Monitoring High Pressure Water Flow in a Waterjet Cutting System

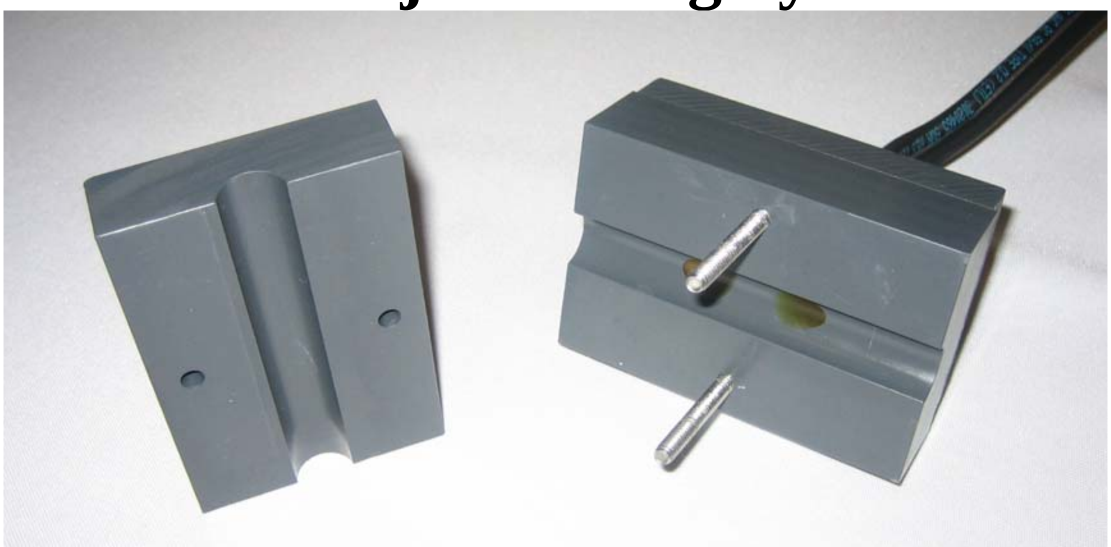

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Table of Contents

Abstract
KMT Robotic Solutions Inc. manufactures waterjet cutting systems. The systems use ultra high pressure water (up to 60,000 psi) flowing through tubing on a robotic arm. The flow of ultra high pressure water is regulated using a valve. Water exits this valve through a small orifice (usually .008") at high pressure, thereby cutting material. Problems with leaks, and contaminants in the orifice lead to reduced flow rates causing missed cuts. The purpose of this project was to create a system to indicate when the flow rate is not within a desired range. This report details our efforts in this regard.

Introduction
KMT Robotic Solutions wants our team to design a flow monitoring system for their waterjet cutters. The waterjet cutters produced by KMT use high pressure water between 30,000 to 60,000-psi in conjunction with a robotic arm to manufacture a variety of items and are often used in the manufacture of automobile parts. KMT wants a flow monitoring system suitable for a high-pressure environment that can accurately detect if the flow-rate is within acceptable limits during a cutting operation and signals the computer system whenever the flow-rate is within the acceptable, user-defined range.

During the cutting process, the high-pressure flow of water is turned on and off repeatedly and typically makes many cuts into a single part. Currently, a water pressure monitor, in conjunction with an intensifier pump, ensures that the ideal pressure levels are maintained. However, on occasion, an insufficient amount of water will flow out of the orifice due to blockage of the nozzle or leakage in the high pressure line. This results in the water jet cutter occasionally missing a cut. This results in a lower quality level for parts shipments, which is not ideal. The introduction of a flow monitoring system on the waterjet cutters would prevent this occurrence and increase the quality of parts manufactured using KMT’s product. KMT believes that this flow monitoring system would be a very popular addition to their waterjet cutters.

Information Search
We performed an information search on the internet in order to find the technologies that currently exist for measuring fluid flow rates in high pressure environments. An explanation of some of the major flow rate metering technologies researched can be found on the following page, with information from reference 1.

A patent search was also undertaken. The patent search found an electromagnetic flow meter designed for a high-pressure environment. The patent does not specify how high a pressure this device could withstand, but the architecture, with the magnetic field generated inside the tubing, made us hopeful that the electromagnetic flow meter could be modified to accommodate the high pressure environment we had to consider.

A search of Thomas Register and flow meter manufacturers resulted in two available flow meter technologies that are rated to run at 60,000-psi. The first is a thermal-type mass flow meter, and the second is turbine-type volume flow meter.

Several handbooks and textbooks were used to give us a deeper understanding of the operation and design guidelines for existing flow meter types. The textbooks did not detail methods for producing a high pressure flow meter, however.

A search on Google scholar and ISI Web of Knowledge was undertaken to first determine if a flow meter was developed for waterjet cutting research. This search provided useful insight into the behavior of the waterjet cutters, but it did not yield any information on existing technologies.

MAGNETIC FLOW METER A magnetic flow measures flow-rates by measuring the voltage difference induced between a set length of tubing when a magnetic field is applied to the fluid. The voltage difference induced when a conductor moves through a magnetic field is proportional to the velocity of the conductor, according to Faraday's Law. This allows the magnetic flow meter to be calibrated to measure the flow velocity of a conducting fluid. In our case, waterjet cutters use tap water as the working fluid, which works as a conducting fluid for the magnetic flow meter.

This method is non-invasive, does not create a significant drop in pressure, is not significantly affected by pressure, and can be placed close to the base of the machine. This method has potential problems, however. The flow-rates seen in water jet cutters are very small and pipe itself is relatively thick. Low flow magnetic flow meters can read down to 0.1-gpm, but it is not known if that accuracy can be achieved in the thick piping needed for our application. Additionally, the conductivity of tap water is likely to be variable which could affect the accuracy of the flow meter especially at such low flow rates.

Overall, a magnetic type flow meter has good properties for our application, but it is questionable whether it will be accurate enough in our application.

MASS GAS FLOWMETER Thermal mass flow meters operate with an insignificant dependence on density, pressure, and fluid viscosity. Rather, they use either a differential pressure transducer and temperature sensor or a heated sensing element and thermodynamic heat conduction to determine mass flow rate.

Potential problems with this technology are that it is invasive and has a dependence on temperature. Due to the strong dependence on temperature, accuracy may be an issue in particular applications of the device. Furthermore, using heat conduction requires a specific type of tubing that may not be able to withstand pressures of 50,000-60,000 psi.

Overall, this application may not be suitable because of accuracy related issues and because it is invasive.

ULTRASONIC FLOWMETER Ultrasonic flow meters are used in dirty applications such as waste water and other fluids which typically cause damage to standard sensors. This sensor operates under the Doppler Effect of an ultrasonic signal when reflected by particles or gas bubbles. This technology utilizes sound waves that change frequency when reflected by moving discontinuities in flowing liquids. By sending ultrasonic sound into a pipe with flowing liquid, the discontinuities reflect the ultrasonic waves at a different frequency that is directly proportional to the rate of flow. Current technology mandates that the liquid contain at least 25 to 30 PPM (parts per million).

This technology is non-invasive, not affected by pressure or temperature, and can be placed close to the base of the waterjet cutter. Potential problems with this technology are the particles in the fluid possibly blocking the orifice or the amount of the particles in the water affecting the cut.

Overall, this application may be possible if the two possible scenarios listed above are avoided.

VARIABLE AREA FLOW METER A variable area flow meter measures the flow-rate by measuring the displacement of a flexibly attached obstruction placed in the flow. As the fluid moves, a greater pressure differential is developed before and after the piston, which acts like an orifice. The orifice is aligned with a cone such that the orifice size increases with greater flow-rate. The piston is attached by use of a spring which stretches under the greater pressure differential, giving the flow rate of the fluid. Alternatively, a spring-loaded vane can be used in a similar fashion.

This is a popular type of flow meter and can be made cheaply. The flow meter, however, is invasive, which will cause some trouble with the connection of the flow meter to the pipe line. Additionally, our application sees significant fluctuations of pressure which may affect the accuracy of such a flow meter. It also may be difficult to make such a flow meter at the low flow rates seen.

A variable area flow meter is not well suited to our high pressure application. Such a flow meter is invasive and may not be feasible for the environment seen in waterjet cutters.

Customer Requirements and Engineering Specifications

To get a clear understanding of the customer requirements, we organized all the information at hand in to a Quality Function Deployment (QFD), as seen in Appendix A on page 24.

CUSTOMER REQUIREMENTS Waterjet cutters are used in various industries in order to make precision cuts in parts. A high pressure jet of water (30,000 to 60,000-psi) is used to make the cuts. Because the flow rate of water is quite low (0.18 to 1.1-gpm), the process can be considered dry. Waterjet cutting is used in mass production of parts, so a highly reliable system is sought. Currently, there are no reliable means of identifying times when water is flowing out of the nozzle. This leads to quality issues, because any debris in the nozzle leads to lowered water flow rate and therefore, an incorrect or missed cut.

KMT RPT wants us to design a flow meter that can reliably provide flow data at high pressures. The solution should be such that it provides the robot’s computer a signal whenever the flow rate is within the user-defined range. It should be easy to calibrate, because each cutter is used to cut a different part, each with its own flow rate requirements.

Due to the high pressures encountered, there is a probability that debris might damage the flow meter if it is placed close to the nozzle. Therefore, the flow meter should be such that it can accurately measure the flow rate at a downstream location, as far away from the nozzle as possible.

Thirdly, the system should be as non-invasive as possible. This will enable the installation to be lower cost and will potentially make the system more reliable than if it were invasive.

ENGINEERING SPECIFICATIONS The main deliverable of our design is an electrical output signal whenever the water flow rate out of the nozzle is within a user-defined range. KMT's existing models have flow rates ranging from 0.18 gal/min to over 1.1 gal/min. Since each machine is customized for the part it will work on, we considered it unnecessary to include this range as an engineering specification, because it would not take into account future models. We determined, further, that data should be measured at least with a frequency of 10Hz, because the system might be used in conjunction with computer software, to automatically control the machine as required. Therefore, we believe that a frequency of 10Hz is adequate. Also, we adjudged that the accuracy of the system should be at least 1%, which will account for any major changes in flow rates.

ORGANIZATION OF QFD To create a QFD, included as appendix A, we listed our customer requirements in detail. We assigned a weight, or relative importance, to each requirement. We then listed potential solutions for all customer requirements and listed these in the upper columns of the QFD, while the customer requirements and their corresponding "weights" were listed on the left most columns.

