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ABSTRACT

The United States Army is beginning to use turbine flow meters to track bulk fluid fuel transfers and receipts from tanker trucks to storage tanks, bags and end users. Previous research has been conducted to improve the accuracy of measurements used to record large-volume fuel transactions. Installation of this research included implementing temperature, density and viscosity correction algorithms and automated reporting on measured fluid transfer volumes onto the embedded processor.

The objective of this research was to use acoustic and vibration data to detect failure modes which can cause flow measurement error. Lab testing on the flow meter’s turbine blades determined key frequency components in the moving parts of the flow meter. Field testing, at a make-shift ARL fuel storage and distribution farm (using water as a surrogate for fuel), determined the characteristics of a normally functioning meter. Several failure modes were detected when field testing these flow meters resulting in flow measurement errors greater than the allowable 0.5% of total volume. After initial analysis, testing was conducted to introduce two faults into the flow meter: air entrainment and debris caught in the flow loop.

Further analysis was performed to identify characteristics of these two failure modes. Air entrainment in the flow meter caused a significant decrease in amplitude to a 4kHz tone normally present in vibration data. Debris caught in the flow meter turbine blades resulted in an overall increase in vibration amplitude as well as a drastic increase in amplitude to frequencies between 1.6kHz and 1.8kHz. Based upon both of these observations, preliminary detection algorithms were developed with the intent of Condition Based Maintenance. Future work to improve flow meter accuracy includes detecting calibration drift and internal sensor placement.
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Chapter 1

Introduction

The United States Army maintains Fuel System Supply Points (FSSP), which receive bulk fuel deliveries from tankers and serve as holding areas for fuel until it is dispensed either directly to users or to secondary bulk fuel delivery vehicles to support forward operating bases and outposts. It is important to accurately track fuel receipts and transfers that take place in these “fuel farms”. One of the current, and less accurate, methods of measuring fuel transfers is using fluid level sensors on the delivery vehicles to detect the amount of fuel in a tank before and after a transaction. Penn State’s Applied Research Laboratory has been working with the Army to develop a more accurate method of accounting for fuel inventory by using flow meters to record large volume fuel flow into and out of the FSSP storage containers. While this method has been shown to accurately track inventory transactions, faults in the flow meters can reduce the accuracy. The research in this thesis will specifically look into detecting faults in these flow meters with the goal of maintaining accurate transaction capture to within 0.5% of the total volume transferred.

1.1 Current Fluid Tracking Systems

In addition to the military, there are many commercial industries and other government agencies that also rely on proper metering and tracking of fluid systems. In any fluid system there is a means of holding fluid (e.g. tanks, bladders and pools), a means of moving fluid (e.g. fans and pumps), as well as methods of tracking fluid flow (e.g. flow meters or fluid volume sensors). One particular example of a commercial industry that relies on fluid systems metering is the
mining industry. Water is used in many drilling applications of mining so a water flow system is necessary. A water tank is required for storing water when it is not flowing, a pump is required for moving water from the tank to the drilling site and finally there must be a metering or gauging technology keeping track of the amount of water flowing through the system. In any application, it is important to gauge how much fluid is being moved from one system component to another.

Army FSSP’s are the tactical method of fuel transfers and receipts between various military vehicles and their fuel source. Figure 1.1 shows an aerial view of an Army fuel farm. Fuel farms have the same components as any fluid system does. Fuel can be held in truck-mounted fuel tanks, shown in Fig. 1.2, and also in fuel bladders, which are large rubber bags that can hold from several 100 to 100,000 gallons of fuel, shown in Fig. 1.3. Diesel pumps, shown in Fig. 1.4, are the typical means of moving fuel from one component of the system to another. Many of these components are visible in Fig. 1.1. There is a defined procedure for a military vehicle acquiring fuel from a fuel farm to ensure an accurate and efficient fuel transaction. This begins with identifying the type of vehicle that requires fuel as well as identifying the fuel type needed. A fuel farm operator will log this information as well as the amount of fuel requested. Another fuel farm operator will open and close the necessary valves to open up the proper flow path between the fuel bladder and the vehicle. Then the operator will turn on the pump and push the fuel from the bag to the vehicle. Finally, the total transaction information will be logged and the fuel transaction concluded. An example of a vehicle receiving fuel can be seen in Fig. 1.5. In this transaction, a turbine flow meter, shown in the red circle, is being used to gauge the volume of fuel being transferred to the vehicle.
Figure 1.1: Birds-eye view of an Army fuel farm [1]

Figure 1.2: Truck-mounted fuel tank used in ARL testing sites
Figure 1.3: Fuel bladder [2]

Figure 1.4: Diesel pump used in ARL testing sites
Due to the large number of vehicles that require fuel, there is a large volume of fuel that passes through a fuel farm on a given day, therefore a reliable and accurate means of keeping track of fuel is essential. A turbine flow meter is a method of tracking fuel on Army fuel farms; an example is shown in Fig. 1.6. Unfortunately, there are several sources of error that can be introduced into this system of fuel inventory via the flow meter.
Proper metering and measurement are both very important to a fluid distribution center that holds such large volumes of fuel. Only minimal measurement errors are tolerated to ensure minimal waste. The function of the flow meter in an Army FSSP is to accurately measure large-volumes of fuel transaction from the storage bags to the end user. A flow meter can be seen in the red circle in Fig. 1.5 being used to verify that the military vehicle is receiving the proper amount of fuel. These turbine flow meters are interspersed throughout Army fuel farms at many measurement points. For a given transaction, these measurements may be compared to ensure accuracy, determine a fault in the flow loop or determine a fault in one of the meters. Typically, they are placed in the inlet and the outlet of a fuel bladder to track fuel going in or out of storage. A flow meter will be placed right before the vehicle that is to receive fuel to compare with the bag-side meters. There will also be a flow meter where tankers bring in fuel to be deposited into the bags for storage. The flow meter’s accurate measurement capabilities enable fuel farms to properly and accurately conduct fuel transactions.
The sources of error that this research explored in particular were air entrainment and large debris in the flow loop. Air entrainment is a form of two-phase flow where air gets caught in the hoses and causes air and fuel to flow through the flow meter rather than just fuel. This causes errors because the turbine in the flow meter will spin, and therefore read flow, whether the pipes are entirely filled with fuel or not. Debris caught up in the flow loop can slow the turbine and also cause an error in the reading. Pieces of rubber and sand or dirt that flow through the meter can also damage the interior and cause it to fall out of calibration. Further details into the nature and effects of faults in the tactical flow meter are described further in Chapter 2. The objective of this research was to study acoustic detection methods to identify faults in the flow loop that could cause an error in measurement or require repair.

