FLOW DYNAMIC ENVIRONMENT DATA BASE DEVELOPMENT FOR THE SSME

C. V. Sundaram
Wyle Laboratories, Huntsville

Abstract

This paper describes the studies being carried out on the fluid flow-induced vibration of the Space Shuttle main engine (SSME) components. This study is being carried out with a view to correlating the frequency characteristics of the pressure fluctuations in a rocket engine to its operating conditions and geometry. An overview of the data base development for SSME test firing results and the interactive computer software used to access, retrieve, and plot or print the results selectively for given thrust levels, engine numbers, etc., is presented. The various statistical methods available in the computer code for data analysis are discussed. Plots of test data, nondimensionalized using parameters such as fluid flow velocities, densities, and pressures, are presented. Comparative studies of these results with results available in the literature are made. Correlations between the resonant peaks observed at higher frequencies in power spectral density plots with pump geometry and operating conditions are discussed. Finally, an overview of the status of the investigation is presented and future directions are discussed.

Introduction

The development efforts expended on the main engine of the Space Shuttle has resulted in the evolution of highly complex machinery which is capable of generating high thrust levels. Even from the earliest days of spacecraft engine development, achieving the highest possible specific thrust, based on engine weight or overall size, has been identified as one of the prime goals. The earlier spacecraft, however, were equipped with power sources which were designed for just one mission. The advent of the concept of reusable space vehicles added a new dimension to the engine design, that they not only satisfy the requirements on thrust but also that they be capable of carrying out multimissions into outer space with, ideally, the least amount of maintenance and component replacements between missions. This has imposed a greater emphasis on preventing failures and prolonging the fatigue life expectancy of the SSME during operation. Furthermore, specific knowledge relating to the frequency characteristics of the pressure fluctuations in rocket engine systems is not well understood. It is important to understand the functional relationships between pressure fluctuations in these systems in terms of the geometrical and performance characteristics because of their effect on hardware lifetime.

The SSME has been subjected to extensive hot firing and flow tests. During these tests, system failures and malfunctions have occurred from time to time. These failures range from wear on component bearings and flow-induced failures to explosions due to intense pressure fluctuations and accompanying dynamic stresses in the pumps, valves, and/or propellant lines. The large volume of data on pressure fluctuations, strain, and acceleration obtained from these tests provide a good basis for studies on the flow-induced vibrations taking place in the SSME.

The sheer volume of test data available makes it absolutely essential that a computerized data base management system be employed to perform any meaningful analysis. Wyle Laboratories is engaged in the development of such a data base management software. This paper provides an overview of the work being performed on the software development and discusses the method of approach suggested for analyzing the data.

SSME Data Base Management

The SSME data base management and analysis system developed at Wyle Laboratories has been designed for use on an Interdata 8/32 computer system and other computer systems utilizing similar file name structures.[1]

Data Filing System

The data base management system is designed to accommodate two types of data: time histories and power spectral density or other frequency domain data. The time history (rms pressure or thrust) data files consist of a pair of values in each record, the first value being the number of seconds into the test and the second being the magnitude. The file may consist of any number of data points (records), but most of the routines presently have an upper limit of 500 points.

Each PSD file consists of a single real number in each record. These are the spectral magnitudes. Since the PSD test data is recorded using constant bandwidth filters, the frequencies corresponding to each PSD value is automatically calculated by the program when the frequency range is entered. A considerable saving in computer disc storage space has been realized by this method because of the large amount of PSD data involved.

Data entry into files can be performed through a digitizing tablet. When the volume of data is large, however, use of a digitizing tablet can be very time consuming. Hence the data in this case is directly read from a digital tape using the dedicated magnetic tape drive units. File names are automatically assigned by the software based on test numbers, engine numbers, channel descriptors, etc., to uniquely identify each data set. Figure 1 provides an insight into the operational sequences and capabilities of the SSME data base management and analysis software.

Figure 2 shows a plot of power versus time, and figure 3 shows the rms pressure variations with time for the low pressure fuel pump. These plots were generated using the data retrieval system described above. Figures 4 shows a PSD plot generated from the digitized data for the high pressure oxidizer pump. The input to the computer to generate these plots are the file names for the time history plots and the test number, time slice, and maximum frequency for the PSD plots.