As a group, we assigned a rating of either 0 (no relationship), 1 (small relationship), 3(medium relationship) or 9(big relationship) to the various factors, in the central matrix. Each rating was discussed, and a consensus rating was assigned.

The upper roof of the matrix relates the potential correlations to each other. Entries were given either a strong positive relationship (++), medium positive relationship (+), medium negative relationship (-) or strong negative relationship (--) rating. A positive rating denoted a positive correlation whereas a negative rating denoted a negative correlation. When no correlation was identified, the entry was left blank.

Concept Generation

The first step in concept generation was to identify the functions necessary to allow for a signal to be sent to the operator when the flow rate is not within the desired range. To perform this task we created a FAST diagram, which is attached as Appendix C. The basic functions that the flow meter will have to have are; handling high pressures up to 60,000 psi, measuring the flow rate, creating an electronic signal, and not interfering with the production of the machine. Subsidiary functions necessary are; checking if the flow rate measured is within the given range, transmitting the electronic signal, and lighting up a green light if within the range or a red light if not within the range. If our device has these functions we should be able to eliminate the missed cuts that are currently happening.

Keeping these functions in mind, we did extensive research by means of the Internet, various handbooks and published papers. Our key resources in the initial stages were our own past knowledge and ideas, various specialty websites on the topic of flow metering, and our client's own ideas. Below are listed some of our initial concepts for measurement of water flow at ultra-high pressures. From these initial concepts we were able to construct a morphological chart, attached as Appendix D, which characterized important sub-functions of our project. After careful scrutiny we were able to narrow our concepts to three viable options.

DOPPLER ULTRASOUND This system will involve a transmitter and receiver, suitably attached to a section of piping. The transmitter will transmit an ultrasound wavelength wave which will bounce off of water impurities and air bubbles before being received by the receiver. By analyzing the frequency shift of the signal, we can program the system to accurately measure the flow-rate of water. A schematic detailing this idea is shown in figure 1.

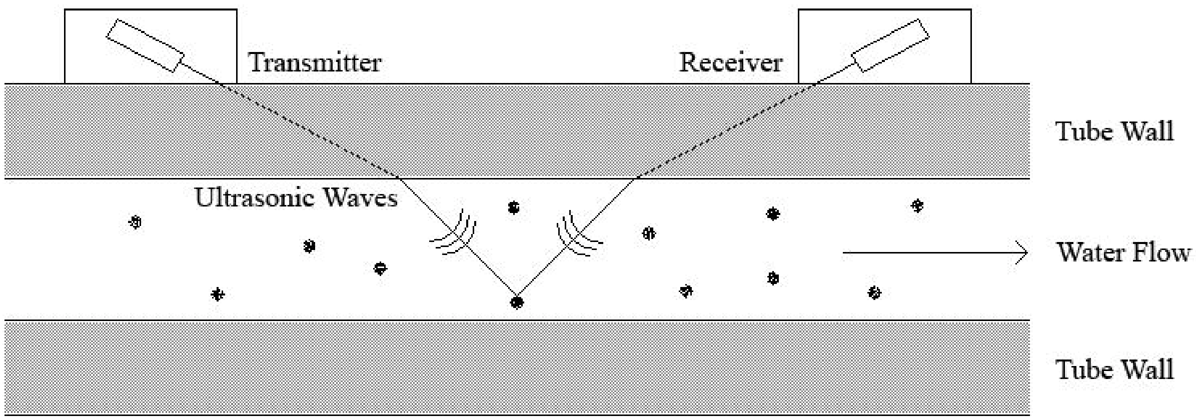

Figure 1: A schematic of the Doppler Ultrasound System

TRANSIT TIME ULTRASOUND This system involves two transmitter/receivers. One transmitter/receiver will be place further down stream of the first transmitter/receiver. The first transmitter/receiver transmits a signal at some angle relative to the pipe's axis. The wave reflects on the interface between the water and the pipe and is eventually received by the second transmitter/receiver. This station then sends another signal back to the first transmitter/receiver. From the time delays between the upstream and downstream receivers, the system can determine the speed of the flowing water without knowledge of the speed of sound in the water. A schematic detailing this idea is shown in figure 2, on the following page.

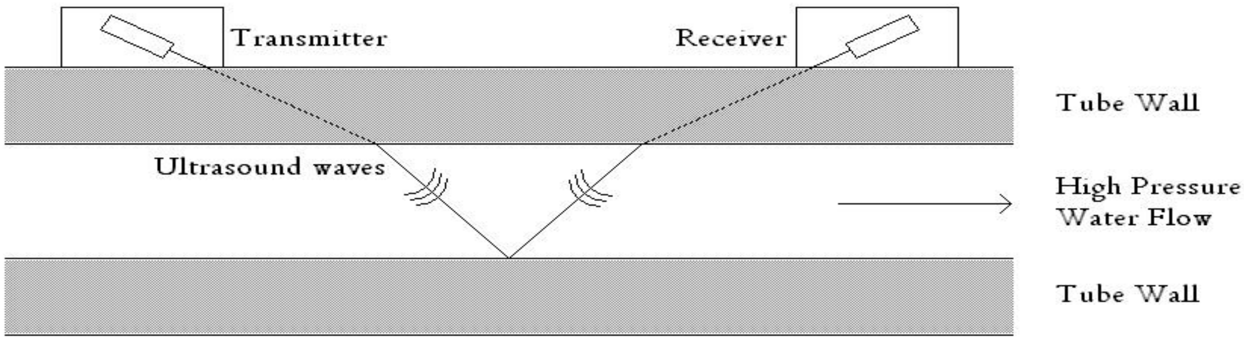

Figure 2: A schematic of the Transit Time Doppler Ultrasound System

OPTICAL TRACKING This system involves the installation of a set of video cameras capable of tracking the flow of water. These cameras will be installed and programmed to initiate an electrical signal whenever water is flowing out of the nozzle orifice.

INFRARED/LASER This system will involve a transmitter and receiver, placed at the orifice. A constant beam of infrared waves or laser will be transmitted and received when water is not flowing. Whenever water does flow, however, it will act as an impediment to the beam of laser/infrared light. This can be calibrated to suit the signal needs of the customer. Actual flow rate can be measured by varying the thickness of the source light beam.

ACOUSTIC This system will involve a careful mapping of the sounds of the surroundings of each water jet cutter. The water exits the nozzle of the water jet cutter at nearly three times the speed of sound and creates a loud noise. The system would the record the sound and from the intensity and frequency characteristics of the sound signal determine if the water jet cutter fired properly.

ELECTROMAGNETIC This system involves applying a magnetic field to the fluid and measuring the induced voltage difference. The induced voltage difference is proportional to the velocity of the conducting fluid. Additionally, this type of flow meter could be designed to measure the flow rate at high pressures. A thin-walled, non-magnetic tube surrounded by coils could be placed perpendicularly to the flow. This would generate the magnetic field and therefore would allow the thick tubing necessary to contain the high-pressure fluid.

VARIABLE AREA FLOW METER A variable area flow meter measures the flow-rate by measuring the displacement of a flexibly attached obstruction placed in the flow. As the fluid moves, a greater pressure differential is developed before and after the piston, which acts like an orifice. The orifice is aligned with a cone such that the orifice size increases with greater flow-rate. The piston is attached by use of a spring which stretches under the greater pressure differential, giving the flow rate of the fluid. Alternatively, a spring-loaded vane can be used in a similar fashion.

THERMAL The thermal flow meter measures the mass flow rate by utilizing two resistance thermal detectors (RTD). One of the sensors is set at temperature above that of the flow and adjusts its temperature as flow passes over it. The other RTD measures the flow rate by measuring the heat carried away from the sensor by passing fluid. This system is completely invasive due to the RTDs being incorporated in the tubing. Also there are no moving parts and pressure loss is marginal.

TURBINE This system includes an electromagnetic system and a submerged turbine. When the fluid flows past the turbine, it will start to rotate. The angular velocity of this rotation would correspond to the flow rate of the fluid. The angular velocity would be picked up by the use of a pulse electromagnetic system.

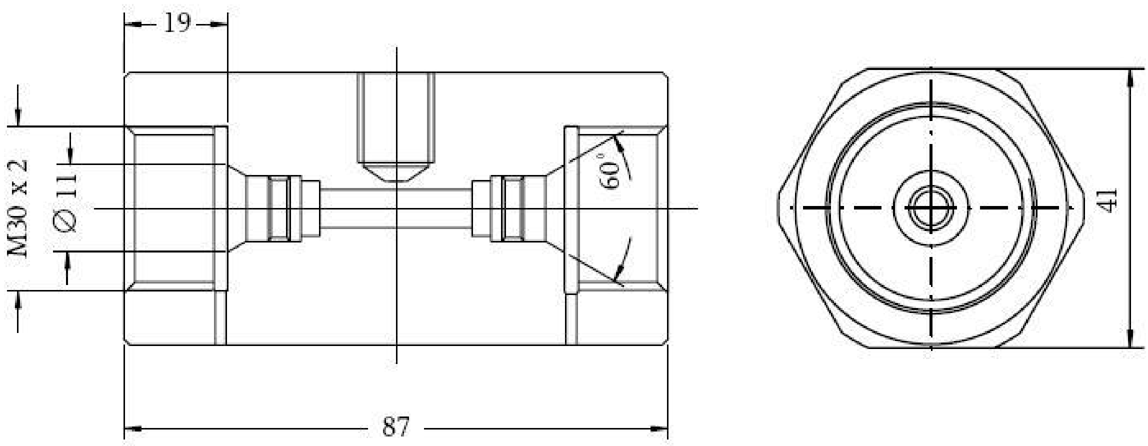

Figure 3: A schematic of the Turbine System

CORIOLIS FLOW METER This type of flow meter measures the flow rate of the fluid by forcing vibration of a curved or straight tube. As fluid flows through the tube, the vibrational characteristics of the forced tube change: an extra frequency is added to the response. From examining this change, it is possible to determine the mass flow rate of the fluid through the tube.

VIBRATION DETECTION This device would involve a sensor to determine the vibration of the flow meter. When the water jet cutter is active and water is flowing, the machine will experience additional vibrations. This idea was to correlate these vibrations to the flow-rate coming out of the nozzle.

THRUST DETECTION This device would sense the force on the nozzle produced by exiting stream. By measuring the force produced by the exiting the stream, it would be possible to correlate this quantity with the cutting force of the water jet thereby detect if a deficient firing of the water jet occurred.

