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A WATER TEST FACILITY FOR LIQUID ROCKET ENGINE TURBOPUMP CAVITATION TESTING

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ABSTRACT

Improved understanding of the physics of turbopump cavitation and its relation to engine design parameters is needed to enhance propulsion system reliability and reduce development costs. A program to investigate cavitation phenomena in liquid rocket turbopumps has been initiated at The Aerospace Corporation to improve capability to predict the phenomena. This paper presents the methodology for the design of a new water-flow cavitation test facility capable of testing a variety of rocket turbopumps over a wide range of operating conditions to simulate the thermal characteristics of cryogenic propellants. This new cavitation test facility is now operational and qualification testing is in progress. Future experiments conducted in the facility will provide valuable data for the characterization of turbopump cavitation phenomena as well as evaluation, development, and validation of cavitation models.

INTRODUCTION

Cavitation in liquid rocket engine turbopumps can result in not only pump performance degradation, but also significantly reduced system reliability through the generation of elevated engine and vehicle vibration environments. A variety of complex cavitation phenomena exist which produce both broadband and discrete frequency excitation that can damage both turbopump and vehicle components. These phenomena can occur at operating conditions well inside an engine’s operating envelope, but often go unidentified during engine development and qualification due to limited predictive capability and complex dependence on engine and vehicle feed system configuration.

Recent advances in computational fluid dynamic modeling of cavitating flows demonstrate a substantial improvement in predictive capability [1-2]. Current models have demonstrated some success at predicting cavitation-induced head fall-off in inducer pumps [3-4]. In addition, unsteady cavitation models have recently demonstrated success in reproducing the periodic behaviors observed on isolated hydrofoils and hydrofoil cascades [5-6]. However, validation of these models, particularly in cryogenic rocket turbomachinery applications, has been extremely limited and, consequently, implementation by the rocket propulsion community has also been limited. Validation of these state-of-the-art methods through comparison of model predictions with high fidelity rig test data would substantiate these tools as a valuable resource for new turbopump development and anomaly resolution in fielded pump hardware.

Current capability to accurately model and predict cavitating turbopump instabilities and their impact on flight hardware is very limited. Consequently, cavitation related problems are often not encountered until late in propulsion system development testing or after deployment. System redesign efforts to address these issues can be extremely costly and result in significant program delays. As existing tools are incapable of accurately predicting unsteady cavitating flowfields, cavitation instability related issues are typically addressed through expensive and time consuming engine or turbopump test programs. Dedicated component test facilities are needed to evaluate cavitation environments early in the turbopump development process. The experimental characterization of turbopump cavitation instabilities and their impact on pumping system dynamics places stringent requirements on the test facility. Additional requirements are imposed by the desire to provide rapid, low cost, test capability with high fidelity dynamic instrumentation and optical access. These requirements can be met by a properly designed water-flow test loop.

The Aerospace Corporation has recently initiated a research program to investigate the physics governing cavitation instability phenomena encountered in cryogenic rocket turbopumps. The goals of this program are to: a) design and construct a dedicated turbopump cavitation test facility, b) investigate and experimentally characterize dynamic cavitation phenomena in turbopumps, and c) evaluate and validate cavitation models for rocket turbomachinery applications. The design of a closed-loop water flow test facility has been completed and The Aerospace Corporation’s cavitation test facility is now operational. The facility has the capability to accommodate a variety of test articles and simulate a wide range of operating conditions commonly encountered in rocket turbopumps. Close-coupled dynamic pressure instrumentation as well as optical access will facilitate identification of dynamic cavitation structures and characterization of the underlying physical mechanisms of inducer cavitation. This highly flexible water flow test loop will also be a valuable tool to support future testing and modeling of anomalous turbopump behavior and engine development as well as flow testing of other launch vehicle components such as valves and seals. Future efforts will include inducer testing to generate model validation data, benchmarking and validation of commercially available CFD cavitation models, and development of cavitation modeling tools applicable to rocket turbomachinery.

This paper presents the methodology used in the design of The Aerospace Corporation's new turbopump cavitation test facility. Key configuration and instrumentation requirements and the associated analyses necessary to achieve dynamic similarity to flight operating conditions are identified. Primary design considerations are given to the precise control of cavitation number, flow coefficient, and a thermal cavitation bubble growth parameter. Specific facility design aspects addressed include, structural support, inlet flow conditioning, feedline configuration, pump orientation, dissolved air content, fluid temperature control, and test instrumentation. The resulting facility design provides capability to investigate turbopump cavitation phenomena over a wide range of operating conditions to address issues ranging from pump performance degradation to inducer blade fatigue and pogo instability.

FACILITY DESIGN

The primary focus of The Aerospace Corporation's cavitation research program is the investigation of the fluid physics governing cavitation instability phenomena encountered in cryogenic rocket turbopumps. Of particular interest are the impact of fluid thermal properties on inducer cavitation behavior and the role of cavitation in propulsion system dynamics. Practical operational and economic considerations dictate that experiments be conducted in a facility using scaled turbopump models under scaled operating conditions which achieve proper fluid dynamic and thermal cavitation similarity. A closed-loop water flow test facility has been designed to achieve these aims and the test facility is now operational. The Aerospace Corporation's cavitation test facility design incorporates best practices identified from the review of United States and international facility designs and capabilities [7-10].

DESIGN OBJECTIVES

The specific design objectives for The Aerospace Corporation's cavitation test facility were derived from the goal to provide a capability to simulate flight turbopump operating conditions in an economical component test facility. The primary objective was to enable testing of actual or geometrically scaled flight engine turbomachinery in order to maintain the closest possible link to flight hardware. Sizing and capability requirements were derived to accommodate a variety of rocket turbopumps.