1.2 Reliability-Centered Maintenance

Originally used in the manufacturing industry [4], Reliability-Centered Maintenance (RCM) was, and still is, a highly effective system for determining the most effective machine maintenance procedure. RCM starts with a Failure Modes and Effects Analysis (FMEA), used to determine any and all of the faults of a machine or system, to serve as a basis for maintenance decisions. This analysis requires that the researcher defines what a failure is, and ultimately the definition of failure depends on the functionality of the machine or system. The second step in an FMEA is to list all of the possible failures of a machine or system and calculate the overall costs of each failure as well as the overall costs of maintenance for each failure. From here, a researcher can determine which failures should be addressed in an RCM analysis as well as which approaches to maintenance should be employed [5]. A full FMEA of the flow meter is detailed in Chapter 2.
An RCM analysis will result in one of four main courses of action: 1. Perform no maintenance until the component fails, 2. Perform Preventative Maintenance (PM), 3. Perform Condition-Based Maintenance (CBM) 4. Redesign. Figure 1.7 provides a visual representation of the three different maintenance options; the redesign option is not considered a maintenance issue and is therefore not considered in this research. The first maintenance option is also known as Run-To-Fail (RTF). For this particular research, this option was not satisfactory due to the costs of the various components in a typical flow loop as well as the time taken to replace a broken component. The second option is PM, also often known as time-based or usage-based maintenance. Due to the variability of flow meter calibration requirements, discussed further in Chapter 3, time-based calibration and maintenance, although standard practice, was unacceptable. The third option is to utilize CBM. This option consists of two different methods: Predictive Maintenance (PdM) and real-time monitoring. PdM involves using data collected from the machine or system to learn how it operates and throw up a flag before a failure occurs. Real-time monitoring will continually collect data on a machine or system and using the most recent data to detect when a failure occurs [5]. Real-time monitoring CBM proved to be the best approach to maintenance of the flow meter because failures were detectable when they occurred and not before they occurred. Further details on detecting failures are presented in Chapter 5. The scope of this thesis focuses on implementing CBM methods to the flow meter. The next section provides further details into implementing CBM.
1.3 Condition-Based Maintenance

Condition-Based Maintenance (CBM) is one of the four solutions to an RCM analysis and is the method of maintenance that is the focus of this research. CBM involves collecting data from the machine or system in question and utilizing this data to predict or detect failure [5]. Due to the commonplace usage of rotating machinery in commercial industry and military systems, extensive research has been conducted in the field of CBM. Plants based in the United States spend hundreds of billions of dollars on systems maintenance and almost half of this cost is due to poor maintenance procedures [6]. The upfront cost of system research, data collection, and monitoring algorithm development can be large, but if an effective solution can be implemented human interaction with the machine would significantly decrease as well as the need for complete system shutdowns for maintenance or failures.
While each piece of machinery is unique, and requires its own detailed analysis to fully understand failure modes, effects, and condition indicators, there is always a similar approach to implementing the monitoring part of the condition-based maintenance for the problem: 1. Data acquisition 2. Data processing 3. Decision-Making [6,7]. Data acquisition is a required first step in CBM to provide behavioral data that describes the system in question. Data processing is required to present the data in a useable fashion and extract the necessary qualities of the data. The final step, the decision-making step, typically involves creating a physics-based model or a data-driven model [7] that paints a picture of how a “healthy”, or properly functioning, machine behaves. A researcher will then develop fault-detection algorithms that compare acquired data against the model. The presented research was conducted in an attempt to create a data-driven model for the tactical flow meter and determine characteristics in acquired data that would indicate a fault.

A CBM approach requires several pieces of equipment to realize: sensors, data-acquisition means, processing methods and reporting methods [8]. Sensors measure the vibrational and acoustical responses of a machine or a system. Data acquisition hardware and software (DAQ) collects the data for storage, processing or reporting. The specifics on the sensors and the data collection means used in this research are detailed further in Chapter 4. Data processing converts the raw data into a useable and readable format for the end user. Chapter 5 describes the processing techniques in greater detail. Finally, there must be a recipient of the data, whether it be a human or perhaps a computer that makes maintenance decisions. Other ARL research has gone into means of communicating the flow rates and receipt/transfer amounts from the flow meters to an operator. There is a mesh radio network that links the meter boards to a central computer that collects the data. There is also a QR code reader app for smart phones that has been developed to keep track of transfers/receipts as well as information about the vehicles and equipment used in a transaction. These two technologies are examples of reporting
technologies that are already in place and that could be expanded upon to report maintenance information from the flow meters.

### 1.4 Scope of Thesis

The goal of this thesis is to explore the capability of acoustically detecting failures in a tactical flow meter. The data collected from running the flow meters supports analysis of air entrainment as well as debris caught in the flow. Part of the damage and debris problem is gradual component damage, which is directly related to issues with calibration. Detecting damage severe enough to break turbine blades or bearings was not considered in this research due to the lack of spare components.

Chapter 2 describes how the FloCat flow meter used in the Army fuel farm operates, the functionality of the ARL-developed modifications and the various faults associated with the flow meter. Chapter 3 discusses the sources of fluid-borne acoustic and structure-borne vibration in the flow meter, the typical behavior of a flow meter, and the characteristics of several of the flow meter faults. Chapter 4 summarizes the test equipment used in collecting data for each test set up. It also describes the different components and procedures for each test set up as well as what data was collected for each set up. Chapter 5 shows the results of all of the collected data and the ramifications of these results. Finally, Chapter 6 includes conclusions that can be drawn from this research as well as potential avenues for future studies with the tactical flow meter.
Chapter 2

Flow Meter Functionality and Faults

The United States Army uses large fluid distribution centers, or Fuel System Supply Points (FSSP), to provide fuel to various military vehicles. Large amounts of fuel are stored in rubber fuel bladders on site and distributed to the end user with diesel fluid pumps. The Army is beginning to use volumetric turbine flow meters as the solution for tracking large-volume fluid transactions at the input and output to Army FSSP’s, or “fuel farms”.

The most commonly used type of meter is a turbine flow meter manufactured by FloCat and modified by Penn State’s Applied Research Laboratory (ARL). The flow meter utilizes a magnetic pickup to read flow rate and the microprocessor on-board reads the data and provides the user with transaction information. This chapter will describe the functionality and current usage of the flow meter, discuss research ARL has already integrated into the design and provide the results of the Failure Modes and Effects Analysis (FMEA) performed.