Concept Evaluation and Selection

We generated a number of interesting ideas regarding flow measurement. After a process of careful analysis, we were able to select five of these ideas for further consideration. Below are listed our ideas. We then further evaluated the top five choices using methods such as a Pugh chart, as seen in Appendix E on page 29.

Ideas that were dropped

These are the ideas we felt were not feasible.

INFRARED/LASER This would probably be effective in determining flow rate and is non-invasive. However, this design would require the unit to be mounted at the nozzle of the machine. This creates problems with debris damaging the unit. Also, there is high probability that the unit might interfere with the functionality of the cutting machine, which is undesirable.

VARIABLE AREA FLOW METER This flow meter will not work at high pressures, so it is not applicable to our criteria. Also, if it were able to be used at high pressures, the spring would not be sensitive enough to detect the small changes in flow rate that we require the device to detect.

ACOUSTICS This system is highly dependant on a huge database of ambient noises to compare measured sounds with. It would require too much research and design to be able to be created within the scope of our project. It also may run into problems with outside sounds. Being that the cutting machines are usually used in some kind of shop/factory, there may be some acoustic interference with the other machines in the area. Moreover, any sound not already in the database will cause errors in the operation of the system. Therefore, due to the huge calibration issues, this idea was dropped.

OPTICAL TRACKING This would be another effective method for tracking the flow. However, since the cutting machines are used in 3-D motion and sometime even go inside of the parts to cut, it would be nearly impossible to have all angles optically covered.

CORIOLIS FLOW METER Being that this flow meter requires vibration of the tubing, this would create a problem. Our tube is fairly thick due to the high pressures, so vibrating for use of flow detection would be unfeasible.

VIBRATION DETECTION The problem with this flow meter is similar to that of the acoustics flow meter. There are a lot of outside vibrations that could cause the flow meter to give false read outs.

THRUST DETECTION There are a couple of problems with this idea. First, the thrusts that we are dealing with are very small (around 4 lb). With such small thrusts, there would be difficulty detecting changes in the thrust. Also, this flow device required a lot of incorporating into the cutting machine which would probably include something integrated at the nozzle. For the same reason as with the Infrared/laser device this would not work. The debris would cause problems, and it would probably be hard to incorporate it into the cutting machine so that it does not impair the machine’s ability to move freely.

Ideas selected for further study/testing

Below are choices of flow meters that we felt would be the most feasible for our application

TRANSIT TIME ULTRASOUND This is very similar to the Doppler/Ultrasound device. The only difference is that it measures the time delay between signals instead of the frequency shift of the signal. An existing prototype exists for this type of flow meter

THERMAL This is another non-invasive idea that already is in use at very high pressures. The only problem is that this device is not normally used with the scale of tubing we will see, so testing will have to be done to determine the affect of geometry. Additionally, the response time (0.5 s) of the production model is too slow for a few of the applications the water jet cutter is used in. Moreover, it may be possible for this response time to be reduced.

TURBINE We believe this is another good idea. It has already been tested at high pressures, and is sensitive enough to accurately determine changes in flow rate as necessary. The only problem that may occur is that the device is invasive. We do not predict that this will be a severe problem, but further research is being performed to determine this.

ELECTROMAGNETIC This is our final idea for a feasible flow rate device. This is fairly low cost and functional. Given the design specifications, it should not be a problem to integrate this into a high-pressure system, but it is still a fresh idea, so testing and research will have to be done on this. Also there may be problems with the invasive aspect of the device. We do not predict that these problems will have any drastic affects so we are continuing pursuing the possibility of this concept.

DOPPLER/ ULTRASOUND This system is non-invasive, is able to read small flow rates accurately (+/- 0.5%) and is not extremely expensive. It is placed on the outside of the tubing, so pressure effects on the device itself are not a concern. The potential issues with this device lie in integrating it into the machine, and getting it to work at the extreme pressures that will be encountered. This flow meter design may not be affected by some of the problems affecting the transit time ultrasonic flow meter currently. The "ringing" in the pipes and penetration issue seen in the transit time ultrasonic flow meter may be alleviated in this ultrasonic design.

Selected Concepts

THERMAL FLOW METER Thermal flow sensing is a unique method used to determine flow rates. It provides accurate and reliable measurements with continuous data output using resistance thermal detectors (RTD). Another benefit of thermal flow meters is that it does not obstruct the flow path of the fluid and the sensors are never in contact with the fluid. A schematic is provided on the next page in Figure 4.

Depending on the application, the dimensions of the tubing can vary; the dimensions are shown in Figure 4. The length of the tubing, A, can vary from 9" to 18" while the outer diameter, D, varies in length from 1.3" to 4.5". The inner diameter, B, is no smaller that .25" and no greater than 3". In addition, the monitor is positioned in the middle of the pipe but is 3" away from the surface of the pipe, dimension E. Additionally, the tubing is made of 316 Grade Stainless Steel.

There are two RTDs located within the piping between the inner and outer diameter away from the high pressure fluid, guaranteeing longer life times. One of the RTDs measures the temperature while the other measures the flow. The temperature sensor maintains a temperature above that of the fluid, correcting itself as the fluid passes over the sensor. The flow sensor operates by heat being taken away from the sensor that is proportional to the mass flow rate.

The accuracy of the flow meter is 2 % of the actual reading and the repeatability of the flow meter is within .2%. The fluid temperature range is -250 °F to 1100 °F (-156°C to 593°C) while maintaining pressures in the range of 0-60000 psi. In addition, the signal that the monitor receives is an isolated 4-20 mADC signal.

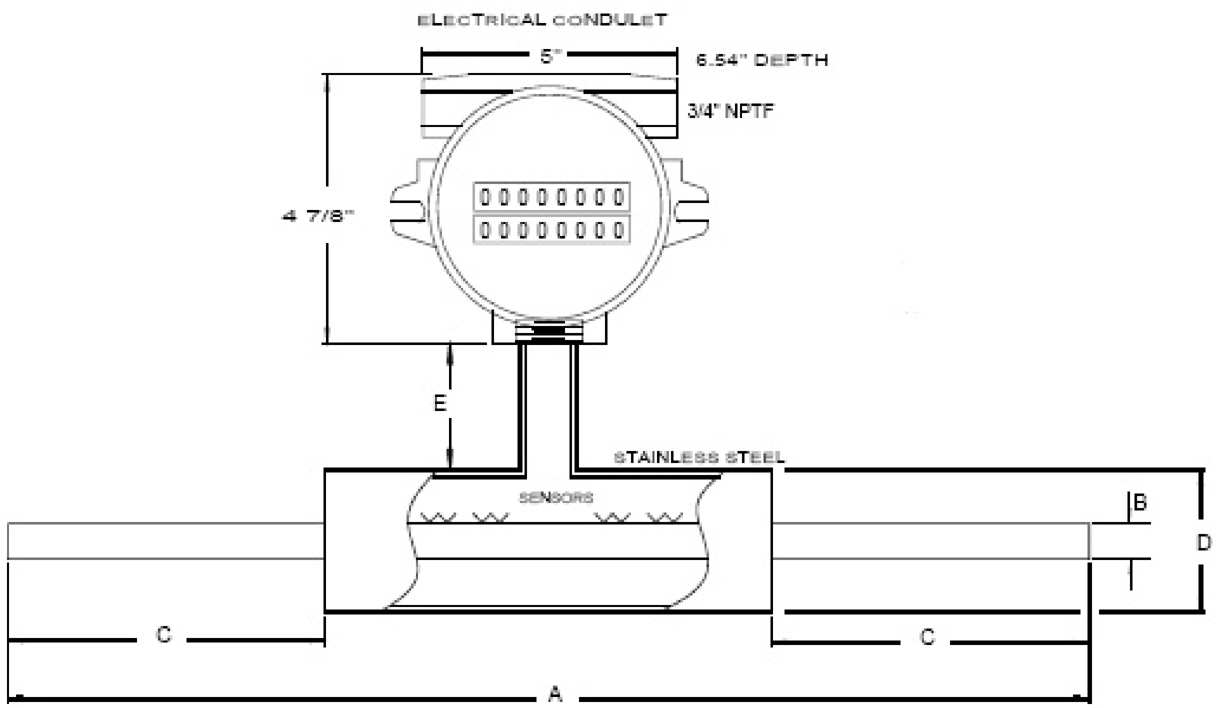

Figure 4: A schematic of the Thermal Flow Meter

DOPPLER TRANSIT TIME METHOD The Doppler Transit time Method is non-invasive, is able to read small flow rates accurately, and is not extremely expensive. It is placed on the outside of the tubing, so pressure effects on the device itself are not a concern. As can be seen in Figure 5 on the next page, this system consists of two transmitters/receivers. To begin measurement, the transmitter/receiver that is further upstream sends out an ultrasonic wave. This wave travels through the tube wall and flowing liquid, bounces off the inner wall and is received by the receiver downstream. The downstream receiver then re-transmits the wave, which is received by the upstream receiver.

The theory behind this system is that since the liquid in the tube has a certain velocity in the downstream direction, the wave should move faster in that direction than in the opposite. Thus, there is a “lag” time, which can be measured, and through calibration, can be converted in to a signal.

At present, we have a prototype that works at lower pressures (~ 100 psi). We are currently in the process of testing this system at various pressure and flow-rate ranges, so that we can better understand the reasons for its failure at high pressures. Due to the fact that RPT's machines are custom built per the customer's requirements, we do not believe that factors such as power requirements etc. are of high importance, since transformers can be easily incorporated to deal with such issues.

