the introduction, there was no geometric similarity between the X-33 linear aerospike engine and the bell type engines. Therefore, instead of scaling from the existing dynamic environments, it was necessary to perform structural dynamic analysis to derive X-33 engine local dynamic environments. The approach is to identify all the potential sources of excitation and then to perform response analysis on the engine system finite element model to determine the acceleration responses at various locations on the engine.

There are two primary sources of excitation for a rocket engine. The first source is the aerodynamic/ acoustic noises generated by the combustion process in the combustion chamber through the nozzle and the second source is the mechanical vibrations generated by the turbopumps and the other equipment with rotating parts. The former generates wide band fluctuating dynamic pressure on the engine walls, e.g. the nozzle ramp, while the latter generates sinusoidal vibration at frequencies related to the rotating speed and multiples thereof. By using CFD models, acoustic codes and empirical data, e.g. sub-scale thruster tests, the fluctuating dynamic pressures in term of pressure PSD's have been defined on various engine surfaces. The excitation sources considered in the analysis are

- Shock-induced oscillating pressure and acoustics at the nozzle ramp
- Random fluctuating dynamic pressure at the thrusters and the gas generators
- Acoustic pressure at the nozzle end closeout
- Pressure fluctuations at pipe bends
- Turbopump unbalances

The oscillating shocks were derived analytically, i.e. CFD models, as well as scaled from the sub-scale test data. The acoustics pressure was derived analytically by Rocketdyne's in-house acoustics code. The thrusters and the GG fluctuating dynamic pressures were scaled from the 40k thrust cell test data. The fluctuating pressure at pipe bends are caused by turbulence and were derived semi-empirically, i.e. formula based on nondimensionalized experimental data.

Parametric studies indicated that the engine responses were dominated by the oscillating shocks exerted on the nozzle ramps. Therefore, more details about derivations of the oscillating shocks will be presented below.

The unsteady shock oscillations caused by boundary layer and shock interaction contribute to the random oscillating pressure exerted on the nozzle ramp. The strength and the location of the shocks are very important, because they will excite the engine differently. At first the forcing function (the old shocks) was estimated based on CFD predictions using the following assumptions:

1. The rms dynamic pressure is a percentage of steady-state static pressure. 30% was used.
2. The oscillating pressure acts for a few boundary layer thicknesses in front and behind the shock. To determine where the shocks were, the dilatation of the velocity field for the sea level X-33 ramp solutions were used. The regions that had negative values of dilatation, i.e. compressed, and had the oblique shocks upstream, i.e. the forward end of the ramp, were selected.

Based on the above assumptions the old shocks were estimated to be ~6 psi rms applied at the forward end of the ramp and spanned about 5". Recently, a series of subscale (1:26) nozzle tests were performed at the Rocketdyne Nozzle Test Facility (RNTF). The test setup is shown in Fig.4 . Pressure sensitive material (coatings) was used to measure the pressure distributions. Based on the test data, new oscillating shock profiles were derived. According to the test data, the shocks were strongly influenced by the pressure ratio (PR), i.e. chamber pressure (Pc) /ambient pressure (Pa). At sea level when the pressure ratios are low, the shocks are stronger (Fig. 5). At higher altitude when the pressure ratios are high, the shocks are weaker (Fig.6). Comparisons of the oscillating shocks are shown in Fig. 7. The aft shocks that occur at sea level only are about 3.5 psi rms. The forward shocks that exist at sea level and at altitude are about 0.4 psi rms. The common shocks that apply to the rest of the nozzle areas are about 0.16 psi rms.

The sinusoidal mechanical vibrations due to unbalances at turbopumps are considered to be localized vibrations and are related to the hardware only. In other words, the sinusoidal vibration levels measured for a particular pump can be used directly without any adjustment. Since the LOX and the fuel pumps for the X-33 engine are nearly identical to those for the J-2S, the sinusoidal vibration levels were derived from the J-2S and J2 engine test data.