2.1 Other Flow Meter Technologies

While the focus of this research is centered around the failure modes of the turbine flow meter, a few other types of flow meters will be briefly mentioned. There are many other categories of flow meters on the market besides the turbine flow meter, some examples of which are mechanical flow meters, pressure flow meters, optical flow meters, ultrasonic flow meters and electromagnetic flow meters. There are many specific types within these general categories that aren’t mentioned because they are so numerous. Mechanical flow meters measure the flow rate by means of the fluid displacing a component of the meter, whether it be a piston, turbine, gear or
impeller. Many pressure flow meters constrict the flow and infer the flow rate from the differences in pressure before and after the constriction. Optical flow meters use two thinly-spaced lasers to detect the speed of small particles that flow along with the fluid. Ultrasonic flow meters utilize an ultrasonic transducer to either reflect sound off of particles in the flow to determine their speed or compare signal propagation times with the flow and through the flow. Finally, electromagnetic flow meters will induce a magnetic field in the flow and determine flow rate from the potential difference that the flow creates. While all of these types of flow meters are used commercially, the turbine flow meter is the one that is the focus of this research.

2.2 Flow Meter Function

2.2.1 FloCat Flow Meters

The flow meter has three main components that contribute to its simple operating principle. First, there is a four-inch diameter pipe with cam locks on either end shown in Fig. 2.1. Hoses are fixed to either end so the flow meter can be inserted into the fluid distribution flow loop. Second, there are two electronics housings attached to the main structure, shown in Fig. 2.2, which protect the microprocessor board developed by ARL. Finally, there are two sets of guide vanes on either side of an eight-blade turbine inside the pipe. Figure 2.3 shows the turbine blade assembly located inside the pipe section. The turbine is the component that converts fluid flow into a mechanical movement, which is the first step in reading flow rate. It is also the only moving part in the flow meter, making it the main source of fluid-borne acoustic and structure-borne vibration energy, discussed further in Chapter 3. In addition to these main components, there is also a roll cage surrounding the entire structure for protection and durability.
Figure 2.1: FloCat flow meter technology

Figure 2.2: Housing for electronics on the front of the flow meter
The turbine is the key to measuring fluid flow rate in the flow meter. A diagram of the process is shown in Fig. 2.4. Fluid passes through the guide vanes and the turbine causing it to spin. Inside the meter is an electromagnetic pickup, mounted near the turbine that generates an AC sinusoidal signal that matches the blade-passage frequency of the turbine as fuel passes through the meter. In the context of this research, the blade-passage frequency is defined as the number of times any of the eight blades passes through the pickup’s magnetic field in one second. The faster the flow rate, the higher the blade-passage frequency. This blade-passage frequency reading is calculated by the embedded microprocessor board and converted to volume velocity (gallons per minute) [9].
2.2.2 Embedded Microprocessor Technology and Research

ARL has performed research on improving the accuracy of the flow meter as well as several means of reporting fluid transaction data to the end user. This research has been implemented on the embedded microprocessor board that is housed in the electronics casings, shown in Fig. 2.2. This is in addition to the primary function of reading the signal from the magnetic pickup and interpreting a flow rate from it. The blade-passage frequency is fed into the board and is compared to the on-board calibration data set provided for the specific flow meter. These calibration tables are provided by Transcat Calibration Services [9]. An example of calibration data is plotted below in Fig. 2.5. The inverse slope at a particular point on this plot will provide the flow rate in gallons per second, and is ultimately reported to the user as gallons per minute. Using allotted run time, a “trip meter” of how many gallons have been passed in a given transaction can be calculated.
The different fuel types stored in Army FSSP’s can vary significantly in density with changes in temperature. ARL has developed density-correction algorithms that have been coded into the embedded processor on-board the flow meter. A resistance temperature detector (RTD) has been mounted in the flow meter to report back the temperature of the fluid flowing through the flow meter pipe. This is used by the embedded processor to provide a corrected flow rate and ultimately, a corrected transaction volume. This was part of the solution to improving the accuracy of the flow meter in the field.

There has also been research and development into the reporting capabilities of the embedded processor in the flow meter. ARL has implemented a mesh radio network that allows the fuel farm operator to remotely get real-time data from the flow meters. Several of the flow meters have these radios mounted on the existing boards, but also have the capability of running without a radio. Another method that has expanded the scope of flow meter reporting is a QR code reading cell phone app. The LCD screens on the flow meter boards display variable QR
codes that provide transaction data to the app. A fuel farm operator will scan the code before a transaction, as well as enter information about the vehicle receiving or providing fuel, and then scan the code afterward to acquire a total volume of the transaction.

2.3 Failure Mode and Effects Analysis

As mentioned in Chapter 1, conducting an FMEA is one of the first steps in performing any Reliability-Center Maintenance (RCM) analysis on a machine or system. It was ultimately decided that Condition-Based Maintenance (CBM) was the best course of action to deal with failure modes in the flow meter. Before an FMEA could be done, a definition of what a failure is had to be provided. For the intended purpose of measuring large-volume fluid transactions, a failure mode in the flow meter is defined as any condition in which the meter reports fluid flow with greater than a 0.5% error in total volume or if the meter reads nothing at all. With this definition, an FMEA could be properly conducted.

Several failure modes were discovered when performing field tests on the make-shift fuel farm. Failure modes that caused the meter to not read at all tended to be problems with the magnetic pickup sensor, the electronics, or the embedded microcontroller board inside the flow meter. Examples of these include components overheating, discrepancies between different board versions, using the wrong components, dead batteries, or the battery case warping. Failure modes that could cause the meter to read greater than 0.5% error tended to be problems with the rotating assembly. Table 2.1 shows a summary of the FMEA and all of the failure modes considered in the analysis. Some of these failure modes can potentially be detected using acoustical and vibrational sensors. These failure modes are examined further in Chapter 3 to investigate their fluid-borne acoustic and structure-borne vibration characteristics.
Table 2.1 High Level FMEA results

