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TURBOMACHINERY FLOW VISUALIZATION

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ABSTRACT

The primary goal of the turbo-machinery Flow Visualization project was to design and build and centrifugal pump with an optically clear housing that would allow the capture of high speed images of the internal flow. Also through an array of sensors and valves the characteristics of the pumps performance can be modified and recorded digitally for future analysis. Three subsystems were designed to meet the final goals, which are the pump (including the motor), fluid flow and storage system, and the controls system. Cast acrylic was chosen for the pump housing and impeller due to its optical properties that would facilitate the visualization. The pump was designed to be modular and separate from the drive motor, which makes changing the impeller blades easy for various laboratory experiments. The flow loop contains a flow meter, inlet pressure sensor, differential pressure sensor and an electrically controlled globe valve for simulating and recording various flow conditions. The entire system can be controlled through a LabVIEW graphical user interface. The following literature will highlight the design, build, testing, and results of the project.

INTRODUCTION

The field of rotary compression machines is for a large part mature in nature with extensive research done on many areas of gas and liquid pumping devices. Internal flows within these machines are generally understood and are often modeled using computers to determine their characteristics. This project will create a modular system capable of observing the internal flows of common existing centrifugal pump designs for the benefit of students of the Rochester Institute of Technology (RIT) as well as advanced research.

Observations will be done using Particle Image Velocimetry (PIV), which uses laser light to illuminate latex particles suspended in the pump medium. A high speed camera capable of capturing images at several thousand frames per second takes a brief video while the pump is running, which is then sent to a computer for analysis. The PIV software goes frame by frame and tracks each particle, using the relative distance moved and camera speed to determine the magnitude of motion at each area within the pump.

The Mechanical Engineering Department at the Rochester Institute of Technology is the primary customer, and was responsible for providing the design requirements for the final product. Dr. Steven Day of the mechanical engineering department was the customer representative along with being the project guide. The project was sponsored by Dresser Rand, one of the largest global suppliers of rotating equipment solutions, which designs, manufactures and services a wide range of technologically advanced centrifugal and reciprocating compressors, steam and gas turbines, expanders, multiphase turbine separators, portable ventilators, and control systems.[1] Dresser-Rand is interested in forming a strong relationship with RIT to increase awareness of opportunities for employment among new graduates as well as knowledge of their products and services through the Multi-disciplinary Senior Design program.

NOMENCLATURE

CAD – Computer Aided Design. Allows the creation of part and system models in a virtual space to analyze design features and assist in part fabrication.

Cast Acrylic – A polymer with optical clarity comparable to glass but much higher strength.

CNC – (computer numerical control) refers specifically to a computer "controller" that reads instructions and drives a machine tool powered mechanical device typically used to fabricate components by the selective removal of material. CNC does numerically directed interpolation of a cutting tool in the work envelope of a machine. The operating parameters of the CNC can be altered via a software load program.[5]

Concentricity – Quality of having a common center or axis

Cylindricity – The quality or condition of being cylindrical.

Open Impeller Configuration

Particle Image Velocimetry (PIV) – A system used to determine velocities of flow within a 2d area utilizing a laser, high speed camera and computer software.

Rapid Prototyping – Often called 3D printing, parts are built layer by layer from CAD models. The resulting parts are semi-functional and have varying attributes. Parts can be created economically and much faster than traditional machining.

Refractive Index – A ratio of the speed of light through different mediums. Responsible for distortion when observing two different mediums from an angle, e.g. water and air.

Stereo Lithography (SLA) – a form of rapid prototyping in which a layer of liquid resin is hardened by a laser. The part descends an incremental amount below the liquid surface and the next layer is hardened on top of it.

SYSTEM DESIGN METHODOLOGY

The primary goal of the project was to create a closed loop system capable of interfacing with a user via a Labview interface which will be easily adaptable to potential PIV setups. This system was broken into three main divisions; the pump subsystem, the external flow loop, and controls and measurement.