Water was selected as the facility working fluid for its simplicity, cost, and safety advantages. A cryogenic test facility, while providing maximum similarity to flight conditions, is excessively complex and expensive to design, build, and operate. Using water dramatically simplifies facility operation including instrumentation and optical access consistent with the goal to provide rapid turn-around, low cost pump component testing. Historically, water has been used in both research and pump manufacturers' facilities as a surrogate for cryogenic propellants in rocket turbopump test programs. Traditionally, in scaled water flow turbopump testing, it has been considered sufficient to match flow coefficient and cavitation number, which are the key fluid mechanical parameters for cavitation similarity. Strict Reynolds number scaling is deemed unnecessary in rocket turbopump testing as these pumps operate at very high speeds in the fully turbulent regime ($Re>10^6$) where Reynolds effects remain relatively constant. In addition to the two fluid mechanical parameters, cavitation physics are known to be impacted by the thermodynamic characteristics of the pump working fluid. Fluid thermal effects on cryogenic turbopump suction head requirements have been studied extensively by numerous researchers [11-15] and corrections based on these studies are routinely applied to water flow test results. Comparatively little research has been conducted on the impact of thermal effects on cavitation instability behavior [16-17], which is currently not well understood. To the author's knowledge, all research in this area has been conducted in facilities outside the United States. This gave rise to an objective to provide the capability to evaluate the suitability of water as a cryogen surrogate in cavitation instability studies. Capability to vary the test water temperature over a wide range provides the means to conduct thermal effects testing to meet this objective.

The characteristics of turbopump cavitation are governed by dimensionless cavitation scaling parameters. Traditionally, flow coefficient (ϕ) and cavitation number (σ) are employed for scaling of experiments from an engine to the test facility environment. These fluid mechanical parameters represent the pump operating conditions in terms of inducer inlet tip relative flow angle and the mechanical pressure balance on the surface of a vapor bubble located at the pump inlet. The parameters are defined

$$\phi = \frac{Q_{inlet}}{A_{inlet} V_{tip}} \tag{1}$$

$$\sigma = \frac{p_{inlet} - p_{vap}}{\frac{1}{2} \rho_{l,inlet} V_{tip}^2} \tag{2}$$

where Q_{inlet} is the inducer inlet volume flow rate, A_{inlet} is the flow area at the inducer inlet plane, $V_{tip} = R_{tip}\,\Omega$ is the speed of the inducer at the inlet tip radius R_{tip}, Ω is the pump rotational speed in radians per second, p_{inlet} is the static pressure at the inducer inlet plane, p_{vap} is the fluid vapor pressure at the inducer inlet conditions, and $\rho_{l,inlet}$ is the liquid density at the inducer inlet. To accurately simulate cavitation of a turbopump operating in the flight environment, the test article must be operated at values of cavitation number and flow coefficient equal to those experienced in flight. Thus, these parameters must be independently controllable over the entire flight range. The target range requirements of $\phi = 0.05$ to 0.11 and $\sigma = 0.015$ to 0.2 were established based on review of the typical operating ranges of rocket turbopumps.

Since the test facility will employ water as a surrogate for cryogenic propellants, matching of an additional dimensionless parameter is required to achieve dynamic similarity between the flight and test environments. A dimensionless parameter governing bubble growth and, hence, the cavitation volume in the inducer can be obtained by combining the asymptotic solution for bubble growth (see Ref. 18 for example), the thermodynamic Clapeyron relation, and the pump size and speed,

$$DB = R\Omega^{3/2}\frac{\rho_l^2 c_{pl} T\alpha^{1/2}}{\rho_g^2 h_{fg}^2} \qquad (3)$$

where the dimensionless parameter, DB, is defined in terms of the pump radius, R, and speed, Ω, as well as the thermodynamic properties of the liquid and gas phases. Brennen [18] has defined a single thermodynamic parameter that combines all of these properties into a single one. In Brennen's terms one may write

$$DB = \frac{R\Omega^{3/2}}{\Sigma} \qquad (4)$$

In which Σ is defined as

$$\Sigma = \frac{\rho_g^2 h_{fg}^2}{\rho_l^2 c_{p,l} T\alpha_l^{1/2}} \qquad (5)$$

In equation (5), ρ denotes the density, with the subscripts l and g distinguishing liquid from gas. The quantity h_{fg} is the heat of vaporization, $C_{p,l}$ the liquid specific heat, T the temperature, and α_l the liquid thermal diffusivity. Facility operating temperature range requirements were derived by examining the typical values of this bubble growth parameter for cryogenic rocket turbopumps. For a test impeller of fixed size, the value of the DB parameter can be varied via pump rotational speed and fluid temperature changes. For practical and safety considerations, the pump rotational speed will be limited to 5000 rpm. Figure 1 shows curves of attainable values of DB for a 76.2 mm (3 in) diameter test inducer operating in water as a function of water temperature and pump speed. Superimposed on these is a straight line indicating a typical value of DB for that same inducer operating in liquid oxygen under typical engine inlet conditions at nominal pump speed. Proper thermal scaling of the experiment can be achieved in water over the entire test pump speed range when the facility operating temperature range is approximately 43 to 121° C (110 to 250° F). It is interesting to note that the value of the DB parameter for ambient temperature testing at typical test pump speeds of 3000 to 5000 rpm is nearly four orders of magnitude greater than that for cryogenic liquid oxygen (or water at 121 C).

