Rocket engine nozzle side load transient analysis methodology- a practical approach

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Abstract

At the sea level, a phenomenon common with all rocket engines, especially for a highly over-expanded nozzle, during ignition and shutdown is that of flow separation as the plume fills and empties the nozzle. Since the flow will be separated randomly, it will generate side loads, i.e. non-axial forces. Since rocket engines are designed to produce axial thrust to power the vehicles, it is not desirable to be excited by non-axial input forcing functions. In the past, several engine failures were attributed to side loads. The J-2S engine had excessive side loads such that the gimbal block retaining bolts failed in tension. The Space Shuttle Main Engine(SSME) had the side load induced 'steerhorn', i.e. a component of the coolant (LH$_2$) feedline, low cycle fatigue cracks that damaged the nozzle [1]. More recently the European Vulcain engine and Japanese LE-7A engine, i.e. the first stage main engine of the H-IIA launch vehicle, also had problems due to nozzle side loads. In order to resolves side loads issues on Vulcain, the Europeans created a very thorough experimental and analytical program to understand the nozzle flow physics that induce side loads[2]. The LE-7A engine nozzle side loads were severe enough to fail the engine actuators and cause the regenerative cooling tubes to rupture [3].

Structural dynamically, two types of analysis have been performed to simulate the flow separation. The first is the large asymmetrical input forcing functions used to simulate the side forces, i.e. non-axial forces, caused by flow separation existing over a large portion of the nozzle due to low chamber pressure. The second type is the symmetrical input forcing functions used to simulate the loading which occurs as the shock passes through the nozzle exit plane. The shock will pulse in and out of the end of the nozzle for a few oscillations. This results in a circumferential loading over the last part of the nozzle. Both types of loading must be accounted for during development. Since the asymmetrical input forcing functions are in the frequency range below 50 Hz, they will excite the entire engine system. The symmetrical ones are in the higher frequency range, and based on the Space Shuttle Main Engine(SSME) experience they are above 100 Hz. Therefore, these forcing functions will excite the local nozzle structure. Based on the observation from the SSME hot fire tests video, the SSME side load transients are depicted graphically in Fig. 1.

According to Fig.1, the quasi-static side load and the dynamic side loads will act simultaneously. The quasi-static side loads are due to dynamic pressure of the free stream flow, i.e. the p_w. The asymmetrical dynamic side loads are due to fluctuating dynamic pressure in the boundary layer, i.e. the p', while the symmetric side loads are due to fluid/structure interaction, e.g. flutter. The J-2S engine hot fire data [4] was used to derive the input forcing functions for the asymmetrical dynamic side loads. The SSME subscale nozzle air flow test measurements were used to develop the input forcing functions for the symmetric dynamic side loads. By applying the forcing functions on the SSME block II engine system finite element model, the 3-σ peak dynamic loads for engine components were calculated. Moreover, the component dynamic loads derived from the SSME hot fire test measurements were used to validate analytically predicted dynamic loads. The results are summarized in Table 1. Based on the results shown in table 1, there are good correlations between test and analysis.
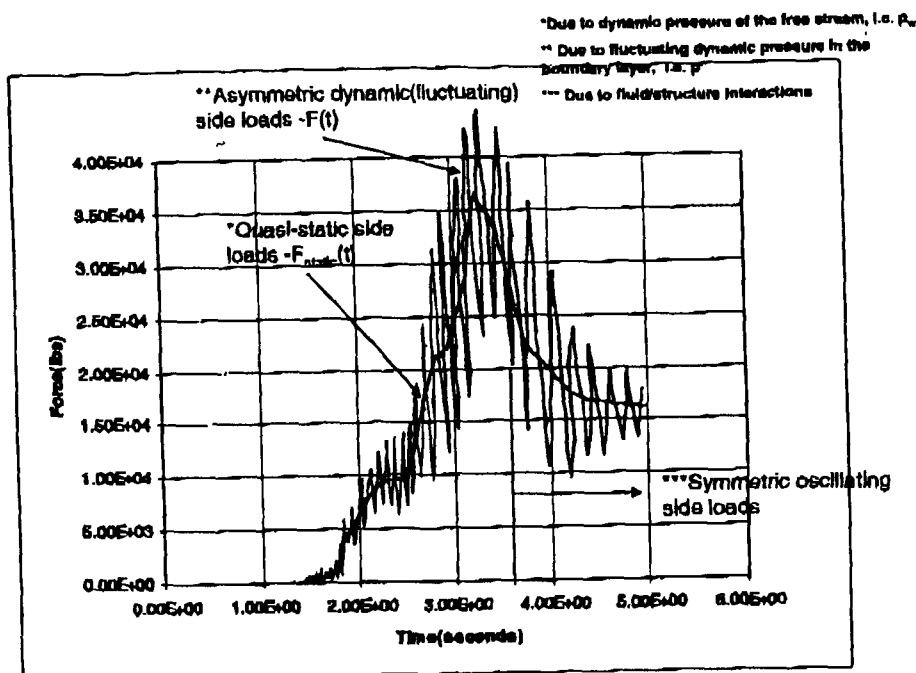
Fig. 1 SSME side loads scenario

Hatband # or actuator	3σ* peak loads based on hot-fire measurements	Predicted 3σ peak loads due to asymmetric side loads (Scaling factor=.13)	Predicted peak loads due to symmetric side loads	Predicted total peak loads**	Predicted loads/ measured loads
6	17,000 In-lbs	6,400 In-lbs	19,200 In-lbs	20,240 In-lbs	1.19
7	25,100 In-lbs	10,300 In-lbs	30,700 In-lbs	32,380 In-lbs	1.29
8	34,400 In-lbs	13,900 In-lbs	41,000 In-lbs	43,290 In-lbs	1.26
9	51,700 In-lbs	16,900 In-lbs	51,800 In-lbs	54,490 In-lbs	1.05
Actuator	64,000 lbs	64,000 lbs	2,300 lbs	64,040 lbs	1.00

* 87 samples for hat bands and 122 samples for actuator

** RSS loads due to asymmetric and symmetric side loads

Table 1 Test/analysis correlation

During the development stage, in order to design/size the rocket engine components and to reduce the risks, the local dynamic environments as well as dynamic interface loads have to be defined. The methodology developed here is the way to determine the peak loads and shock environments for new engine components. In the past it is not feasible to predict the shock environments, e.g. shock response spectra, from one engine to the other, because it is not scaleable. Therefore, the problem has been resolved and the shock environments can be defined in the early stage of new engine development.

References

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