PUMP SUBSYSTEM

Design of the pump subsystem began with an analysis of the possible alternatives from a mechanical perspective. The specific configuration of the pump was a primary concern and system reliability, modularity, effectiveness, clarity, and parts cost were considered

A front inlet, rear shaft, open impeller configuration was determined to be optimal. This approach requires a loss of effective visual area due to the inlet being between the camera and plane of interest totaling 10.3%. See fig 1 below.

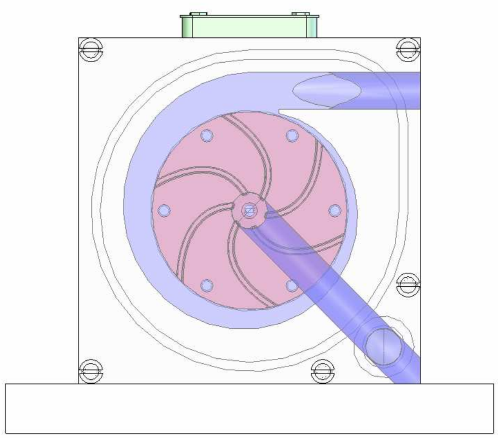

Figure 1: Front view of the housing showing the volute (light blue), and the interfering inlet (dark blue).

This configuration uses fewer custom machined parts and allows for increased system modularity. When the system is not operating, the impeller can be accessed by removing the 5 screws which attach the front housing to rear housing. The front housing swings forward on its flexible outlet tube and the impeller can then be changed with another of the same depth and diameter. To maximize modularity, the volute is built into the front housing, so changing the impeller depth or volute geometry only requires replacing the front housing. Should higher speeds be required, the motor can be replaced easily simply by loosening the shaft coupling and the 6 screws holding it to the base plate.

Impeller diameter is not interchangeable without rebuilding the entire system. Documentation to do so is included however.

The entire system including the motor, pump housing and the connecting shaft are mounted on a 10" wide 1" thick aluminum plate which will extend beyond the front of the housing and serve as a mounting point for the high speed camera. The plate's thickness will reduce motor related vibrations which may impair the ability of the camera to capture a stable image. See fig 2 below. To additionally increase the stiffness, the plate will be rigidly mounted to the system's cart.

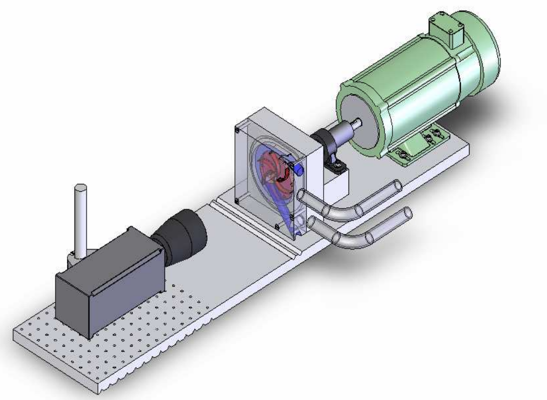

Figure 2: View of the pump subsystem showing the camera, housing, and motor.

The housing and motor are connected by a custom shaft supported radially by two mounted bearings that are carefully aligned during initial installation. This shaft has a rotary shaft seal separating the pump's internal components and the support system. It is connected to the motor with a flexible shaft coupling that takes up both angular and radial misalignment, sufficiently reducing any additional radial loads.

<u>Pump Subsystem – Optical</u>

The front housing required sufficient clarity to allow high resolution images of the flow to be captured with minimal distortion and interference. Material selection for this piece was based largely on machinability, optical clarity, and refractive index. While refractive index does not matter for viewing perpendicular to the face, distortion occurs when observing from an angle. This distortion can be minimized by limiting the difference in refractive indices at each boundary. While no clear solids have a refractive index close to that of air (RI 1.0003), the solid-liquid boundary can be closely matched.

As a general rule, liquids have a lower refractive index than solids, typically between 1.25 and 1.65 [2]. Solids are generally between 1.5 and 2.5 [3]. Liquids generally become more volatile with increasing RI and solids become more brittle with decreasing RI. A suitable pair that shows some notable distortion with full 3D shapes is glycerin and cast acrylic at 1.47 and

1.49 respectively. Due to the flat nature of our current impeller, the system will be filled with water (RI 1.33) as there are no curved geometries that will affect the viewing area. Should a user wish to use more complex geometries, a change to glycerin would be recommended.

