

Overview of Rotating Cavitation and Cavitation Surge in the Fastrac Engine LOX Turbopump

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Observations regarding rotating cavitation and cavitation surge experienced during the development of the Fastrac 60 KlbF engine turbopump are discussed. Detailed observations from the analysis of both water flow and liquid oxygen test data are offered. Scaling and general comparison of rotating cavitation between water flow and liquid oxygen testing are discussed. Complex data features linking the localized rotating cavitation mechanism of the inducer to system surge components are described in detail. Finally a description of a simple lumped-parameter hydraulic system model developed to better understand observed data is given.

Key Words: Turbomachinery, cavitation, rotating cavitation, fluctuating pressure

1. Nomenclature

N	synchronous oscillation
rc	rotating cavitation oscillation
C _p	dimensional pump compliance
M	dimensional mass flow gain factor
N _{ss}	suction specific speed
ϕ	inlet tip flow coefficient
Ψ	stage head coefficient

2. Introduction

During the development of the high-speed turbopump for the 60,000 pound thrust Fastrac rocket engine, complex unsteady flow and shaft vibration due to rotating cavitation were observed. The bipropellant pump (Figure 1) with both a single-stage LOX (shown with axial inlet) and RP inducer-impeller sharing the same drive shaft exhibited independent cavitation induced super-synchronous oscillations concurrently during nominal operation.

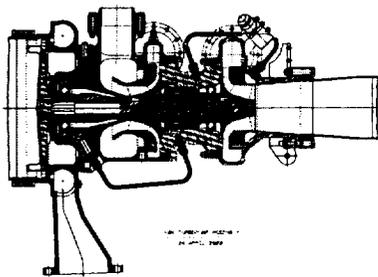


Figure 1. Fastrac Turbopump Assembly

This document attempts to summarize major observations regarding the Fastrac LOX turbopump rotating cavitation anomaly and relay them to a turbomachinery community which must frequently contend with hydraulic system instabilities induced by cavitating pumps. Observations have been derived from LOX pump super-scale model water flow and turbopump component level hotfire test. Characterization and abatement of the cavitation instability were critical issues in the development and certification of the Fastrac engine due to leading edge blade deformations found in both the initial aluminum water flow test article and subsequently in a component level test inducer. Figures 2 and 3 show the damaged leading edge regions in the water flow aluminum and the LOX K-Monel inducers respectively.

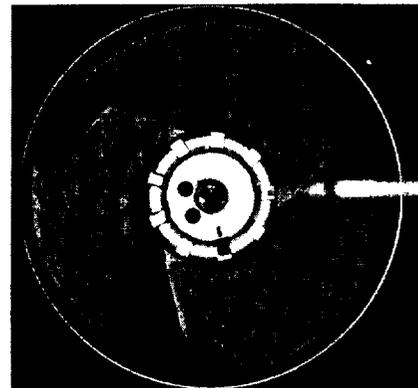


Figure 2. Failed Aluminum Inducer

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Figure 3. LOX Inducer with Slight Leading Edge Deformation

Water flow rig testing of the LOX pump, initiated to verify suction performance, provided valuable insight into the anomaly and produced the first evidence of the severity of the rotating cavitation with the failure of the original aluminum superscale LOX inducer-impeller.¹ Figure 4 is a joint time-frequency mapping of the oscillation taken from water flow test of the LOX inducer at the rated flow condition ($\phi = 0.135$) and a shaft speed of 5000 RPM.

The inducer inlet fluctuating pressure data shows the development of the rotating cavitation oscillation, denoted as “rc” in the figure, during an inlet pressure ramp test (suction pressure decreases going into page). In-depth discussion of the spectral trending will be offered in subsequent sections of this overview. The experimental latitude offered by the water rig testing was crucial in the characterization of the oscillation.

