

SPACE SHUTTLE MAIN ENGINE THE FIRST TEN YEARS

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Part 4 – High Pressure Fuel Turbopump Subsynchronous Whirl

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High Pressure Fuel Turbopump Subsynchronous Whirl

On March 12, 1976, four days after the first stabilized test on the ISTB, Test 901-044 was scheduled for a sixty-five second exploratory test at 50 percent power level with one second at 65 percent power level. Although 65 percent power level was successfully demonstrated (the highest achieved up to that time), the test was terminated at 45.2 seconds due to loss of axial thrust in the HPFTP. After the test, the HPFTP was bound up and could not be rotated with the turbopump torque test tool (normal post-test checkout). This condition was later found to be caused by the failure of the HPFTP turbine end bearings. A review of the test data revealed two major abnormalities. The HPFTP turbine gas temperature increased by almost 200 R during the test. This and other measurements indicated a significant loss of turbine efficiency during the test. In addition, high frequency vibration measurements on the HPFTP indicated a large amplitude vibration at a frequency of about one-half of the fuel pump speed. This vibration characteristic was immediately recognized as a rotordynamic instability known as subsynchronous whirl. Although the phenomenon had not been predicted to occur, the potential for this instability had been hypothesized as much as three years earlier [21]. A meticulous review of prior engine and component test data revealed that the phenomenon was present to some extent in most of the tests that exceeded 17,000 rpm; however, it was overshadowed by the transient nature of the tests and the persistence of a HPFTP axial balance piston problem [22].

To expedite the solution of this problem, a combined Rocketdyne-NASA team was formed under the leadership of Matt Ek, Rocketdyne vice president and chief engineer, and Otto Goetz, MSFC's leading turbomachinery expert. The team was ultimately expanded

to include the foremost experts in the field of rotordynamics from industry, government, and the academic community in the United States and Great Britain [22].

The HPFTP is shown in cross section in Figure 11. It is a three-stage centrifugal pump driven by a two-stage reaction turbine, which is part of the same rotating assembly. When operating at FPL, each of the three twelve-inch impellers develops over 60,000 feet of head rise at a LH2 flow rate of 17,000 gpm and a speed in excess of 36,000 rpm. The two-stage, eleven-inch diameter turbine delivers 75,000 horsepower with an efficiency greater than 80 percent at a pressure ratio of 1.5. With a total assembly weight of 775 pounds, and a length of just over three feet, the HPFTP is the most compact, highest power density rotating device known today. The power density of almost 100 horsepower per pound was an order of magnitude increase over prior turbopump designs.

The 130 pound rotating assembly is designed around a central drawbolt threaded into the second stage turbine disc. The turbine disc and the three impellers are rotationally piloted by splined sleeves which also perform the functions of interstage seals and journal bearings. This stack-up is drawn together by a nut on the first-stage impeller end of the drawbolt. The first-stage turbine disc is bolted to the second-stage turbine disc with a curvic coupling. Radial positioning is accomplished by two sets of angular contact, duplex spring-loaded 45 millimeter ball bearings spaced 23.3 inches apart. The bearings are not lubricated but are cooled with LH2 during operation. Axial positioning is maintained by an LH2 pressure balance with the back side of the third-stage impeller acting as a double-acting self compensating balance piston. Balance piston pressure is supplied through an axially sensitive overlapping orifice at the impeller

discharge and vented through an axially sensitive orifice at the hub of the impeller rear shroud. When at rest and at low speed, the rotor is supported by a thrust-bearing assembly at the bottom of the rotor (pump inlet end).

The HPFTP subsynchronous whirl was a violent instability which caused a gyration of the rotor in the direction of normal rotation at a frequency of about half of the pump speed (see Figure 12). This caused a forward precession of the rotor, which was actually an orbiting of the normal rotating axis. Being a true instability, the whirl was self-initiating and would usually start when the pump speed exceeded twice the first critical speed of the rotating assembly, with an inception frequency equal to the first critical speed (originally about 8,500 rpm). The amplitude would increase rapidly; and within half a dozen cycles, with bending of the rather flexible rotor, the normal clearances would be breached and internal rubbing would occur at many locations. With clearances closed and bearing supports bottomed out, the system stiffness increased significantly, preventing further increase in amplitude (limit cycle) and raising the first critical speed and, therefore, the whirl frequency. Bearing loads in the limit cycle condition were higher on the turbine end than the pump end by a factor of three, and a signifi-

cant number of turbine bearing failures were experienced.