To accommodate the PIV system, a breadboard was built at the end of the mounting plate with ¼-20 threads at 1 inch increments. This allows movement of the camera to focus on different areas within the pump. The laser will be introduced as a two dimensional vertical sheet from the side, through the front housing and into the volute and impeller (which protrudes into the volute space).

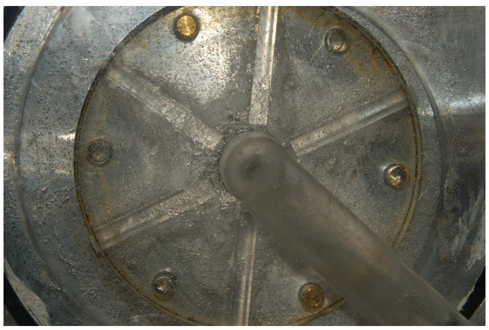

Figure 3: View of optically clear pump housing (at 1700 rpm) and results that can be achieved with a high speed camera

Pump Subsystem – Performance

Major factors in the performance of any centrifugal pump are the impeller diameter, rotational velocity, impeller and volute geometry, impeller depth, and the piping leading to and from the pump.

Because the camera that will be used with the system is only capable of recording 2000 frames per second, typical pumps which operate at speeds of roughly 3500 RPMs would only produce 34.5 frames per rotation or roughly one frame every 10 degrees. This could cause difficulties in the computer analysis if particles have moved too far between one frame and the next. To avoid this, a motor designed to operate at 1750 RPMs was chosen, resulting in almost 69 frames per rotation, or approximately one shot every 5 degrees at max speed.

Due to the nature of the project, to design a modular system capable of testing alternative geometries, no new pump designs were considered. Impeller and volute geometry were taken as much as possible from existing commercial designs, although the modular nature of the project limited volute and impeller geometries to two dimensional options, at least on the rear housing face. Pump performance curves for a commercially available pump of appropriate size (Grainger Part #4TE49) were scaled down to lower speeds based on Equation 1 below [4].

$$\frac{\Delta p_1}{\Delta p_2} = \left(\frac{n_1}{n_2}\right)^2$$

Equation 1: n = speed in RPMs

An optimal recreation of the design should produce roughly 5.5 psi of differential pressure at maximum system restriction and a flow rate of 40 gallons per minute at minimal restriction.

FLOW LOOP AND RESERVOIR:

The flow loop was constructed of standard schedule 40 PVC pipe. For optical clarity, key points along the flow loop were made with a clear PVC to aid in troubleshooting and cavitation visualization. The layout of the flow loop is primarily focused on achieving the goal of packaging all of the instrumentation in a manor of least possible restriction. Pipes used were kept to a consistent ¾" Schedule 40 diameter. This was maintained throughout the flow loop to achieve consistent readings throughout the instruments. However, to reduce the amount of inherent head loss caused by narrow diameter pipe, the size was increased to 1.5" once all of the instrumentation was accounted for.

The flow loop has been designed from the ground up to be used both as an automated system and as a manually operated system. This requires the motor control module to be mounted to the cart. Despite losing the Labview interface, functionality remains intact. Extra ports were added to allow for manual gauges to be installed to take measurements of the pressure differential of the pump. This is accompanied by a variety of manual valves that can restrict the flow either before or after the pump. This results in full capability to induce cavitation and stagnation pressure.

Due to the mobile test stand nature of this device, packaging was of utmost concern. Therefore, all of the instrumentation and piping was affixed to the top of the cart, above the water level of the tank. This made for a system that required active priming. This was accomplished by the use of a dedicated prime pump, which, through a system of valves, is used to prime the pump before operation. Afterwards, once the main pump has reached operating condition, the priming system can be isolated from the main pumping loop with the closing of the valves.