A desire to investigate the role of inducer cavitation in propulsion system dynamics gave rise to several additional facility design considerations. The first was a capability for variable feedline length to enable investigation of cavitation interaction with feedline dynamics important to pogo suppression. The second was a capability to measure cavitating pump dynamic transfer function that is instrumental to accurate pogo stability modeling. These would require the addition of a feedline accumulator to simulate a tank boundary condition in the feedline and flow fluctuators and unsteady flow measurements both upstream and downstream of the pump test article. Although these capabilities were not included in the current facility design, the test facility was designed to accommodate these future enhancements without requiring major modifications.

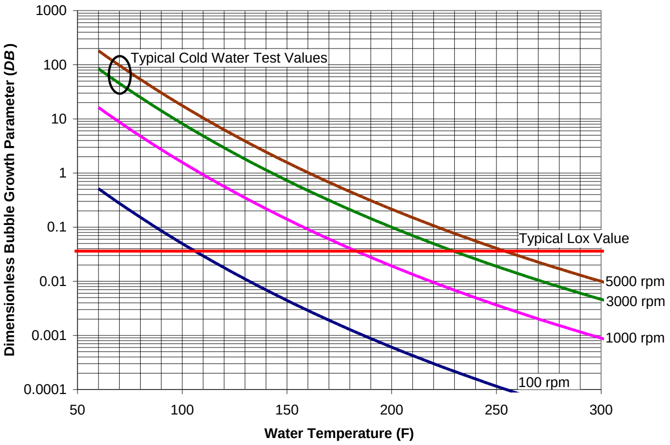

Figure 1: Dimensionless Bubble Growth Parameter Variation with Temperature and Speed (3" dia. pump inducer)

LAYOUT AND COMPONENT CHARACTERISTICS

The Aerospace Corporation's cavitation test facility, schematically depicted in Figure 2, is a closed, recirculating, water-flow loop consisting of a reservoir tank, pump test article, and suction and discharge piping with associated temperature, pressure, flowrate, and rotational speed controls. Water leaves the tank and enters the 6-inch diameter stainless steel piping system through a honeycomb inlet. After turning to the vertical direction, the flow passes through an inlet flow conditioning section before accelerating into a 1-meter straight vertical section of 76 mm diameter pipe that represents a propellant feedline. The water flows vertically upward through the feedline and subsequent inlet instrumentation section and enters the pump test article. A 76 mm diameter discharge line containing a flowmeter and terminated by a flow control valve returns the water from the pump outlet to the tank. A photograph of the facility is shown in Figure 3.

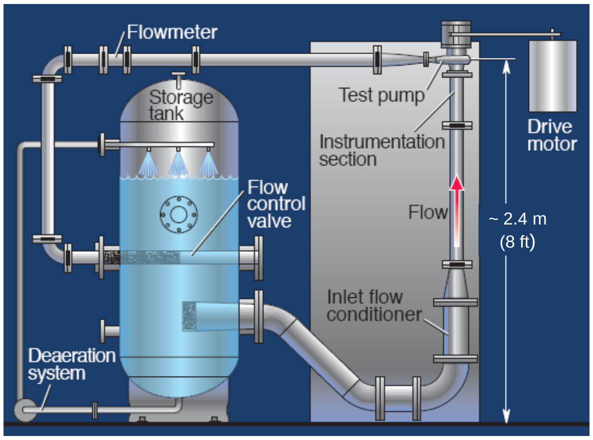

Figure 2: Cavitation Test Facility Schematic

Figure 3: Cavitation Test Facility

Facility water is held in an 830 L (220 gallon) stainless steel reservoir tank. The tank is a certified ASME boiler tank designed specifically for this application, capable of operating at elevated pressures and temperatures up to 1 MPa at 121°C (150 psi at 250° F) to accommodate the temperature range required to achieve thermal cavitation scaling. This tank also acts as a settling chamber for the resorbtion of recirculated vapor bubbles during facility operation. An over-pressure relief valve in the top of the tank limits the system to its maximum safe operating pressure.

The test pump located in the upper right corner of the facility schematic is the fundamental component of the test facility. The Aerospace Corporation’s cavitation test pump design shown in Figure 4 consists of 4 main subcomponents: 1) the rotor support system, 2) the test inducer and interface shaft, 3) the modular inlet, and 4) the universal pump discharge housing. The rotor support system consisting of the bearing box, main shaft, bearings, and seals, is based on the design of NASA Marshall’s Inducer Test Loop (ITL) bearing system. The Aerospace Corporation’s design uses the same proven bearing and seal hardware and bearing support design providing high confidence the system will meet design requirements. This robust rotor support system employs an axially preloaded, duplex, angular contact ball bearing design to provide the high radial bearing stiffness required to accommodate testing of a wide range of test inducers.

Rotordyamic analysis of the pump rotor support system was employed to ensure stable operation over the intended operating range. This analysis was used to predict the critical speeds of the pump rotating assembly (inducer, shaft, and bearings) to establish margin between the rotor first critical speed and the 5000 rpm maximum design operating speed of the pump. The analysis was performed conservatively assuming a rotor having twice the mass of the heaviest test article under consideration to provide additional margin. The predicted damped first critical speed of the rotor at 7540 rpm ensures that the rotor will operate subcritically with approximately 50 percent margin at the maximum operating speed.

