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STEADY AND UNSTEADY BLADE STRESSES WITHIN THE SSME ATD/HPOTP INDUCER

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INTRODUCTION

NASA has been developing a new liquid oxygen turbopump for the space shuttle main engine (SSME) for many years. This program is officially designated as the alternate turbopump development (ATD) high pressure oxygen turbopump (HPOTP). This report will explore some of the experimental aspects in the development of the ATD HPOTP inducer which is a critical component of the turbopump.

As the liquid oxygen (LOX) enters the turbopump, the first rotating "pumping" component that it encounters is the inducer. Approximately 30% of the total pressure rise within the pump is accomplished by the inducer while the impeller is responsible for the remaining pressure rise (70%). Physically, the inducer resembles a four-bladed marine propeller. From the structural design standpoint, one the main concerns is the high-cycle fatigue life of the inducer. High rotational velocities (25,500 rpm) coupled with unsteady fluid flow, including cavitation, produce a high-cycle fatigue environment.

The inducer design criteria requires an infinite design fatigue life. Based on experience with early rocket engines, NASA [1] adopted a design specification for the magnitude of these unsteady dynamic fluid pressures. After calculating the steady-state fluid pressures acting on the inducer blades, the magnitude of the unsteady fluid pressures are assumed to be 20% of the steady-state pressures. This assumed 20% variation from steady-state pressures was later changed to 30% by industrial NASA contractors to produce a more conservative design criteria. To experimentally verify this 30% unsteady pressure excursion value, NASA/Marshall began developing an Inducer Test Loop facility (ITL) in 1990.

The ITL facility is a closed loop water flow system consisting of a test loop and auxiliary loop. The auxiliary loop removes dissolved air from the process water and maintains the process water temperature within a narrow band through use of a heat exchanger. Water filtration and treatment is also performed within the auxiliary loop. The ITL facility does not attempt to completely replicate the inducer working environment., i.e. water is the working fluid in the test loop compared to the LOX employed in the actual SSME turbopump. In addition, a full-scale, clear, acrylic model of the turbopump housing is utilized in the ITL to facilitate inducer flow visualization studies.

The use of the "low strength" acrylic housing model precludes operating the inducer at the rotational speeds common in engine operation (25,500 rpm). The maximum speed possible with the acrylic model is 6,000 rpm. Consequently, scaling of the experimental results is necessary with regard to both the working fluid density and the rotational speed to match true operating conditions.

EXPERIMENTAL PROGRAM

There were two main goals of the ATD HPOPT inducer test. First, determine the steady and unsteady inducer blade surface strains produced by hydrodynamic sources as a function of flow capacity (Q/N), suction specific speed (Nss), and Reynolds number (Re). Second, to identify the hydrodynamic source(s) of the unsteady blade strains. The reason the aforementioned goals are expressed in terms of blade strains as opposed to blade hydrodynamic pressures is because of the interest regarding the high cycle fatigue life of the inducer blades.

The assumed 30% variation is blade pressure, about the steady-state mean pressure, due to unsteady hydrodynamic sources converts directly into a 30% variation in the blade strains and stresses about their mean levels. This pressure-strain-stress conversion is done using the assumption that the inducer material (Inconel) behaves in a linear manner. The validity of inducer high cycle fatigue life prediction is completely dependent on the accuracy of the steady and unsteady (alternating) blade stress values.

This report will focus on the first goal of the test program which involves the determination of the steady and unsteady strain (stress) values at various points within the inducer blades. Strain gages were selected as the strain measuring devices. The strain gages were electrically connected to the instrumentation via an actively-cooled, slip ring on the rotating inducer shaft.

Concurrent with the experimental program, an analytical study was undertaken to produce a complete NASTRAN finite-element model of the inducer. Computational fluid dynamics analyses were utilized to provide the estimated steady-state blade surface pressure loading needed as load input to the NASTRAN inducer model. The results of the NASTRAN analysis indicated that for the ITL test conditions, the steady-state blade strains would be very small ($< 40\mu\varepsilon$). These low estimates for the strain levels coupled with the hydrodynamic test environment created some stringent conditions on the strain gage installation.

A. INSTRUMENTATION

The combination of the centrifugal and pressure loading results in both bending and extension (radial and circumferential) of the inducer blades. Bending is the dominant loading, but the extensional loading is significant. The two main issues which had to be addressed during the instrumentation selection phase were the low anticipated strain levels and the need to develop a "robust" gage installation capable of surviving the hydrodynamic environment.

To compensate for the low strain levels, semiconductor gages were selected for the majority of the gage locations. It was felt that the high strain sensitivity of the these gages would allow for the most accurate measurement of the small unsteady (alternating) blade strains while foil gages were selected to measure the steady-state strain levels. The use of semiconductor gages to measure the steady state strains was considered to be less desirable than the use of foil gages due to the significant thermal shift of the semiconductor gages compared to the foils. The gage thermal shift behavior becomes more critical as the measurement time span increases, such as the case for determination of the steady-state strain levels. Once it was decided to employ both the foil and semiconductor types of gages, the next set of decisions concerned the type of bridge to be employed (quarter, half or full) and the gage pattern at each of the strain locations.