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Component</th>
<th>Failure Mode</th>
<th>Reason</th>
<th>Operational Impact</th>
</tr>
</thead>
<tbody>
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<td>Control System</td>
<td>Micro-processor Board</td>
<td>LCD overheats</td>
<td>LCD fails above 156 degrees</td>
<td>Meter reads nothing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Incorrect Components</td>
<td>Board revisions, some components don't get populated onto new board</td>
<td>Batteries die</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Incorrect Batteries</td>
<td>Generic 9V batteries aren't powerful enough</td>
<td>Meter reads nothing</td>
</tr>
<tr>
<td></td>
<td>Battery Case Warped</td>
<td>Battery cases warp when replacing batteries</td>
<td>Meter reads nothing</td>
<td></td>
</tr>
<tr>
<td>Rotating Assembly</td>
<td>Turbine and Bearings</td>
<td>Air Entrainment</td>
<td>Turbine spins regardless of what fluid/gas passes through it</td>
<td>Meter reads incorrect output</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Turbine Obstruction</td>
<td>Material from the bladders and gaskets get caught in turbine</td>
<td>Meter reads incorrect output</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Out of Calibration</td>
<td>Usage over time causes the meters to fall out of calibration</td>
<td>Meter reads incorrect output</td>
</tr>
<tr>
<td></td>
<td>Damage/Wear and Tear</td>
<td>Silica, metal shavings and sand get caught in flow/damage parts</td>
<td>Meter reads incorrect output</td>
<td></td>
</tr>
</tbody>
</table>

The first of the rotating assembly failure modes is air entrainment. When emptying either a tank or a fuel bag, air gets caught and mixed in with the fluid entering the flow loop and produces a “gurgling” effect. This air will travel down the hoses with the fuel as air “slugs” and pass through the meter turbine entrained in fuel. Since the turbine will spin whether you push fluid or air past it, the meter will over-estimate the amount of fuel in a given transaction.

Another cause for error is debris caught in the meter. The kinds of debris that are typically found in fuel farm applications are large pieces of rubber, coming from the fuel bladders, pieces of gasket material from couplers and connectors, or environmental debris such as grass or sand. On occasion, pieces of rubber dislodge themselves from the hose coupling in the bladders and enter the flow loop. They will then encounter a flow meter turbine and impede it
from spinning properly as well as causing additional flow turbulence. An example of debris in the flow meter is shown in Fig. 2.6. Things such as vegetation or sand are less obvious impediments. Strands of grass will wrap themselves around the turbine shaft and cause it to spin incorrectly, as shown in Fig. 2.7. Sand or other dirt can also get caught between the turbine shaft and the bearings.

Figure 2.6: Rubber debris caught in flow meter turbine
Meters that are out of calibration will also read incorrect flow. Any meter usage will change the condition of the turbine and the bearings. A meter will fall out of calibration because of regular wear and tear over time as well as any damage to the turbine or the bearings. Meter calibration currently occurs once per calendar year, regardless of its actual condition. When a meter is brought in for calibration, the technician will calibrate it against a master meter and generate calibration curves based upon its current condition. If any of the parts, such as the turbine or the bearings in the guide vanes, are damaged or broken beyond use, they are replaced.

Finally, any damage to the meter’s turbine or bearings will cause it to report inaccurate flow. Related to the debris mode, sand and metal shavings caught in the flow can irreparably damage the bearings or the turbine. Since the journal bearings inside the meter are self-lubricating during normal usage, air blasting the meter (passing air rather than fuel) can also damage the bearings. One of the goals of this research is to develop methods to detect that a meter is out of calibration; thus allowing a transition from time to condition-based calibration and maintenance.
Chapter 3

Acoustics of the Flow Meter

This chapter explores the airborne acoustic and structural vibration properties of the flow meter. This includes typical characteristics of the flow meter, the fluid-borne acoustic and structure-borne vibration sources and the processes that go into the failure modes of the flow meter. Since this research is largely driven by constructing a data-driven model rather than an analytical model, several data sets will be presented in this chapter to use as a basis of analysis. Data from initial field testing will be presented as well as extensive modal analysis testing to compare theoretical and measured acoustic characteristics. Also included is a more in-depth analysis of the rotational assembly failure modes discussed in the previous chapter.

3.1 Typical Flow Meter Characteristics

Before discussing the sources of fluid-borne acoustics and structure-borne vibration in the flow meter, field data is presented to show the typical frequency characteristics of measured acoustic signals. This will provide a basis for the subsequent analytical study. The initial field data was collected at a makeshift Fuel System Supply Point (FSSP) constructed by the Applied Research Lab (ARL) at Penn State to serve as a fuel and logistics technology Systems Integration Laboratory (SIL). More details on the FSSP SIL are discussed extensively in Chapter 4. Many datasets were produced in this initial testing to ensure a solid understanding of how the flow meter functioned under typical operating conditions. The majority of fluid transactions performed at this test site produced the same frequency characteristics. This meant that the behavior of the flow meter was not only predictable, but also repeatable. An example spectrogram from a flow
meter fluid transaction is shown in Fig. 3.1. This dataset was collected with an accelerometer mounted on the exterior of a flow meter body and has the same three frequency bands typical to a flow meter vibration response (details on the sensor placement and DAQ parameters that produced this data are discussed further in Chapter 4). Figure 3.1 shows strong energy at 4kHz, 1.6kHz-1.8kHz and 1kHz-1.1kHz. The origin of these frequencies is discussed in the next section. Figure 3.1 also shows the three stages of a fluid transaction: ramp up, main flow, ramp down. The ramp up stage occurs when the pump is turned on to idle speed and then the speed is increased to move more fluid. The main flow stage is the stage of flow where the pump speed is at a maximum and where most of the fluid in a transaction is moved. The ramp down stage occurs when the pump speed is brought back down to idle then finally turned off.

![Example accelerometer response spectrogram](image)

Figure 3.1: Example accelerometer response spectrogram
3.2 Sources of Acoustics and Vibration

While the turbine is the only moving component of the flow meter, there are several potential sources of fluid-borne acoustics and structure-borne vibration that contributed to the typical flow meter frequency response. Some of the sources are a result of the turbine, such as the turbine blade modal frequencies and the blade-passage frequency. Other frequency components are artifacts of fluid flow, such as flow turbulence. Regardless of whether they all contribute to fault detection, all of the sources of acoustics and vibration will be discussed in this section.