A multidisciplinary approach was pursued by the team, which included historical research, literature surveys, mathematical models, and consultations with universities and other companies with related knowledge or experience. A vigorous test program included laboratory, component, subsystem and engine tests. Twenty-two potential drivers were identified and analyzed; however, it was eventually concluded that two factors were far more significant than all the others. The most significant destabilizing effects were, hydrodynamic cross-coupling of the pump interstage seals combined with the low natural frequency of the rotating assembly [22]. These effects were attacked by a series of design changes to decrease cross-coupling drivers and provide damping at the seals and to increase the rotor critical speeds by stiffening the shaft and bearing supports. Over a ten-month time period, the whirl inception speed was gradually increased from 18,000 rpm (below MPL) to above 36,000 rpm, which allowed whirl-free operation to above RPL.

As the design changes allowed operation at higher speeds, it became evident that the turbine bearings were being overheated by some mechanism unrelated to whirl. Instrumentation added to the turbopump to

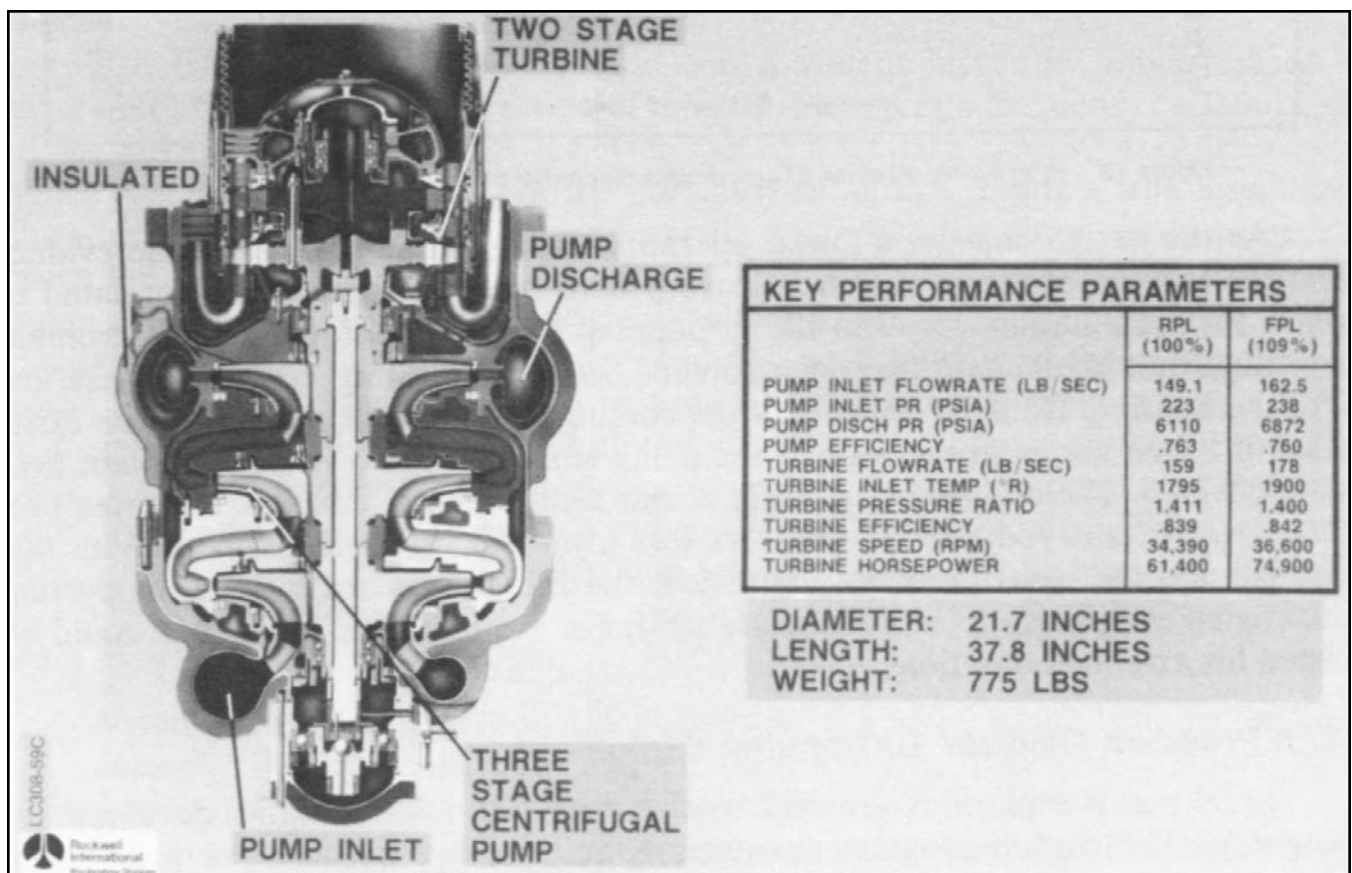


Figure 11. SSME High Pressure Fuel Turbopump (Photo No. LC308-59C)

gain data for the whirl problem indicated that inadequate hydrogen coolant flow was allowing hot gas to backflow into the bearing. Detailed analysis of the cooling system finally identified the existence of a free vortex at the base of the pump shaft through which the coolant flow was provided. The addition of a baffle at this location changed the free vortex to a forced vortex

and reduced the pressure loss from 500 psi to 12 psi [23]. With this change, and the whirl problem eliminated, the HPFTP was capable of supporting the engine test program in mid-January 1977. For the first time, the SSME could be tested for extended durations.