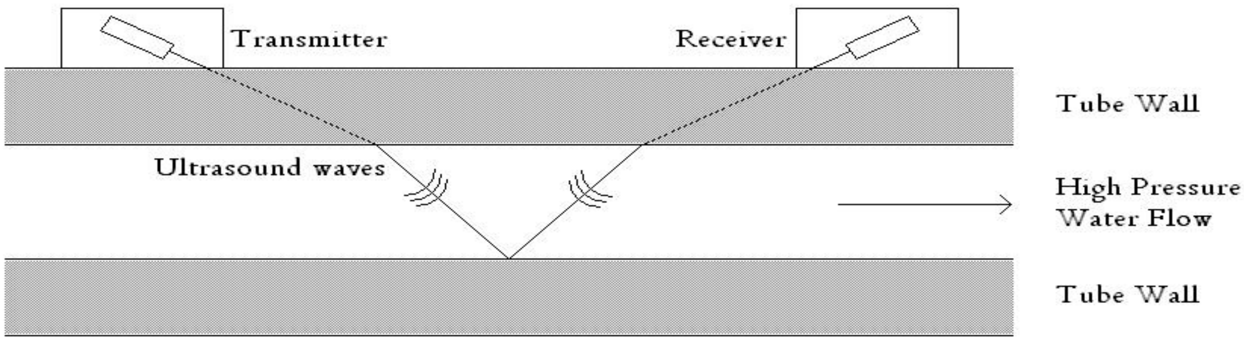

Figure 5: A schematic of the Transit Time Doppler Ultrasound System

TURBINE The turbine system produced by AW Company is capable of handling a low flow-rate of 0.08 gpm, which is within the upper limit for flow rates seen. The system is also rated for 58,000-psi, which is slightly below the upper range of pressures seen in our waterjet cutter. We have received indication from AW Company that they could make a custom designed system with a higher pressure rating. The system has a response time of 5 – 50 ms and an accuracy of +/-0.2%, both of which are higher than what is needed for our application. While able to accurately measure similar flow-rates at a high frequency sampling rate, the turbine flow meter is heavily invasive, requires the line to be broken, and overall appears to be the most difficult to use of the selected concepts.

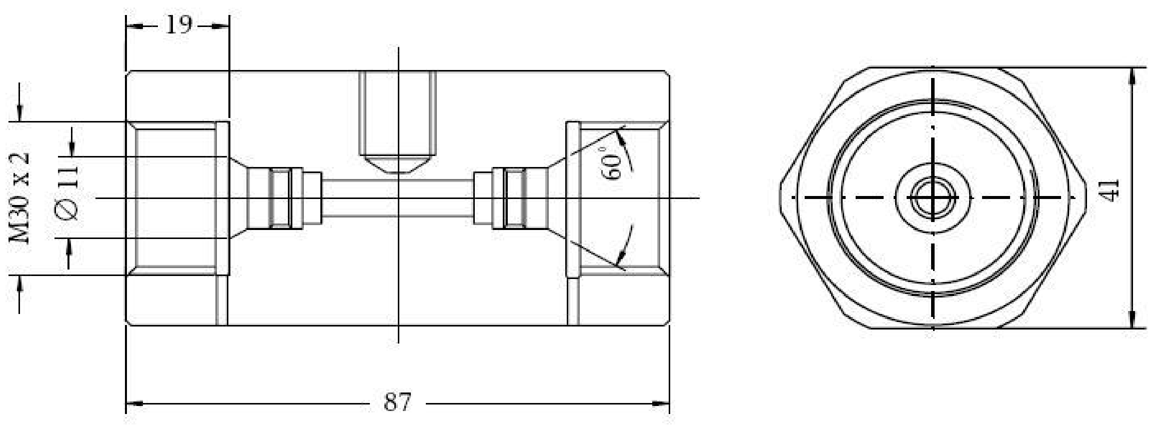

Figure 6: A schematic of the Turbine System

Engineering Analysis

Our design team decided to pursue two flow meter designs: the transit time ultrasonic flow meter and the turbine flow meter.

TRANSIT TIME For the transit time ultrasonic flow meter, an ultrasonic pulse travels inside a pipe with a flow medium, in the case water. Due to the high frequency ultrasonic pulse, it is necessary to consider the ultrasonic wave propagating in a cylindrical waveguide. The wave equation becomes the following in the case of a flowing fluid which has a flow profile that depends solely on the radial coordinate, where Φ is the complex pressure fluctuation, r is the radial coordinate, $\vec{r}$ is the position vector in cylindrical coordinates, a is the inner radius of the pipe, and Δ is the Laplacian :

$$\frac{\partial^2 \Phi(\vec{r},t)}{\partial t^2} - (c_0 + u(r))^2 \Delta\Phi(\vec{r},t) = 0 \quad [7]$$

$$\text{BC: } \nabla\Phi(\vec{a},t)\bullet\vec{n} = 0$$

This equation assumes that the flow speed *u* is much smaller than the speed of sound in the fluid and a constant speed of sound. For our application, the speed remains much greater than the flow speed of the fluid, but the speed of sound is subject to change during operation. However, we do not believe this to be an issue due to the small amplitude of oscillations during use. During operation of the water jet cutter, the system experiences fluctuations in pressure of around 5,000 psi. This results in approximately 1-2% change in the speed of sound according to the UNESCO equation [4], which is likely small enough to neglect. This equation is separable and assuming a time dependence of $T(t) = e^{j\omega t}$ yields the following simplified equation:

$$\Delta\Phi(\vec{r}) + \frac{\omega^2}{(c_0 + u(r))^2}\Phi(\vec{r}) = 0 \quad [7]$$

The theta and z equations are solved similarly and follow the general case of the wave equation inside a cylindrical waveguide. Under flow conditions, the radial coordinate changes and becomes the following, where k_0 is the wave number ω/c under no flow and λ_n is the square root of the nth eigenvalue:

$$\frac{1}{r}\frac{\partial}{\partial r}[rf'(r)] + \left[k_0^2\left(1 - \frac{2u(r)}{c_0}\right) - \lambda_n^2\right] f(r) = 0 \quad [7]$$

$$\text{BC: } \frac{\partial f(a)}{\partial r} = 0 \text{ and } |f(0)| < \infty$$

As done by Willatzen [7], this new phase speed can be gotten from this equation by perturbation analysis. This perturbation analysis requires that the flow speed u(r) be much smaller than the speed of sound. Following this perturbation analysis, Willatzen derives the following equation for the phase speed of the acoustic pulse:

$$c_{pn} = \frac{\omega}{\sqrt{\frac{\omega^2}{c_0{}^2} - \frac{j_{1n}}{a} + U}} \quad [7]$$

In this equation, the j_{1n} is the nth zero of the Bessel function of the first kind of order 1 and U is the quantity $\int_0^a u(r) f^2(r) r dr$.

It follows, according to Willatzen, that the phase speed of the first mode adheres to the following equation where $\overline{u}$ is the average speed of the flow profile:

$$c_{p1} = c_0 + \overline{u} \, . \quad (1)$$

As is seen, the increase in the phase-speed for the first mode is exactly the mean speed of the flowing medium. This enables transit time flow meters to accurately measure the flow rate of the water, Q=$\overline{u}$ A. Also, it allows the designing of a transit time flow meter which measures the flow speed without knowledge of the speed of sound, as will be described. This fact means that the theoretical operation of the transit time flow-meter is entirely independent of the static pressure of the problem, insofar as the static pressure remains relatively constant during measuring. The transit time flow meter is therefore well-suited to handle the high pressure environments seen in the water jet cutter.

Our device determines the flow speed by measuring the time delay between pulses, and using equation 1, we are able to determine the flow rate of the water. The upstream transmitter/receiver (T/R) transmits an ultrasonic pulse which is received by a downstream T/R with some time delay t_{down}. The downstream T/R then transmits another signal upstream where it's received by the upstream T/R after some time delay t_{up}. These time delays can be written in terms of the mean speed of sound, the distance between T/R stations (L) and the incident angle θ_{i}.. Following the propagation of the first mode, given a uniform flow profile U, the flow speed can be calculated by the following equation:

$$U = \frac{L}{2\cos\ \theta_i} \frac{t_{up} - t_{down}}{t_{up} t_{down}}$$

The transit time ultrasonic flow meter is a dφ-type transit time flow-meter, meaning that the ultrasonic pulse is sent at some angle, θ_i, relative to the transverse axis of the pipe. The ultrasonic pulse, as it passes through the steel/water interface is refracted to some resultant angle θ_T. Modeling the ultrasonic pulse as a plane-wave yields the following equation for θ, power transmission coefficient T_Π, (the ratio of pressure amplitudes between the transmitted wave and the incident wave), and reflection coefficient R (the ratio of amplitudes between the reflected wave and the incident wave) through the steel/water interface:

$$\theta_T = \arcsin(\frac{c_2}{c_1}\sin(\theta_i)) \qquad T_\Pi = (4\frac{r_2}{r_1}\frac{\cos\ \theta_T}{\cos\ \theta_i})/(\frac{r_2}{r_1}+\frac{\cos\ \theta_T}{\cos\ \theta_i})^2 \qquad R_\Pi = 1 - T$$

In these equations, r denotes the characteristic impedance of the material given by $r = \rho c$ with K being the bulk modulus, c is the speed of sound, and ρ is the density of the material. The speed of sound in stainless steel is 5790 m/s and the characteristic impedance is 47 x 10^6 Pa-s/m. The speed of sound in water at high pressures is calculated using the UNESCO equation [4] as an estimate of the speed of sound at high pressures for the tap water as was done by Foldyna et al. [5]. This yields an estimated speed of sound at 20 °C of 2060 m/s. The density of water, in g/ml, approximately follows the equation $\rho = [(P+P_0)/(T+T_0)]^{1/6}$ [6], where P_0 = 378 MPa and T_0 = 85 K. This yields a characteristic impedance of 23.2 x 10^6 Pa-s/m.

So, at 60,000 psi with a 20° angle of incidence, 13% of the ultrasonic pulse is reflected back into the steel. Following the equations through one reflection at the bottom of the tube, the main pulse is transmitted to the receiver at 9.9% of its original power. Examples of the actual signal strength received by the transmitter are generally 10-15%, implying reasonable accuracy for this simplified analysis. The high pressure in fact aids the transmission between the water, considering that 88% of the initial pulse would be reflected into the steel at atmospheric pressure. Because our design involves very thick tubing, it was possible that the reflected wave, which in the case of thin tubing would reflect many more times than the main pulse and thus have a lower power, would throw off the reading. From our calculations, this does not appear to be the case.

TURBINE The turbine system uses a rotating turbine placed inside the flow in order to determine the flow rate. Flow rectifiers are used to lower the turbulence intensity of the flow before the turbine. The angular velocity of the turbine blades is thus directly proportional to the flow speed. A magnetic field is applied over the turbine and thus the rotation of the turbine blades causes a sinusoidal voltage signal to be generated with a frequency, *f*, which is directly proportional to the angular velocity and flow speed. The equation to calculate the flow speed becomes the following equation, where *k* is a calibration constant:

$$f = kU$$

This allows accurate monitoring the flow. Because flow velocity field is independent of the static pressure, it follows that the calibration constant k is roughly independent of the static pressure of the flow.

