

Rocket engine nozzle side load transient analysis

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Introduction

- Rocket engine nozzle is subjected to unsteady aerodynamic forces during start and shutdown within the atmosphere
 - Non-axial forces, i.e. side loads, caused by flow separation due to prolonged operation at low chamber pressure (P_C)
 - Space Shuttle Main Engine (SSME) hot-fire test movie
E:\ssme_nzzl_shck_oscilltn.mpg

Introduction

- During new engine development in Rocketdyne, two engine failures were produced by side loads



- The J-2 engine with 27-1/2:1 expansion ratio (ϵ) had a failure due to large side loads when tested under sea level conditions
 - **The gimbal block retaining bolts failed in tension**



- On two occasions during the SSME* ($\epsilon = 77.5$) development, a component of the LH₂ feedline (called the steerhorn because of its shape) failed during the cutoff transients
 - **One failure was due to a bad weld**
 - **The other had failed in low cycle fatigue with normal weld**

* Space shuttle main engine

Introduction

- Structural dynamically, two types of analyses have been performed to simulate flow separation
 - Used asymmetrical input forcing functions to simulate the side forces caused by separation existed over a large portion of nozzle due to low P_c
 - Based on J-2 engine experience it is in the frequency range below 50Hz
 - Used symmetrical input forcing functions to simulate 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
 - Based on SSME experience, the oscillating frequency is above 100 Hz

Introduction

- Developed asymmetric side load transient analysis methodology to support rocket engine system design
 - From Aerodynamics and Structural Dynamics view points

Asymmetrical side load transient analysis methodology

- Based on the results from the J-2S side loads test program conducted at Rocketdyne in 1972 and 1973
 - The side load transients exhibited both frequency and power(P_c) dependency
 - Relatively flat spectrum in the 5 to 50 Hz frequency range
 - The RMS dynamic side loads proportional to quasi-static side loads at any time
 - $F_{rms}(t)/F_{static}(t) = \text{constant } \underline{\text{scaling factor}}$
where $F_{rms}(t) = \text{rms dynamic side load at time } t$
 $F_{static}(t) = \text{quasi-static side load at time } t$

Asymmetrical side load transient analysis methodology

- Used “skewed plane” separation technique to determine quasi-static side loads (F_{static})
 - Developed by Aerodynamic Process at Rocketdyne
 - Nozzle flow separation occurs randomly when
$$1/4 < P_w/P_a < 1/2$$
 - Maximum quasi-static side load occurs when $P_w/P_a = 1/4$ at the nozzle exit