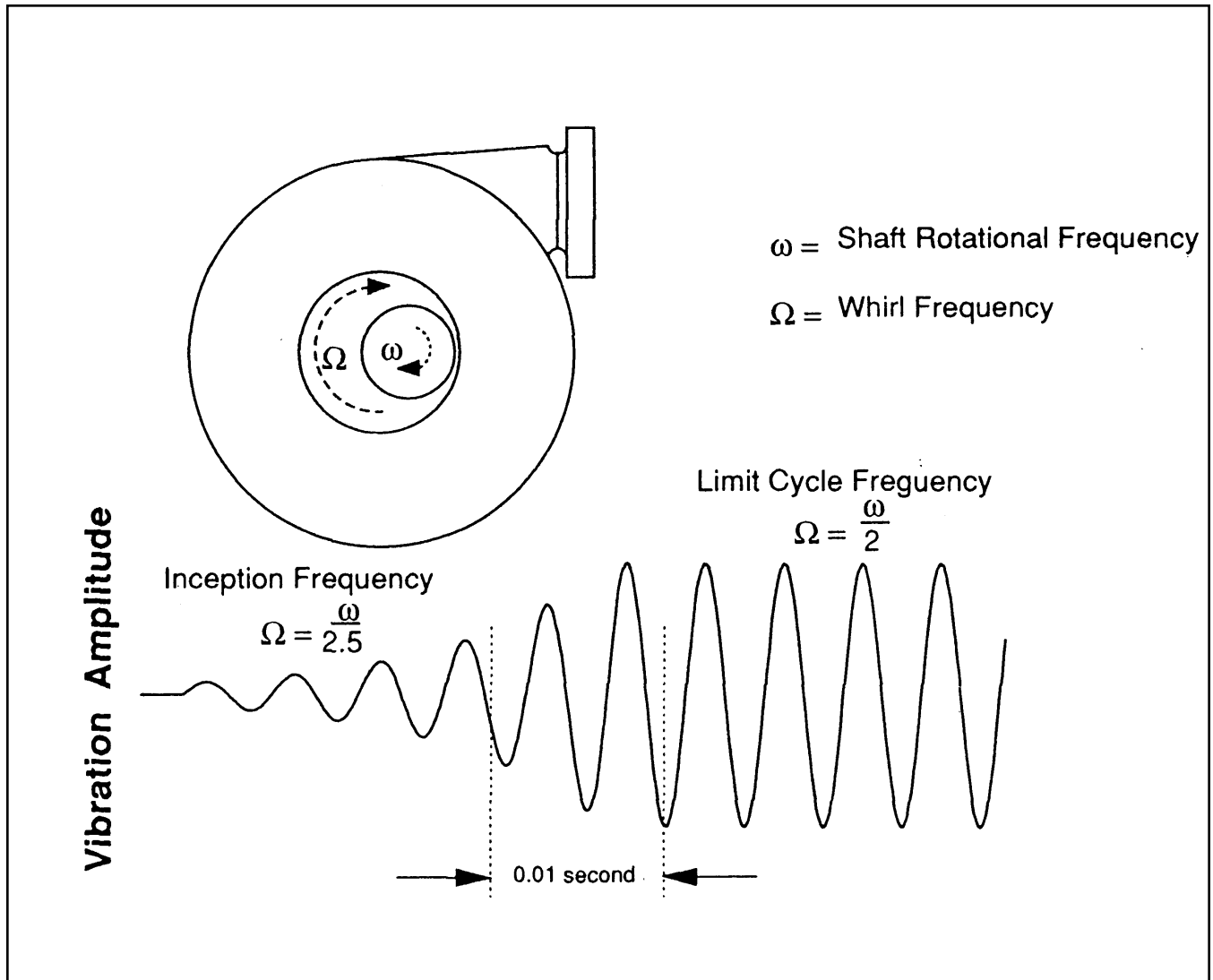


Figure 12. HPFTP Whirl Vibration Characteristics (Photo No. 89c-4-1017)