CONTROL SYSTEM:

The control system of the Turbomachinery Flow Visualization utilizes a variety of sensors in conjunction with a LabVIEW interface. This was engineered such that the operator can easily modify flow parameters on the fly and easily draw conclusions based on sensor output.
All sensors, the motor controller, and restrictor valve are tied into a central data acquisition unit manufactured by National Instruments. This DAQ is the brain where all inputs and outputs are interfaced from.

PX-81 Differential Pressure Transducer, Omega Engineering

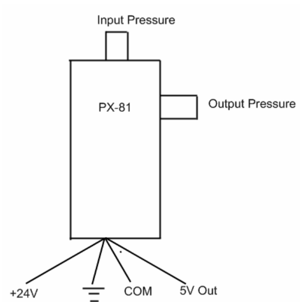

Figure 4: Wiring Diagram on PX-81

The PX-81 Differential Pressure transducer measures the difference in pressures between two pressure inputs. In the Test Stands setup, input and output pressure from the pump is measured. The specific sensor chosen has a range of 20psi which directly correlated to the output voltage of 0-5V. For example, a sensor output of 3.27V would be interpreted as 13.08psi.

PX-209 Gauge Pressure Transducer, Omega Engineering

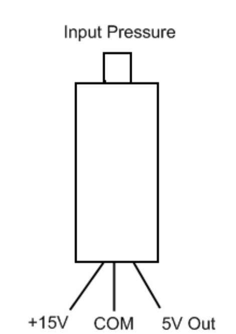

Figure 3: Wiring Diagram of PX-209

The PX-209 Gauge Pressure transducer measures the gauge pressure relative to atmospheric pressure. In the Test Stand, the sensor is tied into the pumps output pressure. Originally designed to measure the input pressure, it was determined that the inlet pressure was below atmosphere, and thus below the 0-30psi range of the gauge pressure sensor. This sensor also utilizes an output of 0-5V which directly correlates to a distinct pressure between 0 and 30psi.

FP7002 Paddle Wheel Flow Sensor, w/ Temperature Output, Omega Engineering

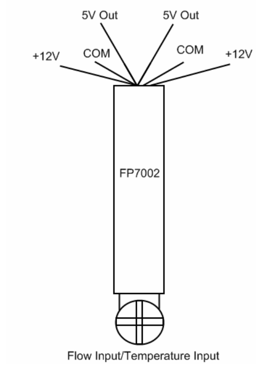

Figure 4: Wiring Diagram of FP7002

The FP7002 Paddlewheel Flow and Temperature Sensor are used to monitor volumetric flow rate and fluid temperature during pump operation. Natively, each sensor outputs a 4-20mA signal, therefore, in order to convert this to a voltage output, a Bridge Resistance of 250Ω must be added in parallel with the 5V signal and common wires on the DAQ. Consequently, the voltage reading is now between 1-5V for both temperature and flow rate, not 0-5V. Flow rate is directly proportional to 1-5V on a scale of 0-30 gallons per minute. Likewise, fluid temperature is directly proportional to 1-5V on a scale of 0°-100°C (32°-212°F). It is critical for this sensor to be placed in an area that exhibits fully developed flow; otherwise any obtained reading would be suspect. As a general rule for this particular sensor, it should be placed no closer than 15 diameters of pipe diameter from any upstream obstruction and no closer than 5 diameters from any downstream obstruction.

DC Motor Controller, Dart Controls

An advanced microcontroller purchased from Dart Controls is used in maintaining a user specified motor RPM from feedback from a Hall-Effect tachometer attached to the motors shaft. This RPM specification can be made directly on the auxiliary unit, or from the LabVIEW User Interface and sent via RS-232 communication

VA-4322-GG2 Electric Valve Actuator, Johnson Controls

The Electric Valve Actuator purchased from Johnson Controls allows the use to restrict the fluid flow out of the pump proportional to a voltage output from the

DAQ. An adjustable slider on the GUI allows the user to keep the valve fully-open or to restrict the valve on a scale of 0-3V. 3V does not completely close the valve as a safety feature as to not overload the pump components with extreme internal pressure.

FABRICATION / TOLERANCING CHALLENGES:

Open impeller configurations require tight tolerances to be effective or too much of the pump median will simply flow back into the inlet. This poses unique problems from a machining point of view. Because of the tight tolerances, a majority of the parts required the use of CNC (Computer Numerical Controlled) Machining.