Qualitative Analysis

Both of our selected designs are products that are pre-made and can be easily attached to the current waterjet cutting system. In this stage of our project we are solely focusing on getting a flow meter to properly read the flow rate, leaving the electronic controls portion as a secondary requirement. This being said we do not have any manufacturing to perform. Without any manufacturing required it is not applicable to apply the concepts of Design for Manufacture and

Assembly (DFMA), as well as Design for Environmental Impact (DFE), and they will be omitted from our report. We will solely focus on the Failure Mode and Effect Analysis (FEMA) instead.

Turbine Flow Meter

Failure analysis of the turbine flow meter system led to two major areas of failure; the turbine and the tubing. A table summarizing the FEMA of the turbine is included as Appendix G on page 32.

TURBINE The first area that could fail is the turbine. The major failure mode of this part is wear. Within any turbine system the turbine will be subjected to friction between the walls and the turbine. In our case, where the machine will be using tap water, there is also the chance that particulate matter will damage the turbine. Turbine wear will lead to improper rotation of the turbine, resulting in improper flow rates being read. Friction is something that can not be avoided so the only way to monitor for this failure is to monitor the performance of the meter when compared to theoretical values. Increased monitoring will lead to increased detection of the problem.

TUBING The second area that must be considered for failure analysis is the tubing itself. Within the tubing the pressure reaches a maximum of 60,000 psi. This is extremely high pressure and over time the tubing will suffer from fatigue, with the possibility that it will crack and start leaking. Once again this is something that is inevitable, and the only real detection is to monitor the tubing looking for any signs of fatigue.

Transit Time Flow Meter

Failure analysis of the transit time flow meter system indicates three major areas of failure; the sub-system of the transmitter and receiver, the presence of ultrasound gel, and the tubing again. A table summarizing the FEMA of this flow meter is included as Appendix F on page 31. The explanation of tubing remains the same as for the turbine flow meter, see the previous page.

TRANSMITTER AND RECEIVER Similar to the optic system within the turbine flow meter, the transmitter and receiver of the transit time flow meter could become misaligned as a result of the vibrations, and cause major failure. Our prototype has both these pieces encased within an epoxy block. They are encased tightly within the epoxy and this does not seem very likely. The location of these parts makes it extremely difficult to check on. Therefore it is suggested that if there is major failure, and no simpler fixes found, that these parts are looked at to ensure their alignment.

ULTRASOUND GEL When using the transmitter and receiver it is necessary to have a layer of ultrasound gel between the meter and the tubing it clamps onto. This gel increases the conductivity and allows for proper transmission of the signal through the metal. Over time this layer of gel will begin to disappear, as a result of erosion and surging of the pipe. Once the gel is not at a sufficient thickness than the transit time flow meter will not properly work. It is recommended that a routine inspection of the amount of gel be implemented, with this there should not ever be a problem with gel.

Final Design

The final design solution is a transit time ultrasonic flow meter. We have included a CAD model of the flow meter produced by Dynasonics as Figure 7 below. This system works by sending an ultrasonic pulse from an upstream transmitter-receiver to a downstream transmitter-receiver. This transmitter-receiver then sends another pulse upstream to the upstream transmitter-receiver. If the flow rate of water in the pipe is increased, the phase speed of the ultrasonic wave also increases proportional to the flow rate of the water. It is then possible to measure the time delay between transmission and reception of the pulse and determine the flow rate of water in the pipe.

Since this system is placed on the exterior of the tubing, this method of metering flow is non-invasive and thus easier to implement at very high pressures. It is also easy to install, maintain, has high reliability, and a quick enough response time for our application.

We believe that this system will provide KMT RPT with a reliable and cost effective means of monitoring the flow rate within their waterjet cutter systems.

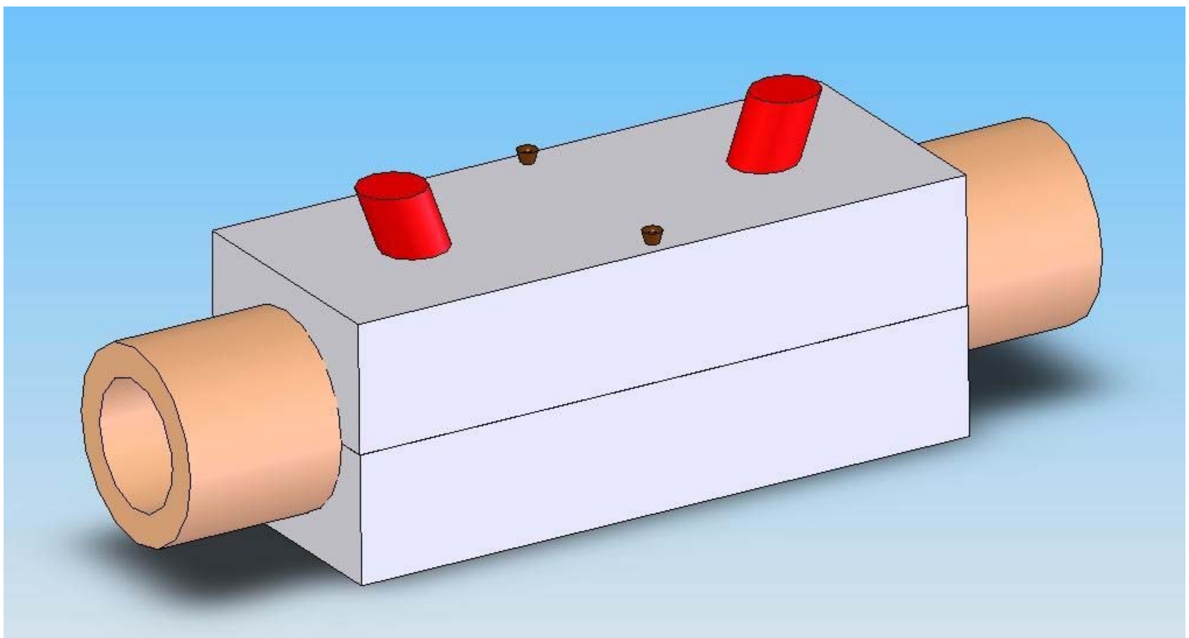

Figure 7: CAD model of the Transit Time Flow Meter

Manufacturing

Our selection of the transit time flow meter, produced by and purchased from Dynasonics Inc., meant that we would not have to perform the physical manufacturing of the meter. We have included the basic manufacturing steps that we believe Dynasonics took to produce their meter. It should be noted that as a result of us not physically manufacturing the part that some aspects of its fabrication are unknown to us. The following is an outline that is intended to allow the reader to fabricate the part, with some additional information.

The flow meter is an epoxy cast made to fit around a 0.25 in outer diameter tube. Two sides of the epoxy were made: one for the top half of the tube, and one for the bottom. After the two molds were set, they could then be machined. Bolt holes had to be drilled into both sides of the molded meter shell in order to provide a secure fit around the tubing. After the basic molds were formed, the holes could be drilled in order to place the transmitter/receiver sensors to measure the ultrasonic waves. Two holes were drilled for the two sensors to be placed at the appropriate angle so that the signal sent/received was at the angle used in the design of the device. After the sensors are places, the holes are filled with transparent epoxy as to not interfere with the ultrasonic signal. In the midst of affixing the transmitter/receivers the electrical aspect of the meter must be accounted for. This aspect of the design is where further information would be needed to reproduce the prototype. Once the electronics have been established the part is ready to be finished and shipped. Figure 8 is a photograph of the finished prototype.

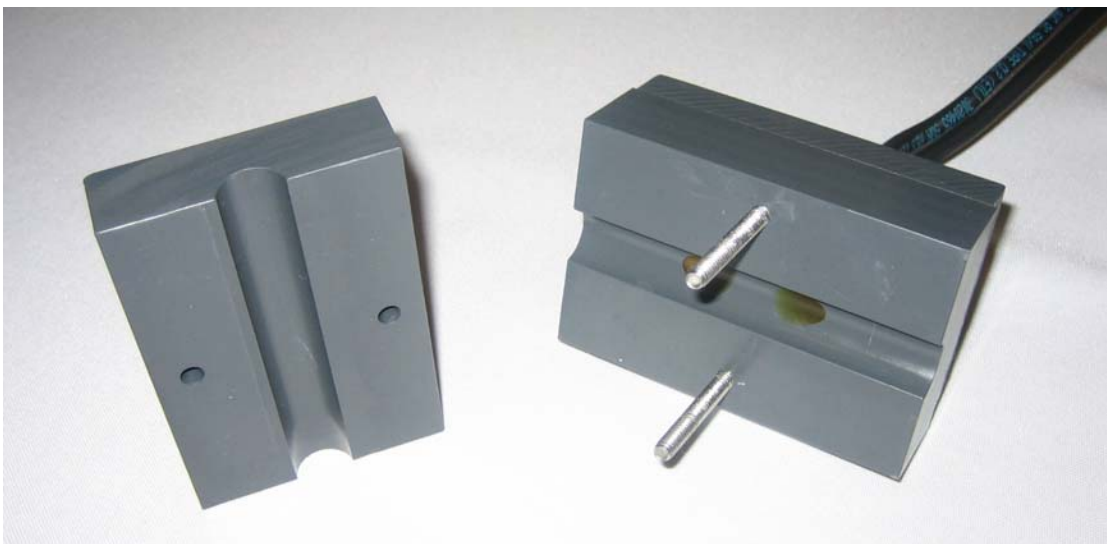

Figure 8: Photograph of Transit Time prototype manufactured by Dynasonics

Testing

Once we finalized our design and procured the equipment, we found that the readings from the device were not in agreement with our expected values. In order to verify the accuracy of our transit time ultrasonic flow meter, we divided the testing into two parts, in order to individually isolate factors that were potentially causing the meter to produce incorrect readings, and procure evidence that if the various external factors were accounted for, the meter would provide accurate results.

We began by analyzing the flow while running the waterjet cutter. We collected data to find correlations between high pressures, pipe expansion, or changes in orifice size at the nozzle. By varying two parameters, pressure and orifice size, we conducted tests at various pressures between 10 ksi and 60 ksi, and various orifice sizes between 0.008" and 0.013". We also accounted for other factors, such as pipe expansion, by measuring, for each run, the pipe diameter. As a result of the first part of our tests, we were unable to find any clear correlation between pressure and flow-rates.