Statistical parameters, such as mean, standard deviation, rms values, third and fourth central moments, and minimum and maximum values and range, can be calculated and plotted with ease for any number of data sets selected based on engine, HPFP, and HPOP numbers; thrust level; and channel descriptors. The abscissa and the ordinate can have any combination of linear and logarithmic scales, and any statistical parameter can be plotted against any other or a frequency scale. The uniqueness of the set of PSDs selected for statistical analysis can be controlled by specifying or leaving out, in any combination, the engine, HPOP, and HPFP numbers.

A detailed description of all the capabilities of the data base management and analysis software is presented in reference 1.

General Character of Turbomachinery Noise

Background

The jet noise theory gained importance with increasing use of jet engines in aircraft. It is well known that the acoustic power generated by a jet exhaust is strongly dependent on the exit velocity (Lighthill's 8th power law[2]). However, during approach configuration of the aircraft, when the jet noise level is generally low, the engine compressor noise was observed to be a major noise source. The study of compressor noise, especially the multistage axial flow types, has acquired great importance during the last 25 years.

Noise Sources in Axial Flow Compressors

In general, the noise spectra of different types of compressors exhibit similar gross characteristics. In this paper, we limit our attention to axial flow compressors because it is believed that their noise characteristics should be more relevant to the noise generation mechanism of the axial flow pumps on the SSME.

The general form of an acoustic spectrum of an axial flow compressor would indicate broadband noise extending over a wide range of frequencies. Superimposed on this are a number of discrete peaks which represent the blade passage frequencies and their harmonics.

The broadband noise component has been attributed to various mechanisms. At least three that merit consideration are[3]

1. The random force fluctuations due to a moving flow on the surface. These fluctuations can be interpreted to act as acoustic sources located within the turbulent boundary layer.

2. The shedding of vortices from the trailing edges of a body immersed in a moving fluid. This vortex shedding imparts to the body fluctuating lift forces that are periodic at low Reynolds number flows and become random as the Reynolds number increases. (It is believed that the periodic component of the shedding does not disappear completely.) This random excitation force of vortex shedding is also considered to be instrumental in the broadband characteristic of the acoustic spectrum.

3. A turbulent flow at the inlet to the compressor sets up fluctuating forces due to flow incidence on the surface. The perturbation velocity component in a turbulent flow is random in nature, and hence the acoustic energy due to the fluctuating forces can be expected to have a broadband nature.

Another significant broadband component in the case of the SSME would be the structurally transmitted secondary vibrations due to the close proximity of the components, all having highly turbulent flow taking place within them. A challenging task in the analysis of SSME component vibration is the development of a prediction scheme that will provide quantitative estimates of the acoustic energy due to flow-induced and structurally transmitted vibrations in a frequency spectrum at various locations on the SSME.

The pure tones, which are a result of the spinning modes of the pressure field, exhibit decaying trends downstream of the rotor when the impeller tip Mach number is below critical, as in the case of a subsonic rotor. For a rotor-stator combination, however, a number of spinning modes are generated, many of which spin at Mach numbers above the critical tip Mach numbers, and these modes exhibit strong propagation characteristics.[4]

SSME Flow-Induced Vibration Characteristics

In this section, preliminary studies conducted on pressure spectra obtained from SSME firing tests are discussed. Fluid flow variables, which may be of lesser importance in conventional axial flow compressors, but which may be of greater significance in the SSME flow environment, are highlighted.

The initial efforts in the data analysis have been directed toward obtaining nondimensional PSD as a function of Strouhal number. The power spectral densities, which have dimensions of mean square pressure per hertz, were normalized as follows:

$$S_p = Q_p(f)/\rho_f^2 V^3 D \qquad (1)$$

where S_p is nondimensional PSD, $Q_p(f)$ is the measured PSD, ρ_f is the local fluid density, V is the mean velocity, and D is a characteristic length. Strouhal number is defined as

$$S_t = fD/V \qquad (2)$$

where f is the frequency.