Skew plane separation pattern for quasi-static side-load predictions

$P_a = 14$ psi

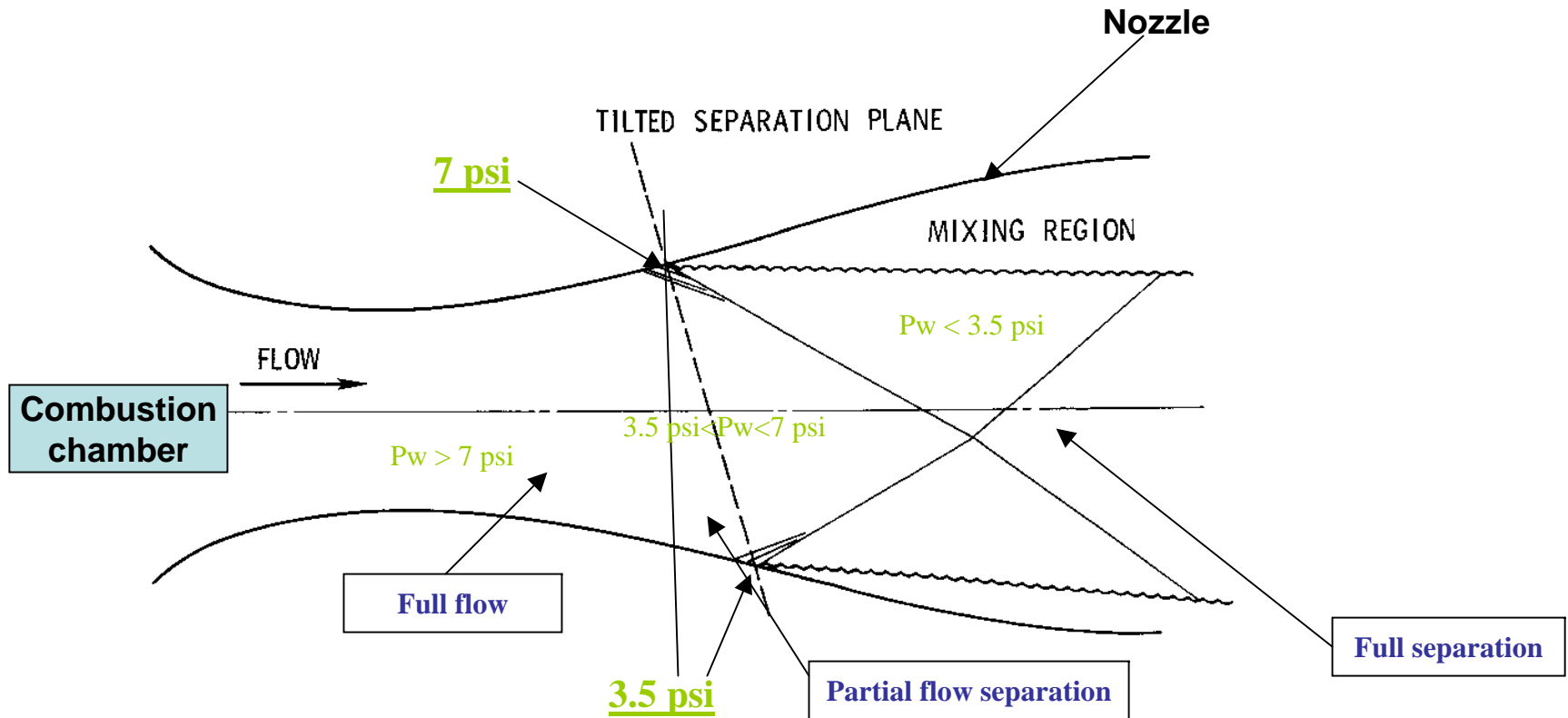
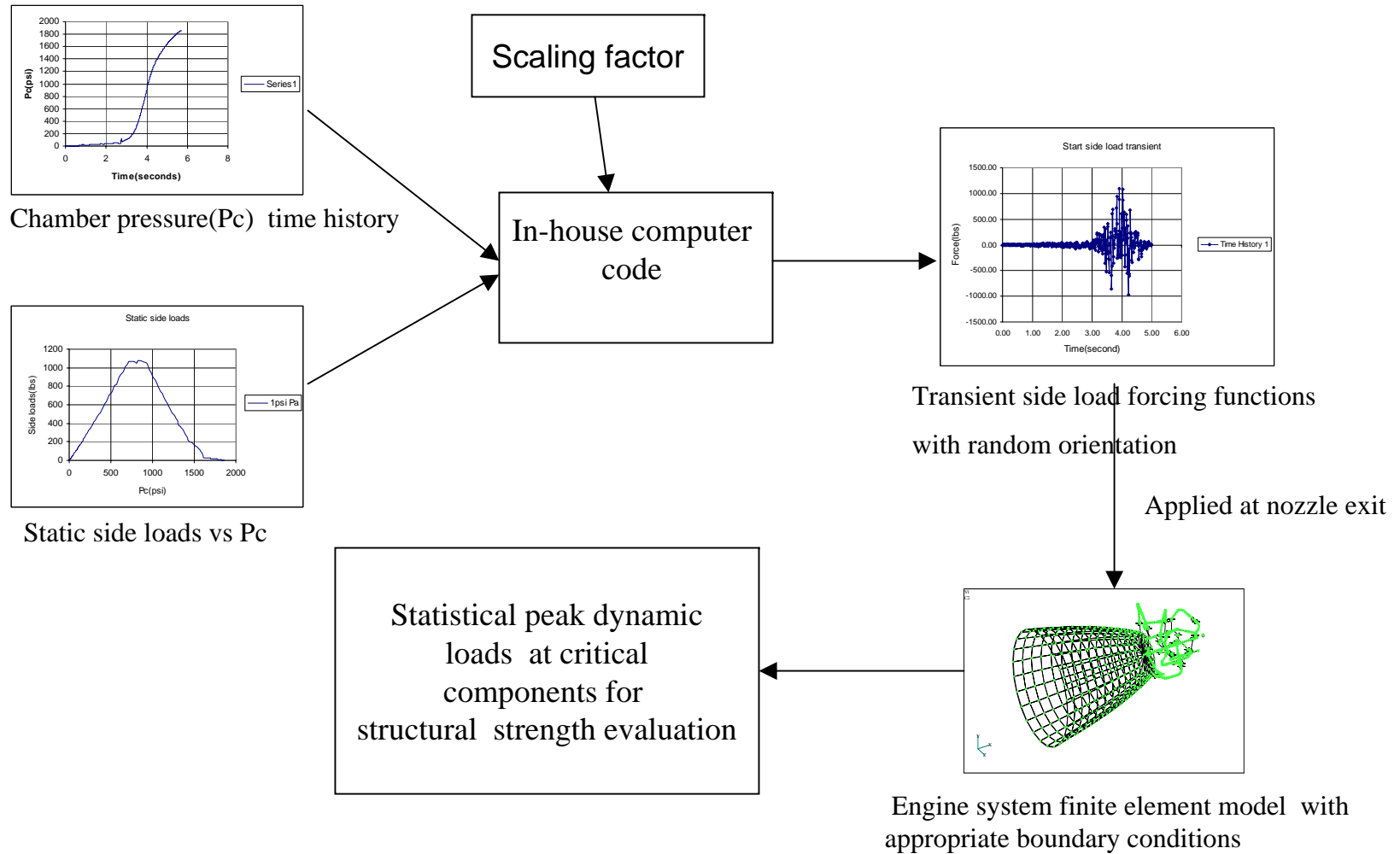