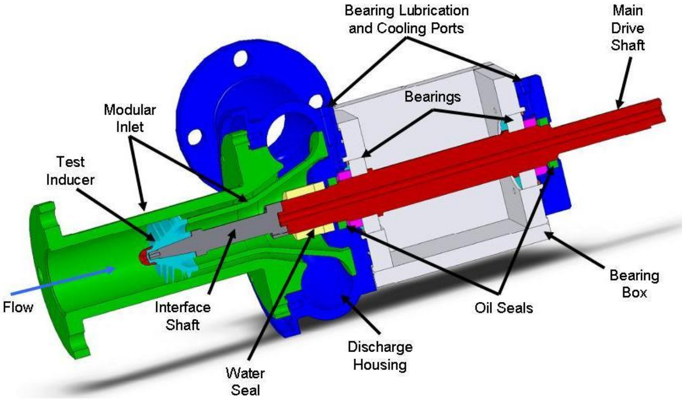

Figure 4: Solid Model of Cavitation Test Pump

The pump employs a modular shaft design in which the test inducer is coupled to the main drive shaft via an interface shaft. This facilitates the coupling of a wide variety of test inducers to the rotor support system without the need for costly and time consuming modification of the main drive shaft. An interface shaft can be designed for each individual test application enabling the facility to quickly and easily accommodate the inducer attachment designs of any test inducers which may be provided to The Aerospace Corporation for future testing. The length of the interface shaft and modular inlet hub extension may also be varied to modify the test inducer axial position as necessary to meet the rotordynamic requirements of future test articles.

The modular inlet design consists of the pump inlet instrumentation section and hub extension shown in green in Figure 3 above. The inlet instrumentation section directs the flow to the pump inlet, shrouds the test inducer, and couples the facility plumbing to the pump discharge housing. It will also house all the high frequency dynamic pressure and pump performance instrumentation (not shown). The hub extension forms the inner diameter of the annular inducer discharge and shrouds the rotating interface shaft from the pump discharge flow. The modular inlet design allows the inlet to be changed to accommodate different test inducers and/or different instrumentation configurations.

The pump discharge housing shown in blue in Figure 4 is a toroidal collector which provides a large discharge volume to collect the annular inducer discharge flow and direct it to the facility discharge plumbing. This universal fluid collector serves to isolate the pump from the downstream plumbing and accepts the modular inlet to complete this highly flexible cavitation test pump platform.

The inlet instrumentation section can be replaced by an outline interchangeable optical access housing to facilitate visualization of inducer cavitation. The optical access housing seen in the pump assembly shown in Figure 5 incorporates an acrylic housing section which extends one diameter upstream and downstream of the inducer blade leading edge. The simple annular acrylic section design was chosen to minimize replacement cost in the event of damage due to cavitation erosion or tip rub. The housing design captures the optically clear section between the flat faces of the inlet and discharge sections and employs 8 precision length struts to limit compression and accommodate axial thermal growth. Sealing is provided by o-rings in the inlet and discharge sections. Concentric alignment of the 3 sections of the optical inlet is achieved during assembly using an expanding mandrel.

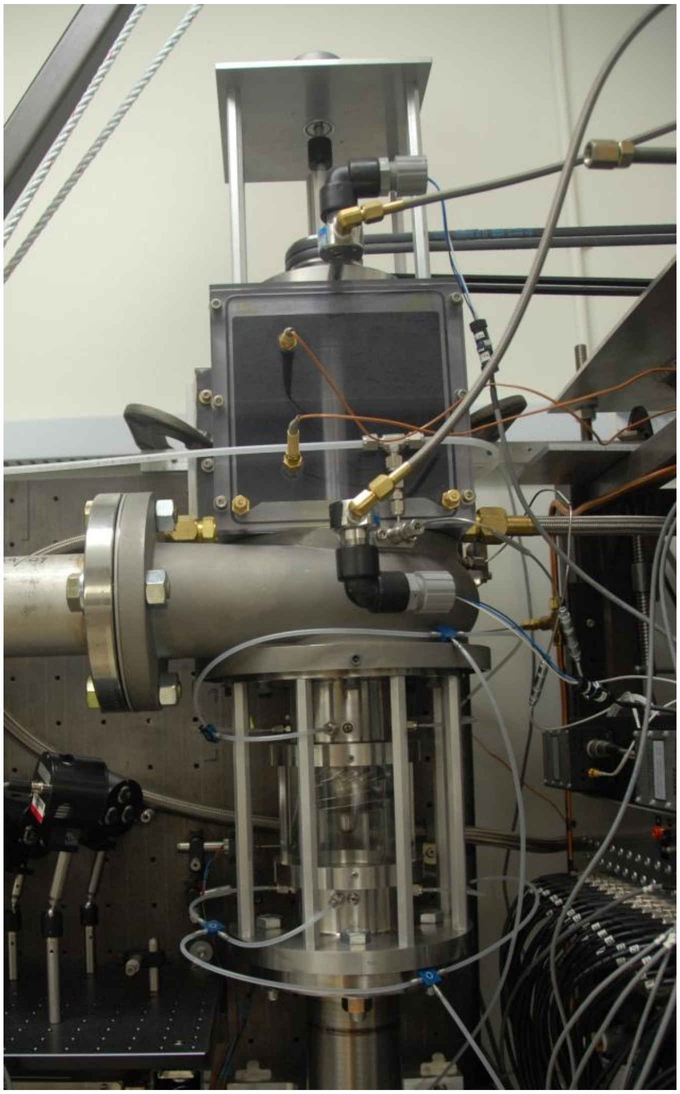

Figure 4: The Aerospace Corporation's Modular Test Pump Assembly with Optical Access Pump Housing

Water is circulated through the facility by the pump test article powered by a Marathon model Y547-A772 10 hp vector-duty AC drive motor with GS3-FB feedback module. The motor is coupled to the test pump via a pulley and drive belt system providing easy coupling to a variety of test articles. Pump speed is controlled to within 0.2% by a DuraPulse model GS3-4010 variable frequency drive. Variable speed control provides operating point selection flexibility and contributes to the available range of all three dimensionless scaling parameters. Maximum test pump operating speed will be limited to 5000 rpm for facility size, pump power consumption, and operational safety considerations.