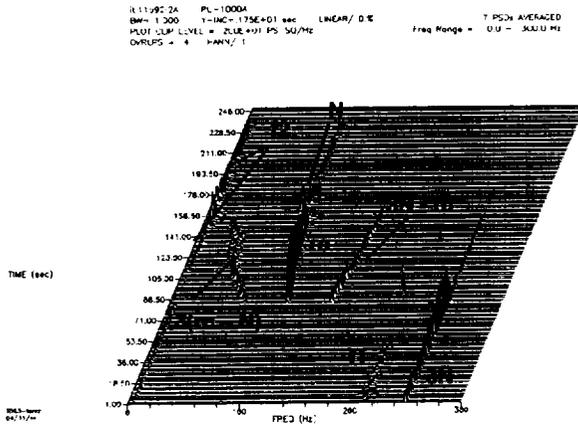


Figure 4. Waterfall Plot of Inducer Inlet Fluctuating Pressure from Water Flow Test

Several features similar to that of the Fastrac turbopump rotating cavitation have been documented by other researchers involved in the development of high speed rocket engine turbomachinery.^{2,3} Tsujimoto, et al., provided an excellent overview of inducer rotating disturbances encountered during the

development of the LE-7 LOX turbopump.³ A majority of the spectral components shown in Figure 4 have counterparts described in the LE-7 cavitation oscillation overview.

3. Rotating Cavitation and Cavitation Surge Data Observations

3.1 Rotating Cavitation

As noted previously, water flow testing offered several experimental opportunities not available in the LOX environment. This included the accessibility of high frequency instrumentation locations and the ability to easily manipulate pump inlet hydrodynamic condition, i.e. N_{ss} (suction specific speed) and ϕ , in the water flow loop (Figure 5). Flush mounted fluctuating pressures at the inducer inlet plane approximately 0.3 inducer diameters upstream of the blade leading edge (instrumentation plane 1000, Figure 5) were used to establish the rotational character of the oscillations shown in the joint time-frequency plot of Figure 4. Hannover plotting of inducer inlet fluctuating pressure relative phase information was used in determining cell number and propagation direction of the major spectral components.⁴

As expected, the peaks denoted as “3N” and “N”, are three and single cell disturbances, respectively. Cross-channel phasing at the inducer inlet plane confirms their lock-in (in a rotational sense) to the three-bladed inducer. The peak denoted as rc in Figure 4, is a one-celled disturbance propagating in a forward direction, i.e. in the same direction as the rotor, at a slightly super-synchronous rate. No significant loss in pumping efficiency was noted in water flow suction performance mappings until the appearance of the synchronous oscillation, N, where stage head coefficient, Ψ , dropped approximately 2 percent from the non-cavitated ($< 15000 N_{ss}$) water flow value. The peak denoted as “f1” in Figure 4 is thought to be a rotating disturbance of high cell count related to backflow vortices. Phasing suggests that the low amplitude oscillation is an eight-cell disturbance with a propagation velocity of approximately $0.32N$. The cell train propagation rate and high cell count are similar to rotating backflow disturbances characterized in Reference 3. However, the phase mapping was not of high enough fidelity (i.e. insufficient number of sensors at inlet plane) to confirm propagation direction and the high cell count of f1.

3.2 Cavitation Surge

During water flow testing of the superscale Fastrac LOX inducer model, strong pump-facility coupling was experienced. Figure 7 is a waterfall plot of an upstream (approximately 1.5 inlet diameters from inducer) unsteady pressure measurement. Amplitude scale is equivalent to that of the inducer inlet waterfall plot of Figure 4. The dominant oscillations registered at this upstream location are $3(rc - N)$ and the component denoted as "f2". Further analysis into phasing and the high frequency content of measured fluctuating pressure both at the inducer inlet plane and elsewhere in the water flow loop revealed interesting attributes of the $3(rc - N)$ component.

Figure 8 contains a series of waveforms (0 - 10 kHz bandwidth) across several locations over 15 cycles of $3(rc - N)$. In sequence from top to bottom are upstream fluctuating pressure, inlet fluctuating pressure, inlet fluctuating pressure at an alternate circumferential location, and finally radial acceleration measured on the pump housing. Clearly, the dominance of the $3(rc - N)$ in the upstream pressure is shown. Likewise the complexity of the nonlinear interaction between the rotating cavitation component and the synchronous rate is very evident in the two inducer inlet pressures.