Figures 5 and 6 show nondimensionalized PSD plotted as a function of Strouhal number for the high pressure oxidizer pump discharge pressure. Similar analyses have been carried out to estimate the pressure fluctuations due to turbulent flow of water at the wall of a duct. Figure 7, reproduced from reference 5, shows the pressure fluctuation dependence on Strouhal number. Figures 5, 6, and 7 indicate similar trends in the variation of nondimensionalized PSD for increasing Strouhal number. The scaling applied to the SSME data is based on the assumption that the pressure fluctuations are flow induced. This assumption is somewhat oversimplified as it does not address the various other noise-generating mechanisms present during turbomachinery operation.

Dimensional analysis studies of blower noise[6] provide a functional relationship,

$$E = F(D,N,Q,f,\rho,\mu, C) \qquad (3)$$

where E is the acoustic power/hertz; D, the blower diameter; N, the rpm; Q, the flow rate; f, the frequency; ρ, the fluid density; μ, the viscosity; and C, the acoustic speed. A similar analysis on the SSME turbopump would require accounting for the acoustic propagation characteristic of the structure.

Another important factor that should be considered is the fluid properties. The fluid flow conditions in the SSME undergo extreme variations in temperature and pressure. The mechanism of propagation of disturbances in fluids at extremely low temperatures and very high pressures requires further studies for proper mathematical modeling. Since the fluid flow conditions experience wide variations in the SSME, it is reasonable to expect variations in local propagation velocities and hence local Mach numbers.

The studies on the flow dynamic environment of the SSME being carried out at Wyle Laboratories are directed toward applying the existing theories on noise generation mechanism in turbomachinery after modifications to reflect the flow environment present in the SSME. An approach that would involve developing an empirical formulation rather than a very rigorous and purely analytical solutions seems to indicate promise. The basic idea involves modeling the noise generation mechanism due to turbulent flow and the pressure pulses generated by the spinning modes of the pressure field due to rotor-stator interactions separately and combining the two components to obtain the total frequency spectrum. That an empirical approach, though somewhat complicated, is not totally impossible has been amply demonstrated through similar studies performed by Van Niekerk[7] and others.

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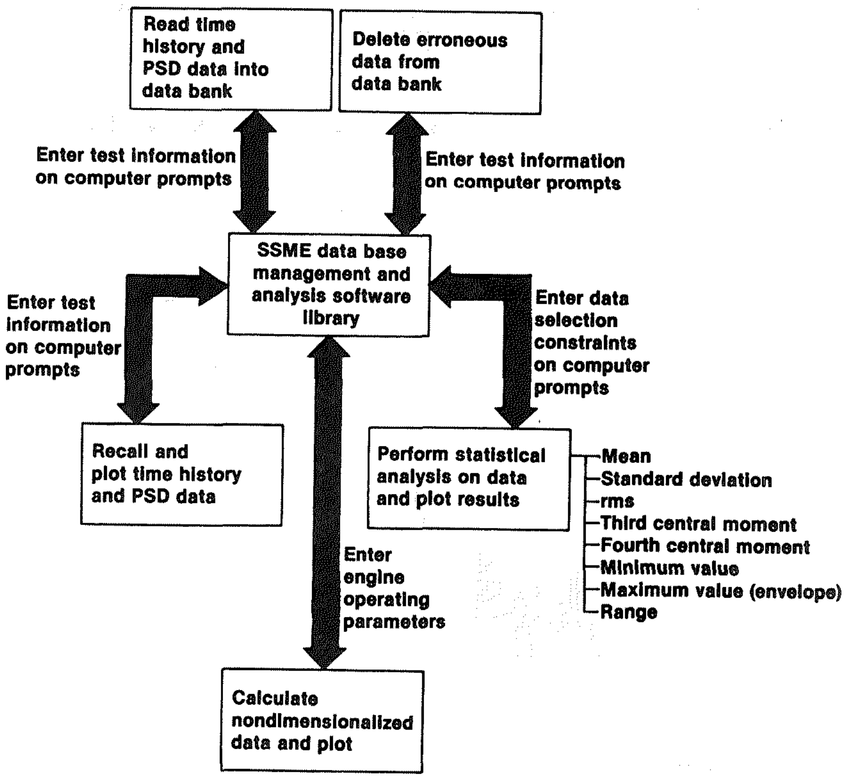