3.2.1 Turbine-Blade Passage Frequency

The first vibration source to consider is the blade-passage frequency. In the context of this research, the blade-passage frequency is defined as the number of times any of the eight blades passes through the pickup’s magnetic field in one second (8x the shaft rotation frequency). Although it isn’t particularly easy to spot in Fig. 3.1, this tone is present in much of the preliminary data. Figure 3.2 shows the average of many smaller FFT’s taken from a typical fluid transaction. This plot was created by segmenting the time series, collected with an accelerometer, of the constant flow portion of the fluid transaction into 100 blocks and averaging their frequency spectra. The 313Hz frequency marker indicates the blade-passage frequency of the turbine for the majority of the transaction, which translates to about 570 gallons per minute (GPM). When the turbine spins, the blades will create a pulse every time they pass by the accelerometer mounting location. These pulses are periodic when the turbine spins at the same rate and therefore show up as strong vibrational energy at this frequency. For a typical transaction, the blade-passage frequency lies anywhere between 250Hz-350Hz, or 450GPM-610GPM (note that the GPM depends on the meter). These findings were verified by also noting the flow rate in gallons per
minute for the majority of each fluid transaction (the flow rate changed due to the changes in
diesel pump speed) and back-calculating the blade-passage frequency utilizing the calibration
data. The back-calculated blade-passage frequency was always within ±3Hz of the measured
blade-passage frequency measured with the accelerometer. Back-calculating the blade-passage
frequency from the flow rate requires a more detailed understanding of the flow rate calculation
discussion from Chapter 2.

![Accelerometer frequency response of fluid transaction (focus on blade-passage)](image)

Figure 3.2: Accelerometer frequency response of fluid transaction (focus on blade-passage)

The flow meter receives the blade-passage frequency measurement from the magnetic
pickup and the on-board processor calculates a flow rate. The blade-passage frequency is defined
as the number of blades that pass through the pickup’s magnetic field in one. Figure 2.5 shows
the details for calculating the flow rate using the turbine blade passage frequency. The blade-
passage frequency (green point) is compared to the calibration data points and the processor
linearly interpolates the cycles per gallon value (red tick mark) from the two points to the left and
right of the given blade-passage frequency (red arrows). With the linearly interpolated 
cycles/gallon value on the y-axis and the blade-passage frequency, the flow rate is calculated 
using

\[
\text{Flow Rate} = \frac{\text{Blade Passage Frequency}}{\text{Linearly Interpolated Cycles/Gallon}} \text{ [gal/s]}. \tag{3.1}
\]

As previously mentioned, ARL developed algorithms to improve the accuracy of the flow 
meter measurements by correcting for fuel viscosity as well as volume fluctuation, which depends 
on the fluid type and the temperature. First, a fluid viscosity factor is multiplied by the flow rate 
to correct for viscosity, which depends upon the diameter of the flow meter, the temperature of 
the fluid and the fuel type. These factors come from a look-up table programed in the embedded 
processor. Since different fluids can change in volume based upon the density of the fluid and the 
temperature of the fluid, a second set of corrections was necessary. Volume correction standards 
were provided by API (American Petroleum Institute) as a look-up table of data to normalize 
volume corrections to a standard temperature of 60°F depending upon the fluid’s density and 
actual temperature. Ultimately, the data from API was linear, so the volume correction factor is 
calculated via linear fit equations interpolated from the look-up tables. Finally, this factor is 
multiplied by the flow rate and reported to the end user.

Since the forward calculation of the flow rate from the blade-passage frequency uses a 
linear interpolation method, and therefore knowledge of what two points the input blade-passage 
frequency lies between, backwards calculating the blade-passage frequency from a flow rate is 
not as simple. The first step was to calculate all of the possible slopes from the calibration data. 
Since there were only ten data points, only nine slopes needed to be processed. Second, nine 
potential blade-passage frequencies were determined for all of the possible slopes calculated 
between the ten calibration points. Next, all nine of the potential blade-passage frequencies and 
all nine of the slope values were used to calculate a 9x9 matrix of 81 potential flow rates. The last
step was to compare all of the possible flow rates to the flow rate originally input into the algorithm and output the blade-passage frequency that produced the flow rate closest to the original. As mentioned previously, the estimated blade-passage frequency was usually within \( \pm 3\text{Hz} \) of the measured blade-passage frequency.

An accelerometer reading of the blade-passage frequency could potentially be a future means of measuring this frequency and comparing it against the existing sensor reading. A tight bandpass filter would be required to isolate the typical range of this frequency. It is also worth mentioning that some of the data sets also showed a peak in vibration at three times this blade passage frequency. This is because there are three guide vanes in front of the turbine blades and each guide vane will interact with each of the turbine blades in a similar manner as the turbine blade interacting with the accelerometer mounting location.

### 3.2.2 Turbine Blade Modal Analysis

The turbine is the only component of the flow meter that moves in the process of a fluid transaction. It is also the component that receives the most excitation from fluid flow. For these reasons, it was determined that many of the typical frequency components were a result of vibration of the turbine blades. Figure 3.3 is a repeat of Fig. 3.2 but with additional frequency peaks identified. This response shows frequency peaks around 1.1kHz, between 1.6kHz-1.8kHz and around 4kHz. These frequencies come from the modal properties of the turbine blades. To verify the source of these frequencies, several laboratory modal analysis tests were conducted on the turbine blades of a flow meter. Additional testing was performed to track the vibrational path of these characteristic frequency attributes. This procedure consisted of two parts: modal analysis in air and modal analysis in water. It is important to note that each turbine blade is manufactured to be the same as others in different flow meters but any slight differences in frequency can be
attributed to manufacturing imperfections. Additionally, each turbine blade on the same assembly is slightly different from the other blades mounted on the same shaft.

Figure 3.3: Accelerometer frequency response of fluid transaction (focus on modal analysis)

To perform the in-air test, the turbine blade and shaft assembly were mounted between the two guide-vane bearing components outside of the flow meter body. This was to closely mimic the conditions in which the turbine normally operates, shown in Fig. 3.4. The measurement microphone was set on a stand pointed directly at the test assembly and one of the blades was struck with the force hammer. Using a force hammer provided data from the input hammer strike which enabled the calculation of Frequency Response Functions (FRF) for the turbine blades. Both sensors were connected to the DAQ and recorded simultaneously. A LabView program was set up to record with a sample rate of 20,000 samples per second for six-second intervals. This was to give the blade enough time to ring out before the next hammer strike. The details of the
DAQ and sensors are described in full in Chapter 4. Figure 3.5 shows the results of several calculated FRF’s averaged together.

Figure 3.4: In-air turbine-guide vane assembly test setup

Figure 3.5: Turbine blade hammer strike averaged FRF

Some of the frequency peaks shown in Fig. 3.5 match up well with the peaks shown in Fig. 3.3. The hammer excited frequencies around 1.1kHz and between 1.6kHz-1.8kHz. The
turbine blades in the flow meter measured in Fig. 3.3 are not the same as the ones analyzed in Fig. 3.5, hence the slight differences in these frequency peaks. One peak that is significantly different is the strong energy at 4.8kHz, where it would be expected to be closer to 4kHz. To explore further, a second vibration test was conducted with the turbine blades submerged in water rather than air. Modal analysis was conducted in water to better replicate the field testing operating conditions of the flow meter.