Inlet flow conditioning is provided by a 305 mm (12 in) long, 152 mm (6 in) diameter section containing perforated plates, honeycomb flow straightener, and screens based on the design used by Ng [6]. This section removes flow disturbances introduced by the upstream piping and provides a uniform velocity field at the pump inlet.

System flowrate is controlled by a flow control valve specifically designed for this application and shown schematically in Figure 2 located in the tank at the end of the pump discharge line. When the facility is operated at constant temperature and pump rotational speed, the valve provides precise independent control of inducer inlet flow coefficient (ϕ).

System pressure is controlled by controlling the pressure of the ullage volume at the top of the reservoir tank. The ullage is purged with helium prior to system operation. The tank ullage can be connected to either a vacuum pump or a pressurized helium source. A control valve is then used to set and maintain the ullage pressure. When the facility is operated at constant temperature and pump rotational speed, this ullage pressure control system provides precise independent control of inducer inlet cavitation number (σ).

The Aerospace Corporation's cavitation test facility employs a unique vertical feedline piping configuration. As shown in Figure 2, the test pump is located at the top of a vertical feedline with the pump axis oriented in the vertical direction and flow entering in the upward direction. Although this significantly complicates facility construction and access to the test article, analysis indicates a significant advantage over the conventional horizontal feedline configuration for test pumps operated at subscale speeds. Test pumps in facilities employing horizontal feedline configurations are subject to a hydrostatically imposed inlet pressure gradient that manifests itself as a gradient in cavitation number across the pump inlet. The magnitude of the pressure gradient is typically small (on the order of several inches of water) and thus the effect on cavitation number is negligible under full-scale test conditions, amounting to only a few percent variation in cavitation number across the pump inlet face. However, when a test pump is operated at the subscale speeds often employed in scaled water testing, the impact on inlet cavitation number variation can become significant. The cavitation number dependence on the square of tip speed (see equation 2) has profound implications for reduced speed pump cavitation testing. The hydrostatic effect is illustrated in Figure 5 where the gradient in cavitation number ($\Delta\sigma = \sigma_{Top} - \sigma_{Bottom}$) from the top to the bottom of a horizontal feedline normalized by the centerline cavitation number (σ_{mean}) is plotted versus mean inlet cavitation number over a flight representative range for a series of scaled test pump speeds. A substantial gradient is clearly experienced by the rotating inducer blades when the pump is tested at relatively low scaled speeds. For example, testing a full-scale, 76 mm diameter inducer in water at a scaled speed of 3000 rpm would result in a cavitation number gradient magnitude that is approximately 26 percent of the inlet centerline cavitation number at a typical operating value of $\sigma_{mean} = 0.04$. The impact of this effect on cavitation inception and cavitation instabilities is unknown and casts considerable uncertainty on applicability of such subscale water test results to full-scale cryogenic operating conditions. The unique vertical feedline configuration employed in The Aerospace Corporation's test facility eliminates the hydrostatic pressure gradient across the inducer inlet thus eliminating this source of uncertainty. An additional advantage of locating the test pump at the top of a vertical feedline is that it enables operation at lower pump inlet pressures, avoiding cavitation in components upstream of the inducer inlet by placing the pump inlet at the point of minimum system pressure.

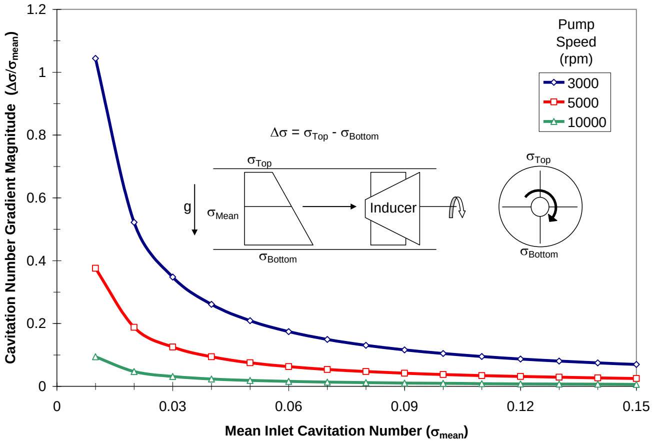

Figure 5: Hydrostatic inlet cavitation number gradient imposed by horizontal pump/feedline orientation at scaled test pump speeds.

Another important consideration in the design of the test facility is the design of the structure that supports the test pump and system plumbing. This is particularly important for a facility to be employed in the study of cavitation instabilities. The ideal support structure should have no structural vibration modes having frequencies in the anticipated frequency range of interest for cavitation instabilities. For inducers typical of modern turbopump designs, this frequency range extends from cavitation surge frequencies (0.4 – 0.5 Ω) to high order rotating and surge cavitation frequencies (~6 Ω). For the 5000 rpm design speed of The Aerospace Corporation test facility, this equates to a frequency range of approximately 30 – 500 Hz. To achieve this goal, The Aerospace Corporation's facility employs a unique support structure in which the pump and piping are mounted on a 1000 Kg (2200 lb) cast iron plate supported on a hinge cylinder and anchored to ground via a pair of vertical flexural beams as shown in Figure 6. This arrangement provides an extremely rigid support structure having all flexible mode structural frequencies well above the frequency range of interest for cavitation instabilities (>500 Hz). The hinged mounting arrangement in conjunction with the high system mass and tuned bending stiffness of the flexural support beams was designed to set the rigid body pitch and bounce mode frequencies of the support structure at approximately 2 Hz and 500 Hz respectively. Tap testing of the support structure after installation confirmed that the design provides a wide frequency range of separation between modes of the facility support structure and expected frequencies of cavitation instability modes that will be under study.