Next, we performed low-pressure testing by detaching the meter from the main line and conducting a controlled experiment, using tap water at approximately 30 psi. We let the water flow into a container while recording the time it took for the water to reach a certain level. This approximation of the flow-rate was compared with the output from the meter to see if the method worked in principle. What we found is that the flow meter does provide positive correlations; however, it does not have the desired accuracy. As can be seen in Appendix I, on page 34, this inaccuracy can be as high as 30%.

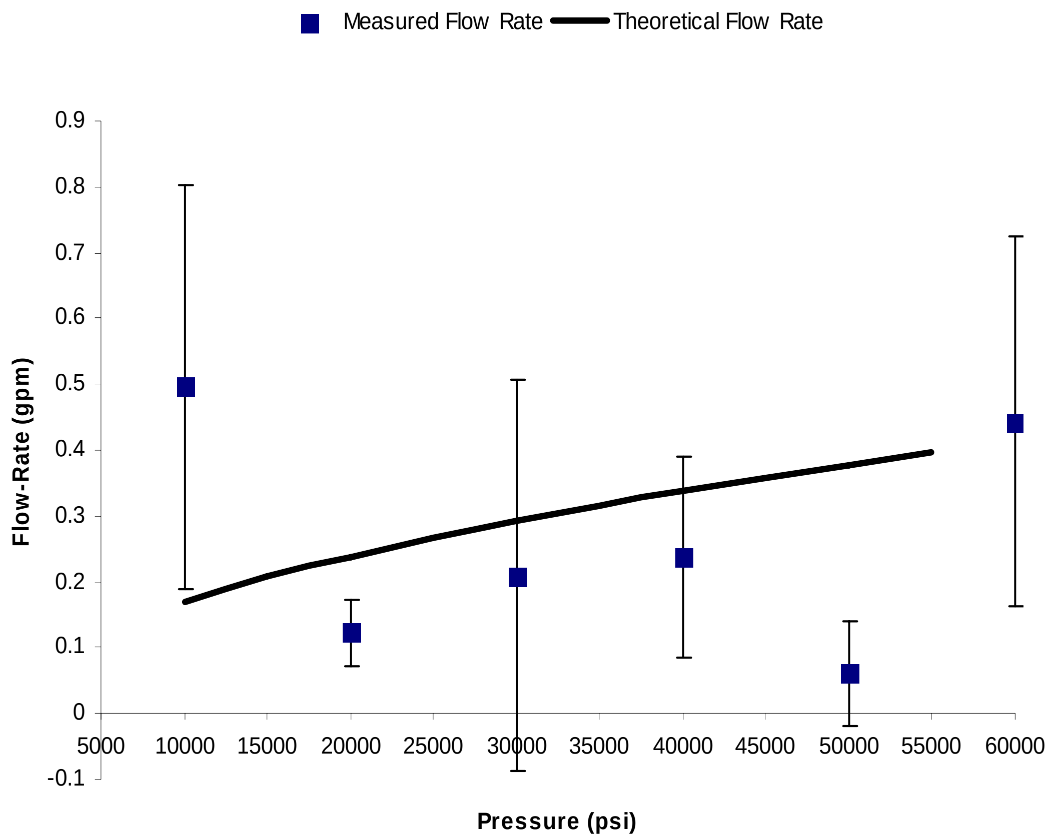

Figure 9: Chart of experimental flow rates vs. theoretical from our testing

Figure 9 is a graphical representation comparing our average experimental data, with error, and the theoretical flow rates provided to us by RPT, Appendix J on page 35, against pressure. From this chart it can be seen that the accuracy of our flow meter is not consistent. The errors at the various pressures range from small, about 0.08 gpm, to quite large, 0.3 gpm. Our experimental values do match the theoretical values, within error, at both 30 and 40 ksi; this also appears to be the case when the theoretical flow rate is extrapolated to 60 ksi. Data such as this is promising, but with such high error it is not accurate enough for our use and further measures must be taken to increase this accuracy.

It is important to note that the aforementioned tests are not the only procedures our team had in mind. There were other tests that are team believed were imperative to conduct and not brought to fruition. These other tests included vibration damping for the system, moving the flowmeter further upstream to reduce backflow of water and the effects of water hammering, and increasing the lengths of the straight section of the pipe so that the flow regime will be as laminar as possible.

The reasons why those additional tests were not conducted are mainly due to lack of testing time as well as the inability to modify the waterjet cutting system. Due to a number of reasons, our client, KMT RPT ended up having to cancel appointments with us or only promise us limited usage to the waterjet cutter. This limited usage often consisted of just watching the results of the flowmeter while the customers used the machine. During that time we would not be allowed to move the flow meter or conduct any other experiments. Furthermore, we were required to, and unable to, get clearance to modify the machine. We strongly believe that if given the opportunity to fully test the unit, we would have further improved upon it.

Future Work/Improvements

Testing has shown conclusively that our device works. However, it does not work as per our expectations. We believe that several factors have contributed to this situation. These are detailed below:

We believe that vibrations in the system need to be dampened further. The equations used in our calibration assume that the flow of fluid is uni-directional, along the longitudinal axis of the tubing. Vibrations cause the fluid to gain velocity in other directions, thus rendering our calibration inaccurate. We believe that dampening of vibrations by further isolating the unit from the waterjet cutters and holding the tubing in place will contribute to better quality readings.

Another contributor to incorrect readings is a potential backflow of water, also known as the water-hammer effect. The waterjet cutter is rarely run at constant pressure. There is always some variation of a few thousand psi; sometimes the unit is cycled all the way back to zero pressure. Whenever there is a sudden drop in pressure, the direction of water will change momentarily as the water, in essence, “hits a wall”. This change in direction could be a potential reason for the negative readings seen by our meter.

Changes in pipe dimensions can be another cause of incorrect readings. We measured the outer diameter of the pipe in use, at various pressures from 10 ksi through 60 ksi. As can be seen in Table 1, there is no measurable change in the outer diameter in the pressure range. We believe that changes in the internal diameter could be a factor and should be accounted for, or discounted (as a factor) through further testing.

Pressure (ksi)	10	20	30	40	50	60
Tubing Outer Diameter (in)	0.534	0.534	0.535	0.534	0.534	0.534

Table 1: Outer diameter of tubing at various pressures

Another area we considered testing, but due to time constraints were unable to test, was the length of the tubing the meter was attached to. In the current design the tubing is approximately a foot long, with an orifice at each end of the tube. The orifice upstream of the meter causes non-linearities to occur within the flow. The equations we have governing this meter assume that the flow does not have these non-linearities. We feel that by lengthening the tubing that the meter is attached to will allow for the flow to become fully developed by the time that the meter interacts with it.

Another issue that we thought of is nonconformities within the actual water. The use of tap water means that there is no regulation of the quality of the water. The amount of particulate matter can vary greatly. We feel that there issues could arise from an increased amount of particulate matter that will deflect the signals. There is no way to account for this using tap water, implementation of distilled water, with a higher level of quality control, would allow for this issue to be accounted for.

Conclusions

Robotic Productions Technology, Inc. contacted the University of Michigan to help with the design of a flow meter for their high pressure waterjet cutting systems. The company currently has no way to determine if the flow at the nozzle is the necessary rate to cut the material, this is leading to deficient cuts. This is causing problems for the customers of RPT when the substandard cuts are not noticed. RPT has not constricted our ideas by giving us many exact specifications to meet; they simply want to know the flow rates of their machines.

From our testing, we have found that that the ultrasonic transit time flow meter does provide positive correlations; however, it does not have the desired accuracy. We believe that this is because of the high number of external factors that contribute to the correlation factor, many of which we have been unable to accommodate in our calibration.

We further believe that if factors such as external vibrations, backflow of fluid due to sudden drops in pressure, changes in the internal dimensions of the pipes and quality of the fluid are accounted for, our system will provide an output with increased accuracy.

The ultrasonic time-transit flow meter provides a safe, reliable, cheap and accurate means of measuring fluid flow-rates at ultra-high pressures. Because it is non-invasive and easy to install and use, we find that it will render itself a useful tool to KMT RPT and its clients.

Acknowledgements

First and foremost, our group would like to thank our section leader, Professor Suman Das, for all of his guidance throughout the semester. We would also like to thank all other contributing faculty members who taught this semester. Lastly, we would like to thank our sponsor KMT Robotic Solutions. Specifically we would like to thank Jim Wogan and Roberta Zald for their assistance, as well as any other employees who aided us in our efforts to test.

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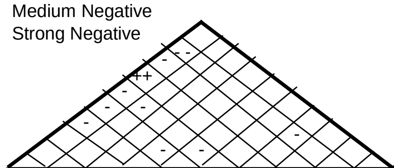
Appendices

Appendix A: QFD Chart

Relationships

++ Strong Positive
\+ Medium Positive
\- Medium Negative
\- - Strong Negative

Quality Function Development (QFD)