A slightly different test procedure was required to test the turbine blade assembly in water. A fully assembled meter was filled with water and tipped on end with one end closed, so that the water wouldn’t leak out, and open on the other, to allow access to the turbine blades. Accelerometers were placed on the exterior of the flow meter (see Chapter 4 for details on field accelerometer placement). Using a real flow meter and using the field procedure accelerometer placement was an attempt to recreate the operating parameters of the flow meter. Rather than using a force hammer in this test, a long screwdriver was used to excite the turbine blades because a force hammer could not fit down through the flow meter pipe. Since an FRF could not be calculated, the relevant data was manually selected from each impulse response, an example of which is shown in Fig. 3.6. This test utilized the same data collection parameters: 20k sample rate and six second snapshot length. The results of this line of experimentation are shown in Fig. 3.7.
Figure 3.6: Example of turbine blade impulse response when struck in water

Figure 3.7: Averaged turbine blade modal response analysis in water
It was difficult to extract results from this particular test due to the small amplitude responses from the exterior accelerometers and the quick decay of the steady-state response. An example of the quick decay of the turbine blade vibration when struck in water is shown in Fig. 3.6, compared to the decay of the turbine blade vibration when struck in air, shown in Fig. 3.8. Analysis was limited to 0.2 second time series from each impulse. All of these factors contributed to a low signal-to-noise ratio. Figure 3.7 is the result of averaging together the FFT magnitude squared of twenty turbine blade strikes and taking the resulting square root. These results show all of the frequency components present in Fig. 3.3: 1.1kHz, 1.6-1.8kHz and 4kHz. It is important to note that the slight differences in exact modal frequencies are due to noise in the signal as well as the fact that the turbine blades present in the flow meter measured in Fig. 3.3 are different from the blades that yielded results in Fig. 3.7. It is important to note that the two frequency peaks surrounding 3000Hz were not considered for this analysis because they were not typically present in field data. These two peaks were likely another modal frequency of the turbine blades that was slightly different in each blade and became two separate tones during the averaging process.
Fluid loading of mode shapes is one possible explanation for the differences in 4kHz modal frequencies between the in-air testing and the water testing. The fluid around a vibrating object acts as an added mass for the structure to move against. The following analysis is a qualitative description for a possible explanation of the differences in 4kHz modal frequencies, not a definite statement of the physics at play.

\[ \frac{f_{\text{fluid}}}{f_{\text{vacuum}}} = \frac{1}{\sqrt{1 + \frac{A}{m}}} \]  

shows the approximate effects of the added mass on a particular natural frequency where ‘A’ is the added mass due to the fluid and ‘m’ is the mass of the structure [10].

In order to determine the ratio of the fluid-loaded natural frequency to the natural frequency in a vacuum, frequency of the fundamental mode shape needed to be determined first. The natural frequency for a thin, rectangular plate with Simply Supported-Free-Free-Free boundary conditions [10], is

\[ f_{ij} = \frac{\lambda_{ij}^2}{2\pi a^2} \sqrt{\frac{Eh^3}{12\gamma(1-\nu^2)}} \text{[Hz]} \]  

where ‘a’ is the length of the plate, ‘\(\lambda_{ij}\)’ is a factor determined by the ratio of plate length to width, ‘E’ is the Young’s Modulus of the material, ‘h’ is the thickness of the plate, ‘\(\gamma\)’ is the surface density of the plate’s largest face and ‘\(\nu\)’ is the Poisson’s Ratio for the material [11].

The ‘\(\lambda_{ij}\)’ factor is the only term in Eq. 3.3 that relies upon the mode shape so this variable corresponds to the required mode shape. Several iterations of this equation were calculated by using different ‘\(\lambda_{ij}\)’ factors until a natural frequency was calculated that was as close to the measured frequency of 4758Hz as possible. The natural frequency of a thin rectangular plate with the dimensions of the turbine blade and the material properties of 316 Stainless Steel, the turbine blade material [9], for the i=1, j=3 mode shape was 4829Hz. Since this calculated frequency only
had an error of 1.5% off the measured frequency in air, it was assumed that this frequency could be associated with mode shape $i=1, j=3$.

Now that the mode shape had been identified, the added mass of the fluid-loaded structure needed to be determined. The estimated mass of fluid loading a cantilevered thin plate for the $i=1, j=3$ mode is

$$A = 0.0803\pi \rho a b^2\ [kg]$$

(3.4)

where ‘$\rho$’ is the density of the fluid, ‘$a$’ is the length of the structure and ‘$b$’ is the width of the structure [10].

Using the density of water and the dimensions of the plate-approximation of the turbine blade, an added mass of $A_{\text{water}} = 0.0204\text{kg}$ was calculated. Also calculated was the added mass due to air fluid loading, $A_{\text{air}} = 2.47\times10^{-5}\text{kg}$ [12]. Equation 3.2 was used to calculate the ratios between the fluid frequency and the vacuum frequency for both air and water. These two ratios were used to calculate the ratio between the natural frequency in water to the natural frequency in air, which was approximated to be 0.8183. This meant that the expected fluid-loaded frequency for the in-water measurement was 3894Hz. Since the measured frequency in water was near 4kHz, this calculated value was only off by 2.7% from the measured in-water frequency. These results would suggest that the 4758Hz tone measured in air modal testing decreased to a frequency of 4kHz when measured in water.

While the discrepancies between the measured and calculated frequencies for both air and water are relatively small, it is important to note that any error in these theoretical calculations comes from the fact that Eq. 3.3 and Eq. 3.4 work under the assumption that the structure is a thin, flat rectangular plate. In reality, the turbine blades are curved. Another source of error is the fact that Eq. 3.3 assumes a simply supported boundary condition with the turbine shaft and Eq. 3.4 assumes a cantilevered boundary condition with the turbine shaft. In reality, the boundary condition that the turbine blade shares with the turbine shaft will be different than either of these
approximations. Despite these discrepancies, fluid loading on a vibration mode of the turbine blade can account for the observed shift in frequency from air to water testing conditions.