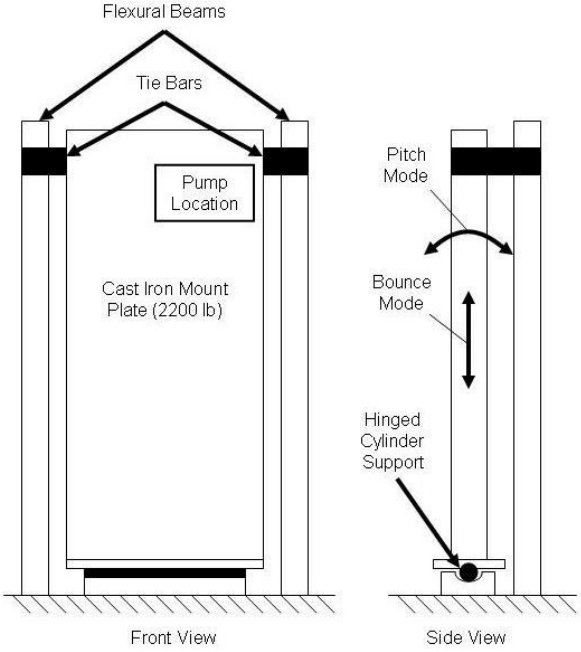

Figure 6: Cavitation Facility Support Structure Schematic

The facility test loop is supplemented by a number of auxiliary support systems. Cavitation phenomena are known to be highly sensitive to the concentration of dissolved gases in the pumped liquid. Previous experience has shown that variations in the concentration of dissolved noncondensibles in the working fluid of a cavitation test facility can have a dramatic impact on the cavitaiton behavior of the test article. The Aerospace Corporation's facility employs an in-tank helium sparging system to remove dissolved air from the facility water prior to testing. A sintered stainless steel helium bubbler inserted near the bottom of the reservoir tank is used to introduce small helium bubbles into the tank. Dissolved gases in the water diffuse into the rising helium bubbles and are transported into the tank ullage where they are removed via an ullage vent. Since the solubility of helium in water is negligible, the helium sparging effectively removes dissolved condensable gases from the facility working fluid. A Foxboro model 873 dissolved oxygen meter is used to monitor the concentration of dissolved gases remaining in the system. In this manner, the test fluid can be preconditioned to achieve a repeatable dissolved gas concentration.

The presence of contaminants in the working fluid in a cavitation test facility is also know to impact observe cavitation behavior. Small particles in the water can serve as nucleation sites for vapor bubble formation and impact the conditions under which cavitation inception occurs. An auxiliary filtration loop in The Aerospace Corporation's test facility employs a 1-micron bag filter unit to remove particles from the working fluid.

Finally, a combination of a 10 KW immersion and 2 KW externally wrapped electric resistance heater and their associated temperature controllers provide the capability to preheat and maintain the system water at temperatures up to 121° C (250° F) for elevated temperature testing. The selected combination of pump rotational speed and water temperature sets the value of the test dimensionless bubble growth parameter (*DB*).

UNCERTAINTY ANALYSIS

Measurement uncertainties directly impact the ability of the facility operating point to be precisely controlled. They also impact the relevance of conclusions drawn from both the comparison of tests conducted under varied conditions and the comparison of test data to model predictions. In addition to its obvious importance in qualifying the data recorded, uncertainty analysis can also be valuable when applied in the facility design process. Careful uncertainty analysis during the facility design phase can be used to support the selection of instrumentation and operating point control strategies. The design of a facility is often constrained by budget and scheduling limitations, and in practice overall accuracy must compete with other factors. Installation of the most accurate and expensive instruments possible will generally keep the uncertainties at a minimum, but such an approach is impractical. Uncertainty analysis facilitates informed design decisions that minimize uncertainty within the prescribed design limitations. Analysis across the entire range of operating points is critical in understanding the range of uncertainties that can be encountered as relative errors often change significantly based on facility operating conditions. The analysis, control, and documentation of experimental measurement uncertainty were considered critical in the design of this facility in light of the aim to provide data for the benchmarking and validation of cavitation modeling tools.

To facilitate the effective design of The Aerospace Corporation's cavitation test facility, an uncertainty analysis was conducted to quantify the impact of control and measurement uncertainties on the derived dimensionless parameters governing turbopump cavitation. The uncertainties in these parameters were derived by applying the uncertainty analysis method of Kline and McClintock [19] to the parameter definitions in equations (1) - (5). The resulting normalized uncertainties in flow coefficient, cavitation number, and thermal growth parameter are given by:

$$\frac{u_\phi}{\phi}=\left[\left(\frac{u_Q}{Q}\right)^2+\left(\frac{-u_A}{A_{inlet}}\right)^2+\left(\frac{-u_r}{r_{tip}}\right)^2+\left(\frac{-u_\Omega}{\Omega}\right)^2\right]^{1/2} \tag{6}$$

$$\frac{u_\sigma}{\sigma}=\left[\begin{array}{l}\left(\dfrac{u_{p_{in}}}{p_{inlet}-p_{vap}}\right)^2+\left(\dfrac{-u_{p_{vap}}}{p_{inlet}-p_{vap}}\right)^2\\+\left(\dfrac{-u_{\rho_{in}}}{\rho_{inlet}}\right)^2+\left(\dfrac{-2u_r}{r_{tip}}\right)^2+\left(\dfrac{-2u_\Omega}{\Omega}\right)^2\end{array}\right]^{1/2} \tag{7}$$

$$\frac{u_{DB}}{DB}=\left[\left(\frac{u_r}{r_{tip}}\right)^2+\left(\frac{3u_\Omega}{2\Omega}\right)^2+\left(\frac{-u_\Sigma}{\Sigma}\right)^2\right]^{1/2} \tag{8}$$