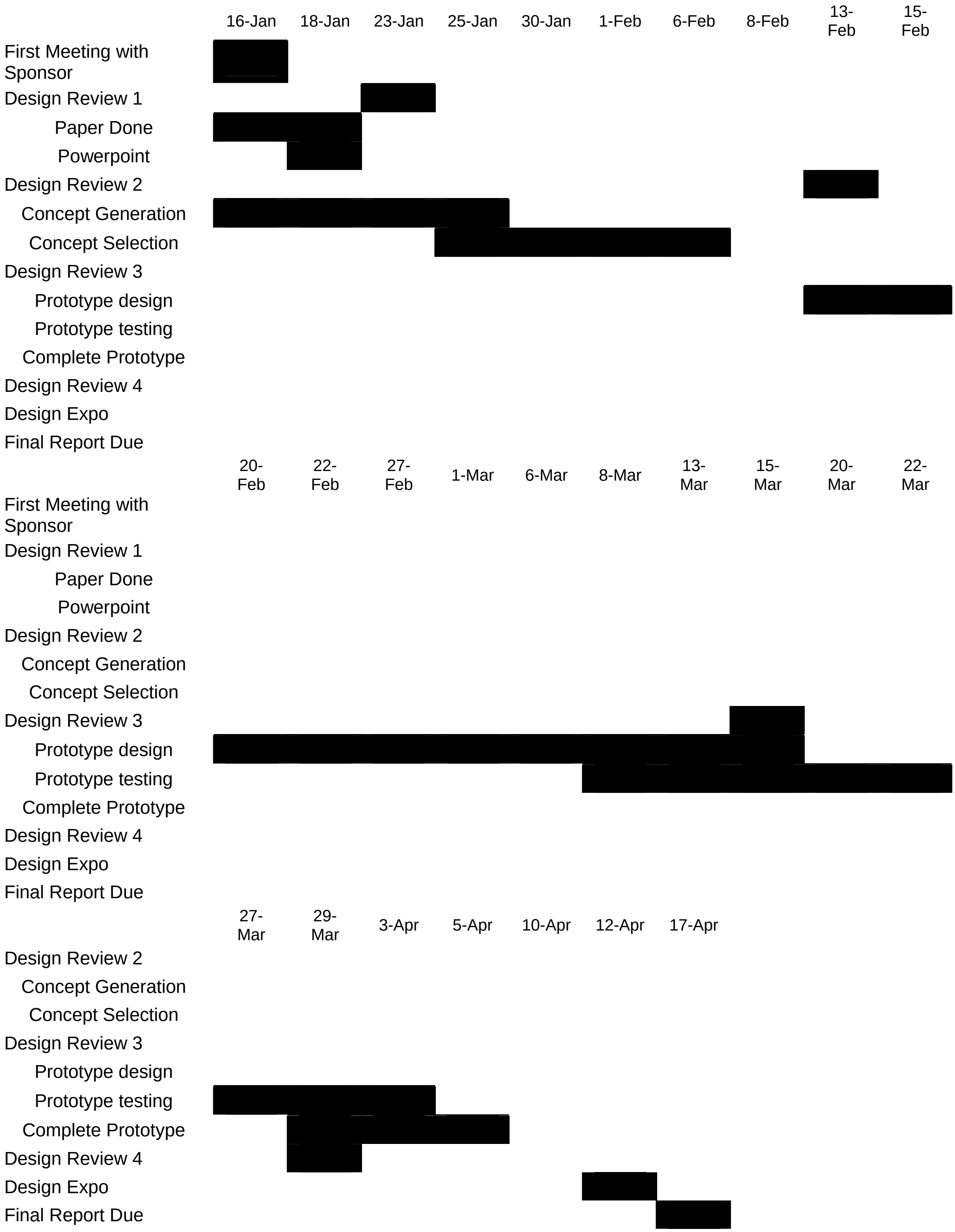
(+) => more is better
(-) => less is better

	Weight*	Laser/Ultrasound measurement	Signal creation/transmission	Material cost	Cutting Distance	Cutting time duration	Power consumption of add on devices	Sensitivity of measurement	Additional weight	Reduction in pressure	
Measure flow rate	0.44	9	9	1	0	9	1	9	1	3	
Be compact	0.05	3	1	3	0	0	1	3	9	1	
Durable	0.05	3	1	3	3	3	0	1	1	0	
Must not reduce performance	0.12	3	0	0	1	3	0	3	1	9	
Must not impede functionality	0.1	1	1	0	3	3	1	1	3	9	
Must be low cost to install	0.04	9	3	3	0	0	0	1	1	1	
Must be easy to manufacture	0.08	3	3	3	0	0	0	9	1	0	
Must have aesthetic qualities	0.04	1	1	3	0	0	3	1	1	0	
Out-of-status must be easy to measure	0.08	3	3	1	1	3	3	9	1	3	
Measurement Unit			V	$	in	s	W		lb	psi	
Target Value											
Importance Rating		**9**	**9**	**3**	**9**	**9**	**3**	**9**	**3**	**3**	
Total		5.6	4.8	1.3	0.7	5	1	6.1	1.6	3.6	0
Normalized		0.19	0.16	0.04	0.02	0.17	0.03	0.21	0.05	0.12	0.00

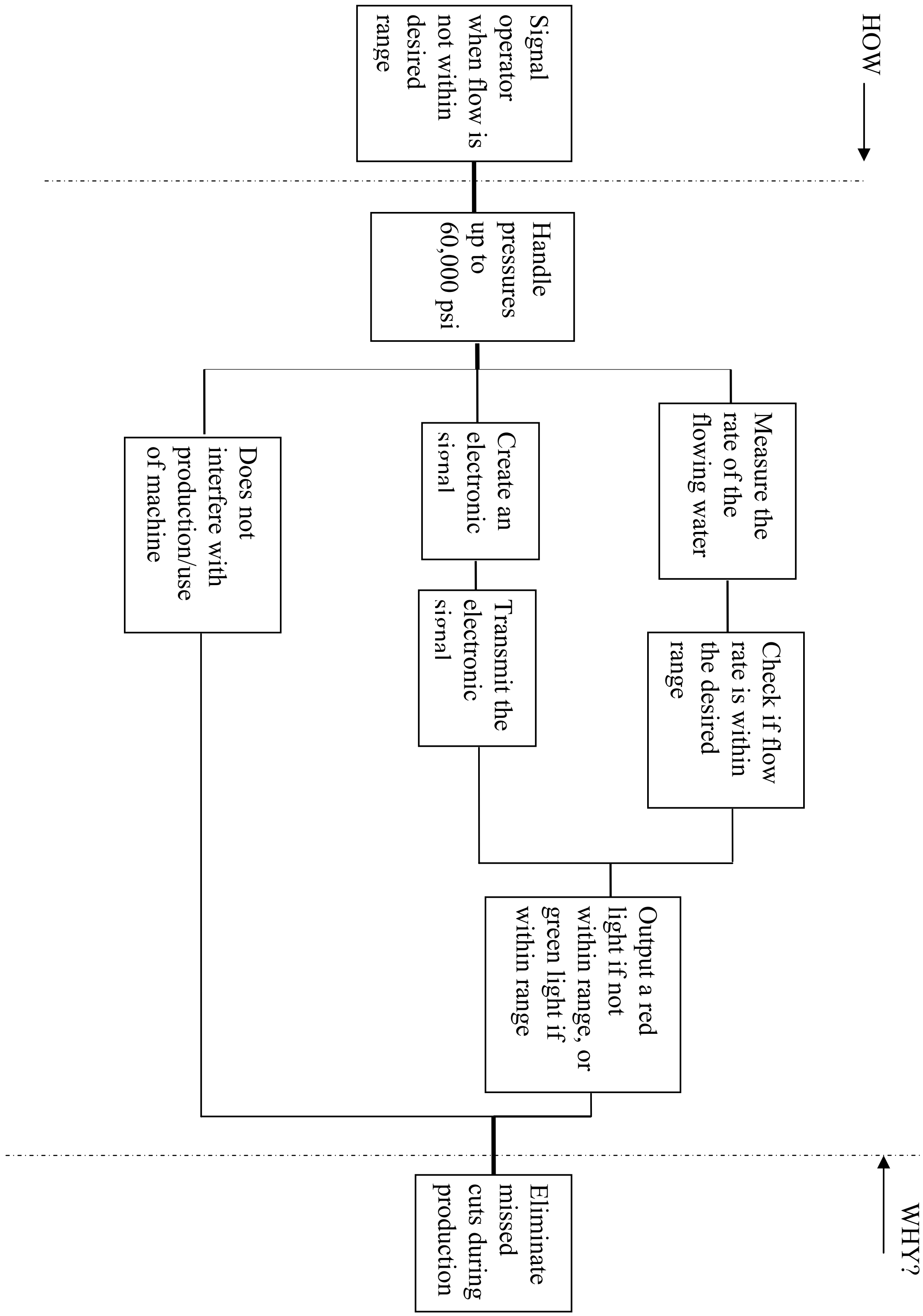
Key:
9 => Strong Relationship
3 => Medium Relationship
1 => Small Relationship
(blank) => Not Related

Weights are figured on a scale of 1 to 10
(ten being most important)

Appendix B: Gantt Chart



Appendix C:FAST Diagram



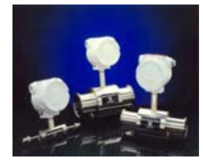
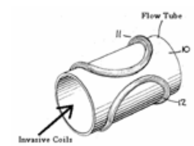
Appendix D: Morphological Chart

Flow Meter / Sub-Function	Thermal	Doppler Ultrasound	Turbine
Non-Invasive	Coupled into the water flow path	Located on outer surface	NA
Invasive	NA	NA	Located within flow path
Pipe Thickness	No smaller than 1/16"	No larger than 3/4"	NA
High Pressure	60000 psi	100000 psi	60000psi
Reaction Time	.5 sec	speed of sound	5 to 50 msec

Flow Meter / Sub-Function	Acoustic	Infrared/Laser	Electromagnetic
Non-Invasive	Filters noise and reads decibel from water flow	Located near orifice of nozzle	Applies magnetic field to the fluid;measures induced voltage difference
Invasive	NA	NA	NA
Pipe Thickness	NA	NA	NA
High Pressure	NA	NA	NA
Reaction Time	NA	NA	NA

Sub-Function \ Flow Meter	Variable Area Flowmeter	Transit Time Ultrasound
Non-Invasive	NA	Utilizes two transmitters and recievers to meaure flow
Invasive	Measures the flow by displacement of a flexibly attached obstruction placed in the flow	NA
Pipe Thickness	NA	No larger than 3/4"
High Pressure	Cannot withstand high pressure applications	100000 psi
Reaction Time	NA	speed of sound

Appendix E: Pugh Chart

	Weight	Doppler Ultrasound	Transit time Ultrasound	Thermal	Turbine	Electro magnetic
						
Measurement of flow rate	0.44	S	S	S	S	S
Compact	0.05	+	+	+	S	S
Durable	0.05	S	S	+	+	S
No reduction in performance	0.12	+	+	+	S	S
No impediment in functionality	0.1	S	S	S	S	S
Low Cost of Install	0.04	S	S	-	-	S
Ease of Manufacture	0.08	+	-	+	S	-
Aesthetics	0.04	S	S	+	S	S
Easy to measure out-of-status	0.08	+	+	+	+	+
Total Pluses		4	3	6	2	1
Total Minuses		0	1	1	1	1
Total		4	2	5	1	0
Weighted Total		**0.33**	**0.17**	**0.38**	**0.09**	**0**