Materials used for the large system components were primarily 6061 series aluminum and 304 series stainless steel due to their corrosion resistance and machinability.

To choose the method of manufacturing, the tolerances would have to be taken into consideration. Rotating assemblies require special consideration to concentricity, symmetry and cylindricity. Combined with the limited number of machines available that were capable of producing the required results, we chose to use CNC machines to produce interpolated cylindrical bores rather than a traditional boring process.

Due to difficulty of manufacture, the original set screw design for the impeller mounting plate proved to be impossible. Therefore, an interference press fit was used, requiring a hydraulic press to attach the shaft to the impeller mounting plate. Serviceability was maintained with the use of a threaded hole in the mounting plate that can remove the plate with a jack screw if desired.

The front housing posed a sizable threat to manufacturability due to the complex nature of the volute curve, the deep inlet and outlet holes that were drilled at angles in brittle material, and the need to maintain an optically clear surface for the visualization. The last problem was difficult because machining acrylic causes a loss of optical clarity. This can be corrected by a chemical polish, but they won't be as clear as the edges are when they arrive from the factory. This was resolved by making the one part from two separate pieces of acrylic and then chemically fusing them together, so the acrylic-water boundary was at a factory edge.

RESULTS AND DISCUSSION

Results from initial test runs showed a significantly lower flow rate than expected, while actually exceeding the Change in pressure.

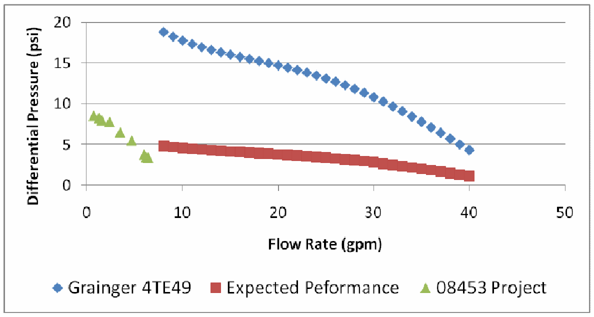

Figure X: Pump Performance Curves

This is likely due to the many variations in geometry that were necessary to construct such a modular pump. By modifying the impellers to a curved blade geometry to more closely mimic the Grainger pump, we would likely extend our flow-rate while reducing our pressures. The specifications for flow-rate and differential pressure were not achieved due to an overaggressive stance when providing initial figures. The pump does however operate effectively below these figures and will still be an invaluable tool for teaching upcoming engineering students.

The motor speed control was proven through the use of a tachometer mounted to the back of the system. The closed loop nature of the controls allows for effective feedback to ensure proper speeds. As a precaution, the tachometer was monitored during runs at different speeds through the labview interface to record the number of revolutions during 1 minute. These numbers had an average error of 2 RPMs, with a max deviation of 6 RPMs, very close to our spec of +/- 5 RPMs.

Many of the specifications regarding measurement accuracy and the labview interface were achieved easily with the proper selection of sensors, and the optical clarity of the cast acrylic was proven using the material property and approval from the client.

CONCLUSIONS AND RECOMMENDATIONS

The project was successful in creating a test-bed system to be used for experiments and research by the RIT engineering community. There are several options to improve upon the design should the time become available.

To more accurately measure the differential pressure, the flow-loop could be modified. It currently has 5 right angles and 3 fittings in between the differential pressure sensors two leads. This leads to head loss (pressure loss), so the values we see in testing are actually lower than what the pump is producing. By modifying the flow loop so that the differential pressure sensor is the first thing to take measurements, some of the head loss may be limited. Removing 2 of the right angles is possible, but would not be easy due to the positioning on the cart.

The pump subsystem would benefit greatly from a set of interchangeable impellers, which due to time constraints were not provided with this project. Due to the design, the impellers (and front housings if different volute geometries are desired) may be machined out of cast acrylic with drawings provided, or rapid prototyped using 3d modeling and service bureaus. The latter process is fairly cheap ($200-$300 for a new impeller blade), and can have results within 2 days.

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