A final series of testing was conducted to identify frequency characteristics that followed a strictly vibrational path rather than propagating through a fluid media. The test procedure was the same as the one used to obtain the results from Fig. 3.5, including the same set-up, shown in Fig. 3.4. The force hammer was again used to strike the turbine blade to excite the modal frequencies but for this particular experiment, an accelerometer was mounted on the guide vane touching the table to measure the response. This was in an attempt to see which vibrations from the turbine blades traveled through the shaft into the guide vane assemblies. A sample rate of 20,000 samples per second was again utilized in this experiment but a four-second snapshot length was used rather than a six-second snapshot length. The change in snapshot length came after analyzing the data from the previous test and realizing that six seconds was more than enough to capture the ring-down of the structure. The results of this experiment are shown below in Fig. 3.9.
Figure 3.9 is the result of averaging the guide vane frequency responses of fifteen hammer strikes to the turbine blades. These results show strong vibration at 1.1kHz, likely from the turbine blades, as well as a broader frequency peak in the vicinity of 3.1kHz. This strong and narrow frequency peak suggests that the 1.1kHz tone that is found in Fig. 3.3 might have come from direct vibrational coupling between the turbine shaft, guide vanes and flow meter pipe structure.

3.2.3 Flow Noise

The blade-passage frequency and the turbine blade modal frequencies cover the tonal frequency information present in Fig. 3.1 but there are broadband sources also present. Turbulent flow energy excites a broadband frequency response [13]. The turbine in the flow meter’s pipe
causes turbulent flow because it is an obstruction to flow as compared to an empty pipe. This flow-induced vibration accounts for the broadband noise during a fluid transaction. Figure 3.1 shows an increase in broadband energy around twenty seconds into the spectrogram’s time series and then a decrease around one minute and twenty seconds. This section of the time series corresponds to fluid flow of a fluid transaction. Any fluid movement against the turbine causes some turbulent flow and therefore, causes a broadband vibration response.

3.3 Failure Mode Acoustics

A detailed Failure Modes and Effects Analysis (FMEA) was performed for this research following the approach described in Chapter 2. Referencing, Tbl. 2.1, there was a group of failure modes that occurred in the control system (microprocessor board) and another group of failure modes that occurred in the rotating assembly (turbine and bearings). It was determined that the control system’s failure modes would not be considered because they could not possibly be detected acoustically, therefore only the rotating assembly failure modes were considered. This section will discuss the acoustics of the four-remaining flow meter failure modes discovered through literature research and data collected in the field. But the scope of this research only included air entrainment and debris in the flow loop.

3.3.1 Air Entrained Flow

As mentioned in the previous chapter, air entrainment causes a measurement error because partial fluid flow will still spin the turbine and be interpreted as full fluid volume flow. Air entrainment was found, during ARL FSSP testing, to most likely occur at the end of a fluid transaction when emptying a tank or fuel bladder of its contents. At the end of a fluid transfer, air
can combine with the fluid as it is drained from the container and gets mixed in while propagating
down the flow hose or pipe. Introducing air into the flow meter fluid system can potentially
change the vibrational characteristics of the flow meter enough to be detected. Since the turbine
blade modal frequencies are the most prominent vibration features of a fluid transaction, see Fig.
3.1, the discussion of the effects of air entrainment will focus on this acoustic source.

Air entrainment is a specific case of a phenomenon called two-phase flow, illustrated in
Fig. 3.10. Two-phase flow occurs when a gas and a liquid simultaneously propagate down a pipe
or hose, whether or not this is the intended operation. In the specific case of ARL’s flow meter
testing, the liquid was water and the gas was the entrained air. If an acoustically-excited turbine
blade vibrates in a meter with air-entrained fluid, the presence of the extra gas inside the pipe
could change the vibration response measured on the exterior of the pipe. A deeper analysis into
the vibration transmission properties of water, air and steel are required to learn more.

![Illustration of two-phase flow](image)

Figure 3.10: Illustration of two-phase flow [14]

The ratio of incident vibration to transmitted vibration across a boundary between two
materials can be calculated by determining the characteristic impedance of both materials,

\[ z = \rho c \text{ [rayls]}, \]  

(3.5)
where \( c \) [m/s] is the sound speed and \( \rho \) [kg/m\(^3\)] is density.

The characteristic impedances of two materials can be used to predict acoustic properties of transmission between the two. By requiring that displacement across the boundary between the two media be continuous, the transfer of displacement between two media can be calculated using the characteristic impedances of the two materials:

\[
T = \frac{2z_1}{z_2 + z_1}.
\]  

Both \( z_1 \) and \( z_2 \) are the characteristic impedances of the two media (1: incident 2: transmitted) and \( T \) is the transmission coefficient between the two media, defined as the ratio of the transmitted displacement to the incident displacement.

Table 3.1 lists the sound speed, density and characteristic impedance for air, water [12] and 316 stainless steel [11], which is the material used to construct the flow meter body [9]. Using Eq. 3.6, the final column in Tbl. 3.1 calculates the displacement transmission coefficient between air and steel as well as water and steel, where \( z_1 \) is the characteristic impedance of either water or air and \( z_2 \) is the impedance of steel. There is a significant decrease in transmitted vibration when switching from a water-filled pipe to an air-entrained pipe. It is possible that certain vibrational characteristics present in a fully water filled pipe would disappear, or significantly decrease in amplitude, when air entrainment is present. The last column in Tbl. 3.1 shows that the transmission coefficient between water and steel is more than three orders of magnitude larger than the transmission coefficient between air and steel. It is important to note that Eq. 3.5 and Eq. 3.6 are valid only for plane waves with normal incidence on a boundary [12]. The real boundary is the inside of a curved pipe, so incidence would be oblique rather than normal, and the acoustic signals may not be plane waves. However, the purpose of this discussion is to simply show that vibration transmission from water to steel is much stronger than vibration transmission from air to steel in a qualitative manner and that air entrainment in the flow meter
might cause the observed behavior in the vibrational response from the mounted accelerometers used to collect field data.

Table 3.1: Material properties and vibration transmission coefficients of air, water and steel

<table>
<thead>
<tr>
<th>Material</th>
<th>Sound Speed (m/s)</th>
<th>Density (kg/m³)</th>
<th>Characteristic Impedance (rayl)</th>
<th>Transmission Coefficient with 316 Stainless Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>343</td>
<td>1.21</td>
<td>415</td>
<td>2.396x10⁻⁵</td>
</tr>
<tr>
<td>Water</td>
<td>1500</td>
<td>1000</td>
<td>1,500,000</td>
<td>0.0830</td>
</tr>
<tr>
<td>316 Stainless Steel</td>
<td>4374</td>
<td>7920</td>
<td>34,640,000</td>
<td>1</td>
</tr>
</tbody>
</table>

3.3.2 Debris

Many different types of debris can get caught in the flow loop depending on the environment and the equipment used. Chapter 2 discussed several of the types of debris that can be found in the flow loop and Chapter 4 identifies the types of debris used in failure mode testing. Foreign objects in the flow causes an immediate error because the object can slow the turbine spin rate and cause the meter to underestimate flow rate. In the long run, debris caught in the flow loop can damage the turbine or the guide vanes and throw off the calibration curves or even cause the components to break.