While the rotation-induced delay of the higher frequency rotating cavitation wavelet is easy to discern between the two inlet pressures, the underlying $3(rc - N)$ wave appears to be in phase. The inducer inlet plane transfer function of Figure 9 confirms this unique phasing at the frequency of $3(rc - N)$. Relative phase at the oscillation frequency is zero with a coherence of nearly unity. Similar phasing and coherence for $3(rc - N)$ were shown with the alternate inducer inlet cross-channel pair.

Before discussing possible physical implications of the complex component $3(rc - N)$, some observations on the transient envelope of the monitored fluctuating pressures are now offered. Figure 10 displays a high-pass filtered version of Figure 8. The data were high-pass filtered at 2 kHz to safely exclude rc and synchronous activity. Of interest in this series of filtered waveforms is the obvious synchronization of wideband bursts at the rate of $3(rc - N)$ across all fluctuating pressures and monitored pump vibration. Envelope spectral analysis of these waveforms has confirmed this synchronization.

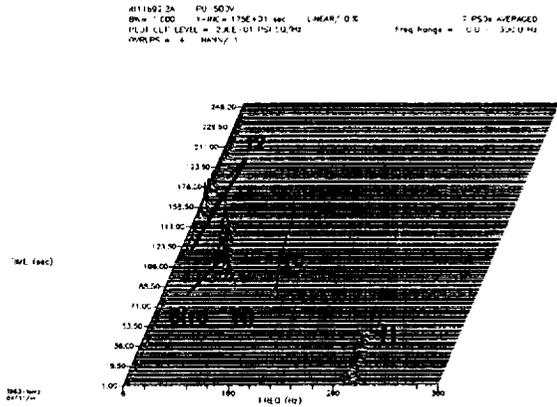


Figure 7. Waterfall Plot of Upstream Fluctuating Pressure from Water Flow Test

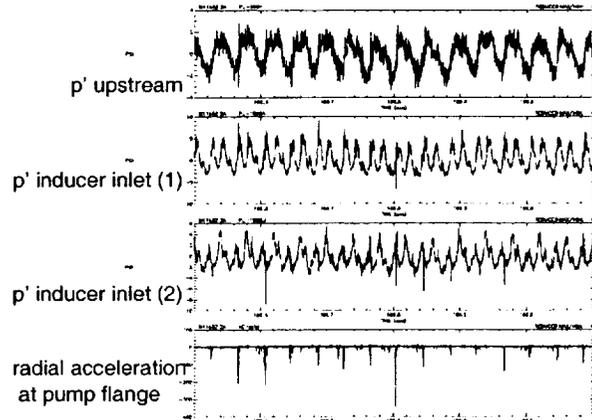


Figure 8. Multiple Location Pressure and Vibration Waveforms During Rotating Cavitation Over 15 Cycles of $3(rc - N)$

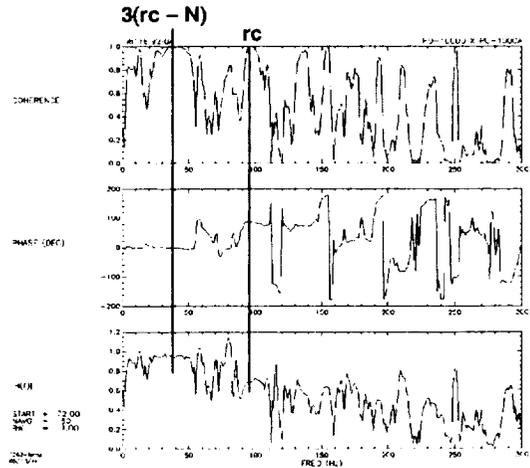


Figure 9. Inducer Inlet Pressure Cross-Channel Coherence, Phase, and Gain During Rotating Cavitation