Figure 1. SSME data base management and analysis software operational sequence and capabilities

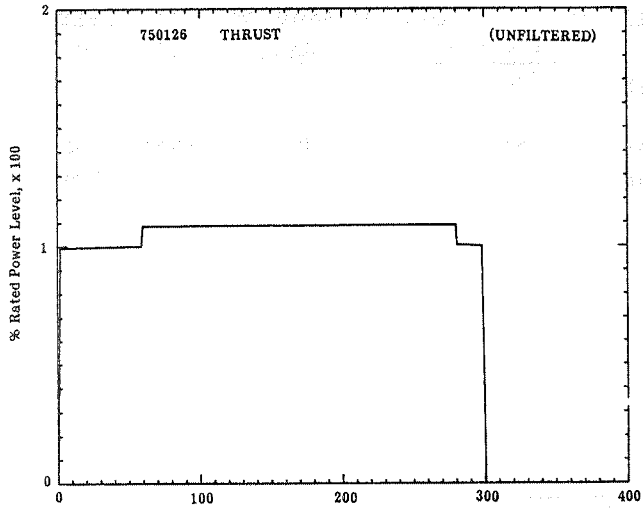

Figure 2. SSME power level variations as a function of time

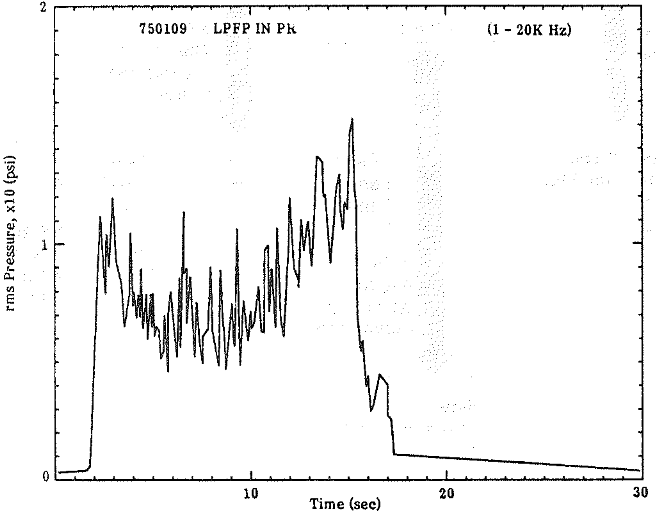

Figure 3. rms pressure time history at the inlet of the low pressure fuel pump

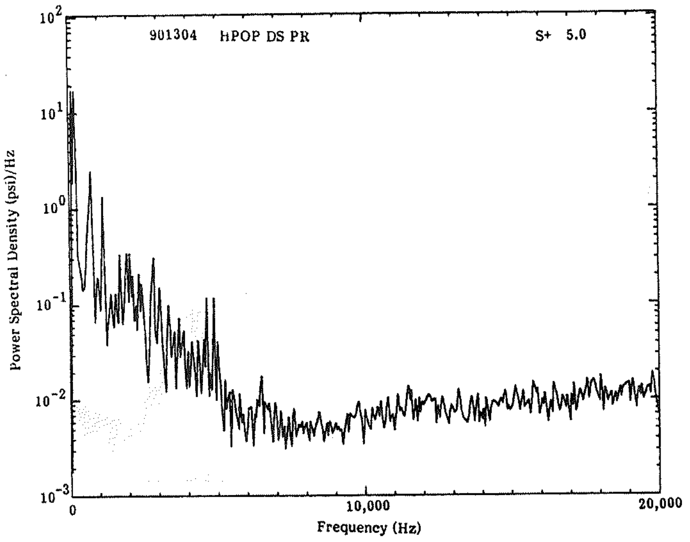

Figure 4. Power spectral density of the high pressure oxidizer pump discharge pressure 5 seconds after SSME startup