where

$$\frac{u_\Sigma}{\Sigma}=\left[\begin{array}{l}\left(\dfrac{2u_{\rho_g}}{\rho_g}\right)^2+\left(\dfrac{2u_{h_{fg}}}{h_{fg}}\right)^2+\left(\dfrac{-2u_{\rho_l}}{\rho_l}\right)^2\\+\left(\dfrac{-u_{C_{p,l}}}{C_{p,l}}\right)^2+\left(\dfrac{-u_{T_\infty}}{T}\right)^2+\left(\dfrac{-u_{\alpha_l}}{2\alpha_l}\right)^2\end{array}\right]^{1/2} \tag{9}$$

and u_x represents the measured or derived uncertainty in the quantity x. These equations define the dependence of the facility operating point control parameters on the experimentally measured flow parameters and fluid properties. Application of the equations over the entire facility operating range provided insight into the capability of the facility to accurately control and measure the cavitation scaling parameters. In addition, examination of the terms in each uncertainty expression provided the ability to rank the relative importance of individual measurement uncertainties. The results of these analyses were employed extensively in the design of the facility to identify the operating point control hardware and instrumentation accuracy requirements needed to simultaneously meet all facility design goals within the imposed constraints.

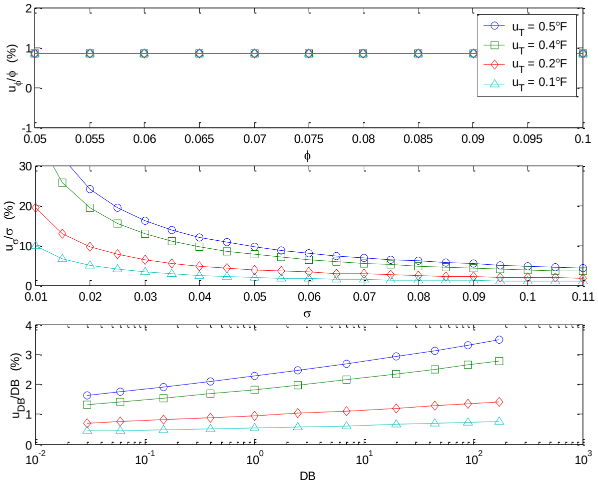

Figure 5 – Cavitation scaling parameter uncertainty analysis results – Effect of fluid temperature measurement uncertainty (Ω = 5000 rpm, T = 93.3°C)

Figure 5 shows the result of a typical parametric uncertainty analysis for the cavitation test facility. Normalized uncertainties in the three dimensionless scaling parameters are plotted over their respective ranges for representative values of measurement uncertainties. All measurement uncertainties are held constant except the temperature measurement uncertainty, u_T, which is varied between ±0.278 and 0.056°C (±0.5 and 0.1°F). The results illustrate the achievable range of scaling parameter uncertainties over the facility operating range as well as the sensitivity of these parameters to uncertainty in the fluid temperature measurement. The sensitivity of cavitation number uncertainty to fluid temperature measurement uncertainty at low cavitation numbers resulted in a requirement for a precision temperature measurement capability. A similar analysis of the impact of pump speed control uncertainty (results not shown) was conducted to select between two drive motor controllers having speed control capabilities of 0.2 and 0.01% of full scale speed. The analysis revealed that the substantially less expensive 0.2% controller was sufficient to achieve the desired scaling parameter control capability allowing allocation of funds to other facility components resulting in improved overall system performance.

INSTRUMENTATION

The test facility is equipped with a suite of instrumentation to accurately monitor and control the fluid mechanical and thermal dimensionless cavitation scaling parameters governing turbopump cavitation physics. Pump inlet pressure and head rise are measured with high accuracy (0.04%) Druck absolute and differential pressure transducers respectively. Due to the criticality of the accuracy of the inlet pressure measurement in the precise determination of cavitation number, both 35 and 100 KPa (5 and 15 psia) inlet pressure transducers are employed to maintain adequate accuracies over the entire cavitation number test range. Flowrate measurement is provided by a Foxboro model 8003 DC-pulse electromagnetic flowmeter positioned in the discharge line. This meter provides a non-invasive flowrate measurement with an accuracy of 0.25% of reading. Measurement of water temperature was determined to be critical to the accurate measurement and control of the cavitation scaling parameters due to the sensitivity of these parameters and the associated fluid saturation properties to temperature. Temperature measurement is provided by an Isotech Model TTI8-2 precision RTD thermometer with an accuracy of ±0.025°C. Pump rotational speed measurement as well as instantaneous rotor position will be provided by a BEI model H25 optical shaft encoder. The cavitation scaling parameters which control pump operating conditions are monitored and controlled in real time using a LabView software driven closed loop feedback computer control system.

A second suite of dynamic instrumentation is employed for the study of pump cavitation instabilities. For this purpose, the instrumentation section located immediately upstream of the pump inlet houses a circumferential array of dynamic pressure transducers. An array of eight equally spaced Entran model EPX-V inlet ring transducers immediately upstream of the inducer leading edge enables spatial-temporal domain analysis of inducer cavitation disturbances to identify the spatial structure and propagation of cavitation instabilities. These transducers were selected for their miniature size, flush diaphragm design, and capability to operate over the wide facility temperature range. Additional dynamic pressure transducers are employed in axial arrays in the pump suction and discharge lines to enable tracking of propagation of cavitation disturbances away from the pump. Data for all pressure transducers are acquired using a 32-channel, high-speed, simultaneous sampling data acquisition system based on National Instruments 8-channel S-series multifunction DAQ boards through SCXI-1125 isolation amplifiers and SCXI-1142 Bessel filters for signal conditioning.