A full bridge arrangement was selected based on three factors. First, a full bridge provides the highest bridge output compared to the either the quarter or half bridge arrangements. Second, the full bridge provides better temperature compensation. Finally, the slip ring is not in the measurement circuit for the full bridge as opposed to the quarter and half bridge circuits.

Once a full bridge arrangement had been determined, the next decision concerned the selection of the gage pattern at each strain location. Two major factors constrained the selection of the gage pattern to a rather limited set of options. The first constraint was the decision to utilize a full bridge arrangement as discussed in the above section which required four active gages at each strain location for effective temperature compensation and bridge completion. The second major constraint arose from the need to recess the gages into the inducer blade to protect the gages from the fluid flow and limit the distortion of the flow pattern over the blade surface during operation. The minimum required depth of the recesses was 0.035 inches. This depth allowed for protection of the gages while still providing sufficient room to fill the recess with an epoxy potting compound that could be smoothed to match the blade surface for flow continuity. This minimum recess depth was significant relative to the total blade thickness which varied from a minimum of 0.090 inches to a maximum of 0.170 inches. As a consequence, it was not considered structurally advisable to recess both the pressure side (PS) and the suction side (SS) of the blade at the same location.

Given the two constraints, the gage pattern that was selected consisted of two gages mounted radially relative to the rotational axis of the inducer and two gages mounted circumferential. This bridge circuit results in the following bridge output equation

$$V_o = \frac{V_i \ GF \ (1-\varepsilon_c/\varepsilon_r)}{[2/\varepsilon_r + GF \ (1 + \varepsilon_c/\varepsilon_r)]} \qquad (1)$$

where
V_o = bridge output voltage,
V_i = input voltage to bridge,
GF = gage factor,
ε_c = circumferential strain, and
ε_r = radial strain.

The derivation of equation (1) is a rather straightforward procedure starting with the general equation for an unbalanced Wheatstone bridge circuit.c

B. DATA REDUCTION

The quantities V_i and GF in equation (1) are known prior to the test and the value of V_o is measured during the test. The two strains ε_r, ε_c and the strain ratio, $\varepsilon_c/\varepsilon_r$ are unknown quantities in equation (1). Calculation of the absolute strain values required the development of a complimentary equation involving the strains to create a system of two equations with two unknown strains. During the search for this complimentary equation, the author examined the NASTRAN inducer model to determine the characteristics of the strain ratio $\varepsilon_c/\varepsilon_r$.

Two characteristics of the strain ratio were clearly discernable from the NASTRAN analysis. First, the strain ratio was a significant value relative to 1.0 and it would be a serious error to eliminate the strain ratio from the term within the denominator in equation (1). Second, the strain ratio value was substantially different at different locations on the blade surface and the ratio values did not correlate well with the Poisson's ratio of the blade material. The author concluded that the most accurate values available for the strain ratio would be those calculated from the NASTRAN analysis results for each of the gaged locations on the blade. The "analytical" strain ratio values were then employed in equation (1) to calculate the experimental strain ε_r. This procedure of employing an analytical value to facilitate the calculation of experimental strains is certainly not an ideal procedure, but the author was unable to develop a more appropriate method.

A simple cantilevered beam specimen was produced to examine the validity of this experimental-analytical method for determining the blade strains. Instrumentation of the beam involved the use of a pattern of four foil gages identical to the foil gages employed on the actual inducer. Machining of the specimen, bonding of the gages, and wiring of the bridge was all accomplished by the same organization responsible for the inducer instrumentation. Loading of the beam involved hanging a set of dead weights at the free end. A finite element model of the beam was constructed from CQUAD4 plate elements using MSC/PAL2 to provide the value of the strain ratio $\varepsilon_c/\varepsilon_r$ needed for the calculation of the experimental strains using equation (1).

This finite element model was employed to allow for the modelling of the strain gage recess machined into the beam. The finite element analysis results clearly showed that the presence of the recess strongly influences the strain state. Based on the results of this simple cantilevered beam test case, the finite element model of the ATD inducer was modified to incorporate the strain gage recesses. To calculate the radial and circumferential strains from equation (1), the values of the strain ratio ($\varepsilon_c/\varepsilon_r$) had to be supplied to the data reduction algorithm via the finite element results.

The final section of the data analysis program involved the conversion of the strain results (ε_r and ε_c) determined from equation (1) by using the experimental bridge output and the strain ratios from the finite element results. These values, ε_r and ε_c, represent the strains at the bottom of the gage recess. The strains that are needed to predict the high cycle fatigue life of the inducer are those at the blade surface of an unmodified inducer, i.e., one with no machined recesses. The conversion from the measured recess strains to the blade surface strains was accomplished through comparison of the modified (with recesses) and unmodified inducer finite element models.