Figure 39. Side Load Tilted Separation Plane

Asymmetrical side load transient analysis methodology

- Developed analysis process to determine the structural dynamic effects of asymmetric side load transients on the engine system
 - A Monte Carlo approach was used to determine time dependent input forcing functions randomly
 - Flat spectrum in the 5 to 50 Hz frequency range
 - Used test measurements to determine the scaling factor empirically
 - Determine statistical peak dynamic loads and shock environments at critical engine components

Engine system nozzle asymmetric side loads analysis process



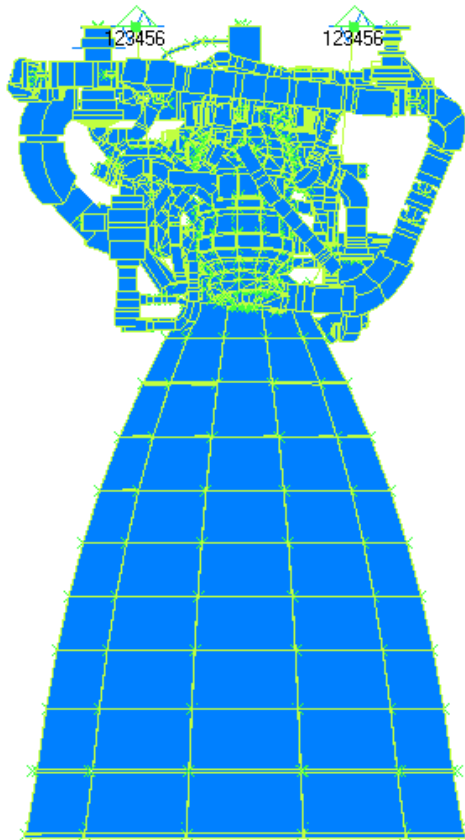
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Asymmetrical side load transient analysis methodology

- Used SSME hot-fire test measurements to determine the scaling factor empirically
 - **Employed SSME Block II engine system finite element model**
 - **Randomly generated 100 cases of side load transients from**
 - **Analytically predicted quasi-static side loads**
 - **A measured P_c start transient**
 - **Excited engine system model (100 cases)**
 - **Calculated mean and 1σ dynamic peak loads**
 - **Determined the scaling factor by matching SSME hot fire measurements**

SSME engine system



Finite element model



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Discussions

- The scaling factor ($F_{\text{rms}}/F_{\text{static}}$) has been determined empirically using the SSME hot-fire measurements
 - 87 samples of hatband strain gage measurements and 122 samples of gimbal actuator load measurements were used
 - Based on limited available J-2S engine test data, the scaling factor is between .1 and .2
 - SSME and J-2S engines were in agreement

Future plan

- It is in the future plan to perform symmetric side loads analysis
 - It will help to resolve the scaling factor differences between the hatband and the actuator for the SSME
 - The nozzle responses are a function of both the symmetric and asymmetric separation shocks while the actuator loads are dominated by the asymmetric shocks