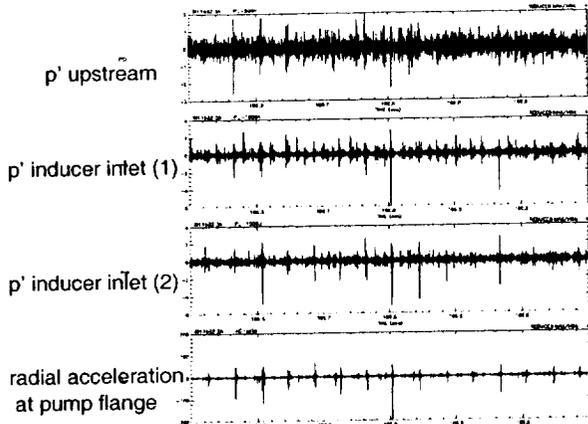


Figure 10. Multiple Location Filtered Pressure and Vibration Waveforms During Rotating Cavitation Over 15 Cycles of $3(rc - N)$

The unique phasing is thought to reflect the complex physical relationship between the localized inducer rotating cavitation disturbance and more global flow instability. A component similar to the $3(rc - N)$ has been documented by Tsujimoto and fellow researchers.³ In their effort, a cavitation surge mode was identified at a frequency corresponding to $(rc - N)$. The frequency variation of their cavitation surge at times lost correlation with those of the rc and N components. In Fastrac LOX inducer water flow testing, correlation of the cavitation surge mode at $3(rc - N)$ with the rotating cavitation and synchronous components was maintained. Figure 11 is a waterfall plot of inducer inlet pressure taken from the last test of the slightly deformed hardware shown in Figure 3. The frequency axis has been scaled to facilitate comparison of water flow data with that of the LOX. During the first portion of the test, the LOX pump experienced an excursion into rotating cavitation (start +52 through 55 seconds). The LOX pump was operating at 88% of rated flow during the transient and traversed the critical N_{ss} region of the rotating - synchronous cavitation boundary (Figure 6, ~16 kNss). The $3(rc - N)$ component is thought to be cavitation surge in the LOX environment. Envelope analysis of both inducer inlet unsteady pressure and pump housing vibration from LOX testing exhibited a well-defined periodicity at the subsynchronous frequency similar to that of water flow. The spectral component labelled as f_2 in Figure 4 showed little dependence on N_{ss} and ϕ in water flow test. The frequency decreased slightly from 4 Hz with increasing N_{ss} . While the $3(rc - N)$ mode appeared to be most active in the vicinity of the inducer, the f_2 mode was much more distributed across the water flow loop.

4. Hydraulic System Stability Analysis

4.1 Analytic Model Overview

In an attempt to better understand observed "system couplings" between the water flow inducer and

test facility, a lumped parameter model of the MSFC Inducer Test Loop was developed. The analytic model was purely hydraulic in that no structural participation was considered.

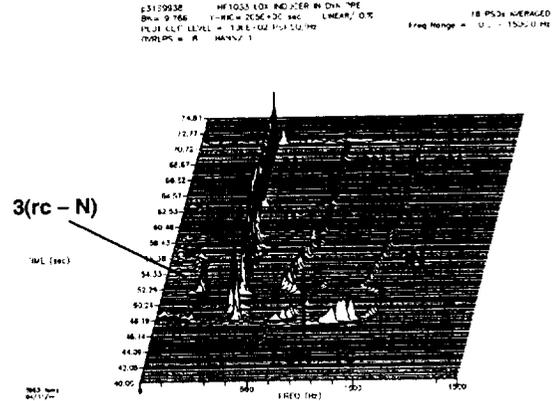


Figure 11. Waterfall Plot of Inlet Fluctuating Pressure from Fastrac Turbopump Hotfire