Appendix F: FMEA for Doppler Flow Meter

Part and Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes/ Mechanisms of Failure	Occurrence (O)	Current Design Controls/ Tests	Detection (D)	Recommended Actions	RPN	New S	New O	New D	New RPN
Transmitter and receiver, Combined these two electronic devices can read the flow rate of the	Mis alignment	If these two are not lined up then they will not properly receive each other's signal	10	Vibration of the machine could cause these devices to become loose within the epoxy shell	1	Comparison of theoretical and actual flow rates will be used to test	1	This failure should not occur, the lack of it's occurrence leads to no recommended actions	10	10	1	1	10
Tubing, water flows through this section	Fatigue	Fatigue will cause the tubing to rupture, causing leaks, lowering the flow rate	9	The continuous high pressure of the water will cause the fatigue	4	Visual inspection of the tubing for signgs of fatigue and leaks	2	Once again fatigue will always happen, but by instituting a system of tubing replacemen	72	9	2	2	36
Lubrication, Ultrasound gel is used to increase conductivity and performance of the system	Erosion	The lack of gel will lead to lowered performance of the Doppler system, giving improper flow rates	8	As time passes the gel will start to erode, as a result of vibration and heat	4	Visual inspection to see if gel is in place	4	Implementation of a system to routinely replace the gel will result in there being a constant layer of gel	128	8	1	4	32

Appendix G: FMEA for Turbine Flow Meter

Part and Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes/ Mechanisms of Failure	Occurrence (O)	Current Design Controls/ Tests	Detection (D)	Recommended Actions	RPN	New S	New O	New D	New RPN
Turbine, water flows past, moving turbine, which is used to measure flow rate	Wear	As the turbine wears it will not measure the flow as effectively	7	Matter in the water can cause wear in the turbine, also there is friction between the turbine and the walls which can lead to wear	3	Comparison of theoretical and actual flow rates will be used to test	2	There is no way to stop wear from occurring, friction will always exist, but by testing performance more often it can be detected earlier	42	7	3	1	21
Tubing, water flows through this section	Fatigue	Fatigue will cause the tubing to rupture, causing leaks, lowering the flow rate	9	The continuous high pressure of the water will cause the fatigue	4	Visual inspection of the tubing for signs of fatigue and leaks	2	Once again fatigue will always happen, but by instituting a system of tubing replacement it 's effects can be lessened	72	9	2	2	36

Appendix H: Bill of Materials

Bill of Materials (BOM)

Quantity	Part Description	Purchased From	Part Number	Price (each)
1	Aquasonic 100 ultrasound gel (set of two 8.5 oz bottles)	Ebay	280093239256	$7.95
1	Turbine Flow Meter	AW Company	N/A	$3,500

Appendix I: Consolidated Testing Data

	Test 1			Test 2			Test 3		
Pressure	**No Flow**	**Reading**	**Difference**	**No Flow**	**Reading**	**Difference**	**No Flow**	**Reading**	**Difference**
10000 psi	-0.34	0.55	0.89	0.00	0.49	0.49	0.00	0.47	0.47
20000 psi	-0.13	0.00	0.13	-0.17	0.00	0.17	-0.14	-0.01	0.13
30000 psi	-0.16	0.00	0.16	-0.14	0.50	0.64	-0.18	-0.14	0.03
40000 psi	0.00	0.08	0.08	0.00	0.24	0.24	0.00	0.44	0.44
50000 psi	0.20	0.21	0.01	0.20	0.23	0.03	0.23	0.25	0.02
60000 psi	-0.34	0.17	0.51	-0.25	0.24	0.49	-0.44	0.28	0.72

		Test 4			Average	
Pressure	**No Flow**	**Reading**	**Difference**	**No Flow**	**Reading**	**Difference**
10000 psi	0.00	0.14	0.14	0.00	0.49	0.49
20000 psi	0.00	0.05	0.05	-0.17	0.00	0.17
30000 psi	0.00	0.00	0.00	-0.14	0.50	0.64
40000 psi	0.00	0.20	0.20	0.00	0.24	0.24
50000 psi	0.00	0.18	0.18	0.20	0.23	0.03
60000 psi	0.00	0.05	0.05	-0.25	0.24	0.49

Pressure	**Theoretical Flow Rate**
10000	0.169
15000	0.207
20000	0.239
25000	0.267
30000	0.293
35000	0.316
40000	0.338
45000	0.358
50000	0.378
55000	0.396

Appendix J: Theoretical Flow Rates Provided by KMT Robotic Solutions

Table 1. Actual Motor Power, Flow Rate, Thrust and Pressure Drop for Jet Cutting Systems

Orifice Size	Tubing Size/ Motor HP (BHP)/ Flow Rate (GPM)/ Thrust (LBS)	Pressure Drop per Foot (psi/ft) at X KSI Operating Pressure									
		10.0 KSI	15.0 KSI	20.0 KSI	25.0 KSI	30.0 KSI	35.0 KSI	40.0 KSI	45.0 KSI	50.0 KSI	55.0 KSI
.004	1/4-in. Tubing	0.4	0.5	0.6	0.7	0.8	0.8	0.9	0.9	1.0	1.0
	3/8-in. Tubing	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	9/16-in. Tubing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	BHP	0.28	0.51	0.79	1.10	1.45	1.82	2.23	2.66	3.11	3.59
	GPM	0.033	0.041	0.047	0.053	0.058	0.067	0.067	0.071	0.075	0.078
	LBS	0.18	0.26	0.35	0.44	0.53	0.62	0.70	0.79	0.88	0.97
.005	1/4-in. Tubing	0.7	0.8	1.0	1.1	1.2	1.3	1.4	1.5	1.5	1.6
	3/8-in. Tubing	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2
	9/16-in. Tubing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	BHP	0.43	0.80	1.23	1.72	2.26	2.85	3.48	4.15	4.86	5.61
	GPM	0.052	0.064	0.074	0.082	0.090	0.098	0.104	0.111	0.117	0.122
	LBS	0.27	0.41	0.55	0.69	0.82	0.96	1.10	1.24	1.37	1.51
.006	1/4-in. Tubing	1.0	1.2	1.4	1.6	2.6	3.0	3.4	3.8	4.1	4.5
	3/8-in. Tubing	0.1	0.2	0.2	0.2	0.3	0.4	0.4	0.5	0.5	0.6
	9/16-in. Tubing	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1
	BHP	0.63	1.15	1.15	2.47	3.25	4.10	5.01	5.98	7.00	8.08
	GPM	0.75	0.092	0.092	0.119	0.130	0.140	0.150	0.159	0.168	0.176
	LBS	0.40	0.59	0.59	0.99	1.19	1.38	1.58	1.78	1.98	2.18
.007	1/4-in. Tubing	1.3	2.5	3.2	3.9	4.5	5.2	5.8	6.5	7.1	7.7
	3/8-in. Tubing	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.9	1.0
	9/16-in. Tubing	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	BHP	0.85	1.57	2.41	3.37	4.43	5.58	6.82	8.13	9.53	10.99
	GPM	0.102	0.125	0.145	0.162	0.177	0.191	0.204	0.217	0.229	0.240
	LBS	0.54	0.81	1.08	1.35	1.62	1.88	2.15	2.42	2.69	2.96
.008	1/4-in. Tubing	2.8	3.9	5.1	6.2	7.2	8.3	9.3	10.3	11.3	12.3
	3/8-in. Tubing	0.4	0.5	0.7	0.8	1.0	1.1	1.2	1.4	1.5	1.6
	9/16-in. Tubing	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2
	BHP	1.11	2.04	3.15	4.40	5.78	7.29	8.90	10.62	12.44	14.36
	GPM	0.134	0.164	0.189	0.211	0.231	0.250	0.267	0.283	0.299	0.313
	LBS	0.70	1.06	1.41	1.76	2.11	2.46	2.81	3.17	3.52	3.87
.009	1/4-in. Tubing	4.2	6.0	7.7	9.3	10.9	12.5	14.1	15.6	17.1	18.6
	3/8-in. Tubing	0.6	0.8	1.0	1.2	1.4	1.6	1.9	2.1	2.3	2.4
	9/16-in. Tubing	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.3
	BHP	1.41	2.59	3.98	5.57	7.32	9.22	11.27	13.45	15.75	18.17
	GPM	0.169	0.207	0.239	0.267	0.293	0.316	0.338	0.358	0.378	0.396
	LBS	0.89	1.34	1.78	2.23	2.67	3.12	3.56	4.01	4.45	4.90

Appendix K: Bios

Robert Knaus

Rob is originally from Longmeadow, MA, graduating from Longmeadow High School in 2004. Longmeadow is a suburb of Springfield, MA, on the Connecticut River in western Massachusetts. Rob is also a transfer student from the University of Massachusetts—Amherst. Rob decided to major in mechanical engineering his last year of high school due to his interest in machines and transferred in as a mechanical engineering major. After graduating, Rob intends to pursue a master's and potentially a Ph.D. in mechanical engineering, specializing in fluid mechanics.

Ninad Naik

Ninad is a senior in Mechanical Engineering. He is from Mumbai, India and was living in Sao Paulo, Brazil at the time of applying to the University of Michigan. He has an interest in cars, and designs/sketches them as a hobby. His love for cars led him to join the Mechanical Engineering program at the university. After graduation, Ninad will join the Huron Consulting Group as a consultant. He has a keen interest in Finance and Corporate Strategy and is the founder of the BOND Consulting Group at U of M.

Devin T. Rauss

Devin has lived his entire life in Grosse Pointe Woods, MI, about 10 miles east of Detroit. Where he attended and graduated, in 2003, Grosse Pointe North High School. Devin always knew that he would attend the University of Michigan, with the precedent being set by his mother, father, brother and sister, as well as various other family members. Devin decided on engineering while he was still in high school as a result of his above average abilities in math and science. The decision was made on Mechanical Engineering after taking an introductory class that summarized all the different fields of engineering. The broad area that a Mechanical Engineering degree encompasses is what enticed Devin to pick this field. In the future Devin hopes to be working, and possibly go back to school for Law school.

Ralph E. Sudderth

Ralph is originally from Alcoa, TN, graduating from Alcoa High School Class of 2003. He chose the University of Michigan because of its academic excellence and deeply cultural environment. He will graduate with a Bachelors of Science in Mechanical Engineering in Fall 2007. He is currently undecided if he will get his Masters degree or go into the work force after graduating. Outside of engineering Ralph is a devoted husband and father.

Christopher VanDeWiele

Chris was raised in a small one light town in eastern Michigan called Yale. He graduated there in 2002. He has wanted to go to the University of Michigan since he was young, and decided that with his exceptional science and math skills that engineering was the perfect choice of degrees to persue. He will be graduating with Bachelors of Science in Mechanical Engineering in the fall of 2007.