The interchangeable optical access section provides visual access to the inducer inlet flowfield for cavitation structure visualization with high speed video. A Photron Fastcam-x 1024 PCI camera will be used to acquire high speed digital video of the cavitation structures for correlation to the pressure data. This camera in conjunction with a Visual Instrumentation high intensity LED lighting system will enable the acquisition of high speed video at 6000 frames per second at exposure times of 1 microsecond resulting in stop-motion imaging of inducer cavitation every 3 degrees of pump rotation.

OPERATIONAL ENVELOPE

A cavitation test facility has been designed to provide capability for testing a variety of flight derived turbopump hardware rapidly and economically in water while maintaining fluid dynamic and thermal cavitation similarity over their full range of flight operating conditions. The operating characteristics of the facility are summarized in Table 1. The facility provides independent control of flow coefficient and cavitation number over the ranges commonly encountered by rocket turbopumps. In addition, capability to operate over wide temperature and speed ranges allows for thermal cavitation scaling over a range that achieves thermal cavitation similarity with common space propellants. The facility will accommodate pumps consuming up to 7.5 KW (10 hp) with inducers up to 76 mm (3 in) in diameter.

Table 1: The Aerospace Corporation’s Cavitation Test Facility Operational Characteristics

Pump Rotational Speed	≤ 5000 rpm
Pump Power	≤ 7.5 KW (10 hp)
Pump Inducer Diameter	≤ 76 mm (3 in)
Suction Pressure	≥ 3.4 KPa (0.5 psia)
Discharge Pressure	≤ 1 MPa (150 psig)
Inducer Inlet Flow Coefficient	0.05 – 0.11
Cavitation Number	0.015 – 0.20
Fluid Temperature	15.5 - 121°C (60 - 250°F)

CONCLUSION

A new closed-loop water flow test facility has been designed and constructed at The Aerospace Corporation to investigate the physics governing cavitation instability phenomena encountered in cryogenic rocket turbopumps. The facility has the capability to accommodate a variety of test articles and simulate a wide range of operating conditions commonly encountered in rocket turbopumps. Close-coupled dynamic pressure instrumentation and optical access will facilitate the identification of dynamic cavitation structures and characterization of the underlying physical mechanisms of inducer cavitation. This highly flexible water-flow test loop will also be a valuable tool to support future testing and modeling of anomalous turbopump behavior and engine development as well as flow testing of other launch vehicle components such as valves and seals. The facility design process identified a fundamental shortcoming of previous scaled water flow test facilities and employs a unique vertical feedline configuration to overcome that deficiency. The test facility also provides capability to operate over a wide temperature range not currently available in the United States cavitation research community. This will enable a unique opportunity to investigate and quantify thermal effects on turbopump cavitation. Finally, the extensive use of uncertainty analysis in the design process enabled design decisions to minimize overall system measurement and control uncertainties within the prescribed program limitations providing maximum fidelity to the experimental data. The facility is now operational and will soon begin to provide data for benchmarking and validation of commercially available CFD cavitation models and development of cavitation modeling tools applicable to rocket turbomachinery.

FUTURE WORK

Testing in the new cavitation test facility at The Aerospace Corporation will focus on the generation of high fidelity data for the validation of computational fluid dynamic (CFD) modeling of cavitating liquid rocket turbopump inducers. The initial experimental effort will support CFD validation utilizing measurements obtained in the newly constructed test facility to quantify cavitating inducer performance in ambient temperature water. These ambient temperature tests will provide a simplified baseline case for future elevated temperature water testing which is believed to more closely simulate the behavior of cryogenic propellants by introducing thermal effects not present at ambient temperatures. These tests will also provide the opportunity for identification of dynamic cavitation structures and characterization of the underlying physical mechanisms of inducer cavitation instabilities.

In parallel with the development of the experimental facility, efforts at The Aerospace Corporation have been proceeding to enable the validation of computational fluid dynamics codes for cavitation modeling. A computational mesh for the initial test inducer has already been created for two commonly used commercial codes, CFX and Fluent. Although both codes' cavitation sub-models are based on Rayleigh-Plesset bubble growth, the differences in assumptions of growth rates and initial bubble formation combined with differences in the underlying fluid solvers will provide different predictions for pump performance. Comparison of the results to experimental data from the facility will yield insight for both users of computational models for cavitation and developers of future models. These simulations will also form a foundation for future enhancement of CFD cavitation modeling including more complicated effects, such as thermal suppression of cavitation and unsteady cavitation

Continued testing will then take advantage of the unique capability of The Aerospace Corporation cavitation test facility to operate at elevated water temperature to evaluate thermal effects on inducer cavitation. These efforts will asses the suitability of ambient temperature water as a surrogate fluid for cryogenic turbopump testing through detailed mapping of the impact of thermal effects on the structure, operating conditions, and strengths of cavitation instabilities over inducer operating ranges typically encountered under flight conditions. This will be accomplished through a series of tests spanning a range of water temperatures from ambient through elevated temperatures at which the thermal parameters governing cavitation bubble growth are similar to those of liquid oxygen.

NOMENCLATURE

A - flow area
C_p - specific heat
DB - dimensionless cavitation bubble growth parameter
h_{fg} - heat of vaporization
p - fluid static pressure
p_{vap} - fluid vapor pressure
Q - volume flow rate
R_{tip} - inducer tip radius
T – fluid temperature
u_x - measured or derived uncertainty in the quantity x
V_{tip} - velocity of the inducer at the inlet tip radius
α - thermal diffusivity
Ω - rotational speed in radians per second
ρ - fluid density
ϕ - flow coefficient
σ - cavitation number
Subscripts
g - gas
inlet – inducer inlet plane
l - liquid

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