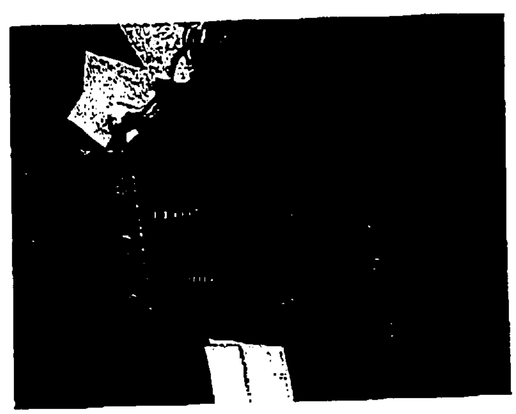

Fig. 4 Linear aerospike test model

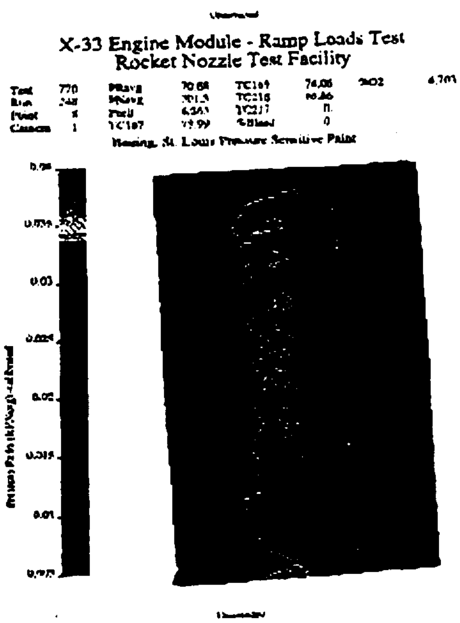

Fig. 5 Oscillating shocks, PR=70

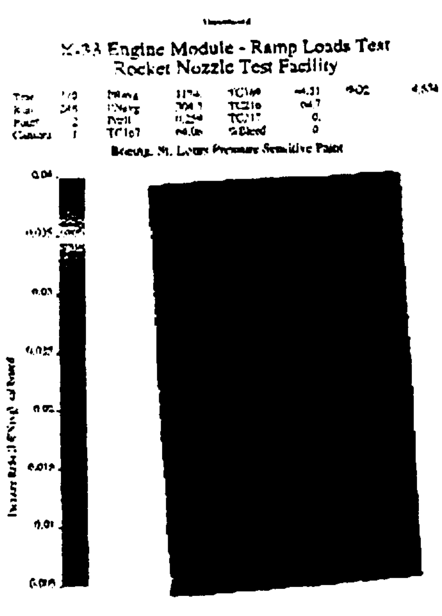

Fig. 6 Oscillating shocks, PR=1174

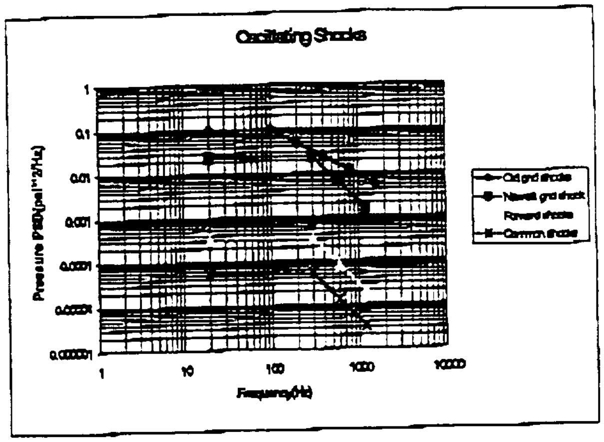

Fig. 7 Oscillating shocks

Results and Discussions

All the forcing functions discussed in the previous section were used to excite the X-33 engine system finite element model. This resulted in a very complicated response analysis with more than 50 input forcing functions. All the forcing functions were assumed to be uncorrelated, since the sources were relatively independent. The objectives were

1.) To determine the dynamic loads and displacements for the engine structural integrity evaluations
2.) To develop engine vibration environments for engine components design and verification/qualification test

The internal dynamic loads for the engine primary structures, i.e. the ribs, the struts, the power pack frame, etc., have been calculated. The dynamic interface loads between the vehicle and the engine have also been determined. Those loads were combined with the static loads due to pressure loads, thermal loads, misalignment, and vehicle g-loads etc., for evaluating structural integrity and performing life predictions.

As for the engine random vibration environments, the zonal vibration criteria have been established as a means of describing the vibration environment experienced by various components in different areas of the X-33 engine.

The predicted environments covered the entire engine and are listed below.

- Forward ramp
- Mid ramp
- Aft ramp
- Lox pump
- Fuel pump
- Gas generator
- End closeout
- Base closeout
- Upper frames
- Power pack frames
- Thrusters

The environments listed above are the primary ones. Special environments for particular components have also been developed when requested. Besides the random vibration environments, the turbopumps also have had the sinusoidal environments defined.