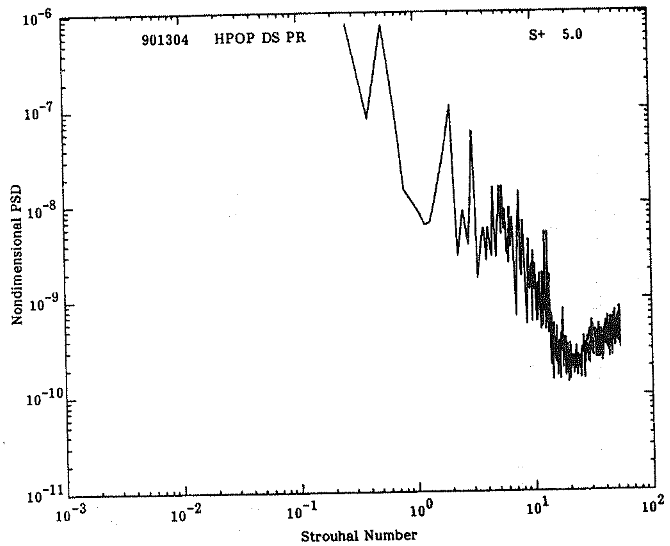

Figure 5. Nondimensionalized frequency spectrum for high pressure oxidizer pump discharge pressure, 5 seconds after SSME startup

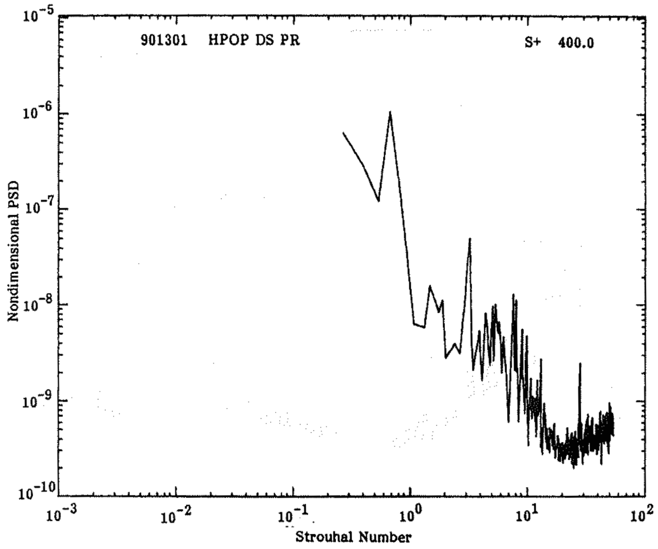

Figure 6. Nondimensionalized frequency spectrum for high pressure oxidizer pump discharge pressure 400 seconds after SSME startup

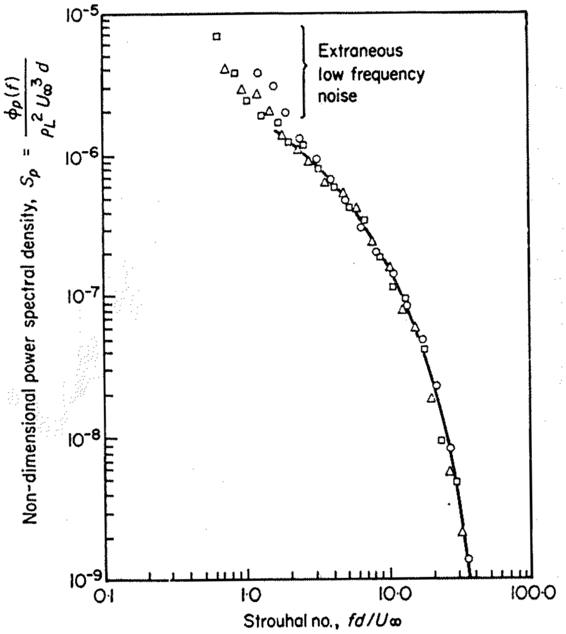

Figure 7. Frequency spectrum of turbulent wall pressure field. (○), 267 in/sec; (△) 450 in/sec; (□) 520 in/sec[5]