The model was composed of simple inertia, resistance, and compliance elements as well as additional terms specific to the pump component. These terms included the mass storage term due to variation in ϕ , or mass flow gain factor, and a pump pressure gain factor.^{5,6,7} The pump was modeled with two characteristic equations consistent with the method of Oppenheim and Rubin used in their Pogo stability analysis of liquid rocket engines.⁶ The pump representation was felt sufficient for a first-order analysis of water flow system stability. The analytic effort was anchored to the subsynchronous $3(rc - N)$ component observed in water flow test. Pump compliance (C_p) and mass flow gain (M) variations with respect to cavitation parameter (N_{ss}) were varied until a characteristic root of appropriate mode shape and frequency variation was obtained. Recently published onset conditions for both cavitation surge and rotating cavitation were used in making initial estimates for both pump compliance and mass flow gain.⁸ Scaling of the mass storage terms to their dimensional forms was consistent with that of Reference 9.

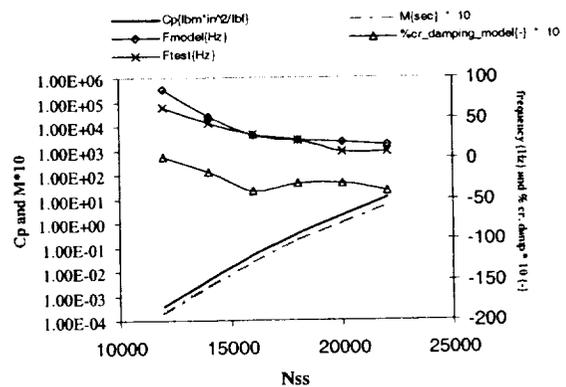


Figure 12. Pump Compliance and Mass Flow Gain Factor Estimates versus N_{ss}

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4.2 System Stability Model Results

Figure 13 displays the pressure mode shape of the system eigen value which was tuned analytically to observed test data. Both fluctuating pressure data and audible observation indicated the cavitation surge to be strongest in the vicinity of the inducer. The pressure mode, normalized by pump inlet pressure response, is plotted versus model element with flow direction going from left to right. Figure 12 shows both the frequency variation of the predicted mode versus N_{ss} as well as that of the $3(rc - N)$ component shown in test. Stability margin for the root was lost at ~ 12 kNss which agreed with test data. Interestingly, the most unstable modes predicted by the model consistently showed a mode shape similar to that of Figure 13, i.e. peak fluctuating pressure (and unsteady flow) at the inducer leading edge.

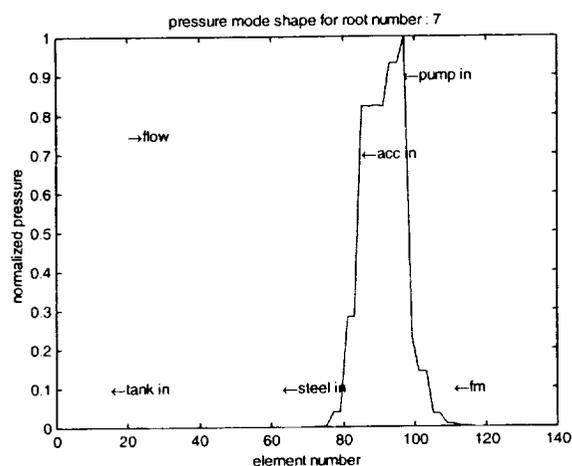


Figure 13. Analytic Instability Mode Shape

5. Concluding Remarks

The Fastrac LOX inducer rotating cavitation shares many of the complex features observed in other rocket engine turbomachines which have exhibited the same phenomenon. The unique interaction between rotating cavitation and cavitation surge at the inducer inlet warrants further investigation. A better understanding of the flow features which induce such complex dynamic signatures will most likely be required in the development of very high suction performance rocket turbomachines. The international rocket engine industry must invest in such research. As an alternative, turbomachinery (and potentially vehicle) unsteady flow and vibration abatement efforts will continue to be reactive in nature, i.e. trying to overcome hardware anomalies and failures late in the development cycle of propulsion systems.

References

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