The predicted environments could be used as component initial design criteria directly or as inputs for component detailed analysis. As an example, the x-axis random vibration environments for the nozzle ramp engine end closeout (EECO) are shown in Fig. 8. Three different EECO random vibration environments were predicted. The first prediction is for the old oscillating shocks that were predicted by CFD analysis. The second and third predictions are based on oscillating shocks predicted by sub-scale nozzle test results.

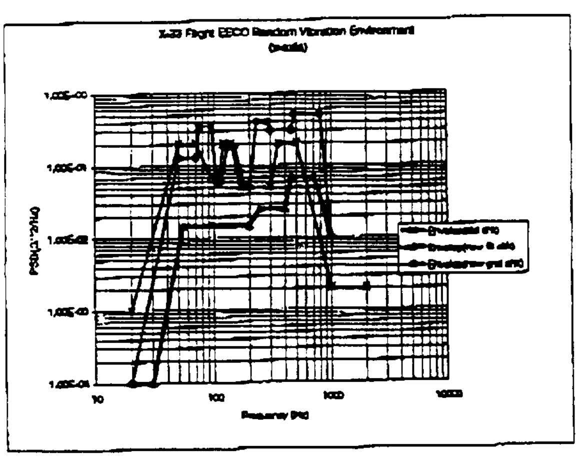

Fig. 8 EECO random vibration environments

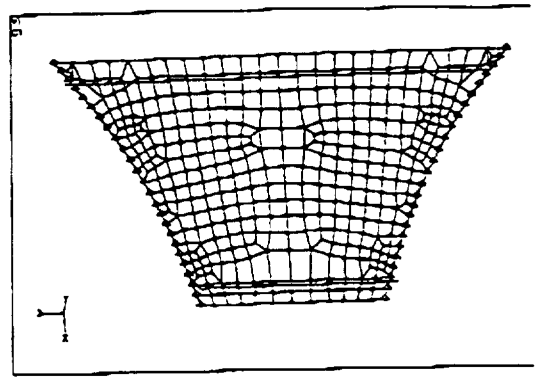

Fig. 9 X-33 EECO finite element model

In the process of designing the EECO, the three environments have been evaluated in order to have a satisfactory design. By applying the predicted x, y and z random vibration environments to the EECO finite element model (Fig. 9), the dynamic loads were calculated. The fatigue life for the EECO was evaluated by combining the static and dynamic loads. At high altitude flight conditions, due to severe thermal environment the EECO titanium support brackets were yielded due to high static loads caused by large deformation of the ramp. When the titanium brackets were yielded, the dynamic loads due to the old shocks limited the life of the brackets to few cycles only. At ground, i.e. sea level, due to a favorable thermal environment, the EECO can operate without life limitations for both the old shocks and the new ground shocks. Furthermore, the EECO will have adequate fatigue life for the new altitude shocks. Therefore, it was concluded that it is adequate to use titanium brackets. The old shocks were too conservative, because the same levels of shocks were used for both the ground and the altitude flight conditions. It was an improvement, when the subscale nozzle test data was used to derive the shocks for the sea level and the altitude flight conditions, separately.

There are twenty thruster support brackets between the X-33 engine and the vehicle thrust frames. The dynamic interface loads have been calculated at each support bracket and at the pump inlets. Two engine models have been used to calculate the dynamic interface loads. The first model represented the engine mounted on the test stand. In this model, the boundary conditions at the thruster support brackets were pinned. The second model represented the flight condition when mounted in the X-33 vehicle. In this model, the substructures of the vehicle thrust structures and the LOX and fuel feedlines were coupled with the engine model. The dynamic engine/vehicle interface loads predicted by the flight engine model are ~30 % lower than those predicted by test stand model.

Conclusions

Structural dynamic analyses have been performed on the X-33 linear aerospike engine. The random vibration environments for the entire engine and the dynamic vehicle/engine interface loads have been predicted. The engine structures and components have been designed with adequate margins based on the predicted dynamic environments and the dynamic loads. The engine is being fabricated and will be ready for ground hot-fire tests at NASA's Stennis Space Center in 1999. Special instrumentation including strain gages and accelerometers will be used to monitor the tests. The predicted dynamic environments will be validated/revised when the test data are available. Moreover, since the dynamic vehicle/ engine interface loads predicted by the flight engine model are ~30% lower than ground test loads, engine ground tests will be sufficient to validate the engine design.

As the project is still on going this paper described the predicted dynamic environments for the X-33 engine only. Future work will consist of comparing the predicted values with the measured values – subject of a future paper.

The X-33 is a subscale test vehicle that will demonstrate the key technologies for the next generation RLV. Therefore, any lessons learned from the X-33 engine will be applied to the RLV engine design.

Acknowledgment

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