The expected response to a failure of this nature is an increase in vibration energy [15]. If a piece of debris encounters the turbine during an active fluid transaction, it will impact the turbine blades or even get caught in-between two of the blades. The impacts will cause the turbine assembly to vibrate more than usual and could also cause the turbine to rattle between its two bearing mounts. Another feature that might present itself as a result of debris caught in the flow is an increase in structure-borne vibration or fluid-borne acoustic amplitude of some of the turbine blade modal frequencies. A piece of debris impacting the turbine blades in addition to the fluid flowing past the blades would result in additional excitation compared to just fluid flow.
Additionally, a foreign object in the flow loop could also potentially cause turbulence in the flow, just like the turbine already contributes. Added turbulence would result in additional broadband vibrational energy. All of these scenarios are possible when a piece of debris encounters the flow meter turbine. The acoustic changes resulting from trapped debris is often detectable by operators.

3.3.3 Calibration Drift and Meter Damage

Neither calibration or flow meter damage were subjects of this research; they were both determined to be failure modes in the FMEA and are mentioned as potential avenues of future research in Chapter 6. As stated previously, the flow meter will fall out of calibration over normal usage and an uncalibrated flow meter will incorrectly estimate flow rate. The calibration curves become invalid because over time, but more specifically over a certain usage period, the state of the flow meter changes from its state at last calibration. This change in state could potentially result in a change in vibration signature of the flow meter. No such testing was conducted in the scope of this research.

Damage to the rotating assembly of the flow meter can occur in several different ways. As mentioned before, pieces of debris that are stuck in the turbine blades long enough could cause severe damage. Regular wear and tear, if left unchecked, can damage the internal components of the flow meter. Even mistreatment of the flow meter, although designed to be rugged, could cause damage to bearings or shafts. Any damage to the flow meter is considered a failure because broken rotating assembly components will not behave properly during a fluid transaction and therefore cause the microprocessor to misread fluid flow. While research into detecting debris caught in the flow was included in the scope of this research, identifying specific damage to either the turbine or the guide vane bearing assemblies was not considered.
Chapter 4

Test Setup, Data Collection and Procedure

Much of the analysis in this research was data-driven. Several different test configurations and sensors were required to fully understand the tactical flow meter functionality. Operation at the Applied Research Lab’s Fuel System Supply Point (FSSP) was similar to field applications so the data collected there was valuable in determining the characteristics of a functional flow meter. Further in-house laboratory experiments were necessary to identify the vibrational characteristics of the flow meter. Finally, indoor laboratory testing also proved useful to explore some of the failure modes of the flow meter. For safety reasons, all testing that involved moving fluid through the flow meter utilized water rather than fuel. The details of the sensors, data acquisition and test set ups will be discussed in this chapter.

In general, testing consisted of three stages: 1. initial field testing 2. laboratory verification testing 3. and fault detection field testing. Figure 4.1 shows the sensor configuration used in the initial field testing to determine the characteristics of the flow meter. Two accelerometers mounted 90° apart and as close to the plane of the turbine as possible were used. An externally mounted microphone was also used, the orientation of which is shown in Fig. 4.1. Laboratory testing was conducted to determine the sources of the different frequency tones present in field data. Accelerometers and microphones measured responses of the turbine blades while a force hammer was often used to collect excitation forces when measuring the system frequency response. Data was collected to specifically test the characteristics of the two primary failure modes. Accelerometers were again mounted on the flow meter body as shown in Fig. 4.1. Finally, experimentation with internally mounted sensors took place in an attempt to study their potential for use in Condition-Based Maintenance (CBM). An accelerometer and a small
microphone board were placed inside the electronics casing and their outputs compared with an externally mounted accelerometer.

![Figure 4.1: FSSP test setup, flow meter sensor placement]

### 4.1 Data Acquisition and Sensors

A PCB 352A60 accelerometer was selected because of its 5Hz-60kHz frequency response (±3dB). This gave the option of detecting possible ultrasonic frequency characteristics in an operating flow meter. After initial testing, it was ultimately decided that this bandwidth was unnecessary for the purposes of this research. The second accelerometer selected for data collection was the PCB 353B16. This accelerometer had a smaller bandwidth than the 352A60, 1Hz-10kHz (±5%). Both accelerometers have a reported sensitivity of 10mV/g and were mounted to the meter with the same adhesive, eliminating a great deal of potential variability between the
two. Compared to other sensors used, accelerometers ended up providing the most useable data. During the laboratory testing, discussed further below, two more accelerometers were used to detect vibration data from four flow meters running simultaneously.

A PCB 378B02, free-field microphone was selected to provide radiated, fluid-borne acoustical data for the analysis. This microphone had a frequency range of 3.75Hz-20kHz (±2dB). In the initial characterization tests the microphone data proved less useful than data acquired from the accelerometers. The microphone mainly picked up noise from the diesel pumps on site. It was eventually removed from this test setup. The microphone was most helpful in experimentally determining the modal frequencies of the turbine blades in air.

A C-LB85-A005 FloCat magnetic pickup was the primary sensing device inside the flow meter. The turbine blades passing through its magnetic field generate a sinusoidal signal that is used by the on-board microcontroller to determine flow rate. For the purposes of this research, the magnetic pickup output was tapped to provide an accurate record of instantaneous flow. This, coupled with the vibration data, proved useful in characterizing different “stages” of flow.

A PCB 086D05 force hammer was used in tandem with the microphone to experimentally determine modal frequencies of the turbine blades. This data could be coupled with the microphone response to measure the frequency response function of the blades. This force hammer had a sensitivity of 0.23mV/N. A steel tip was used for all testing involving this force hammer.

A WM7121PE analog silicon (MEMS) microphone was used to experiment with internal sensor placement in the flow meters. Figure 4.2 shows the microphone, inside the red box, mounted on an amplifier circuit board. This microphone has a ±3dB frequency range of 62Hz-13kHz and has a sensitivity of -38dBV (re: 1V) at the test condition of 94dB SPL (re: 20µPa). This particular microphone was used because of its size. Due to its small size (3.76mm x 2.95mm), it could easily fit inside of the electronics casing of the flow meter.
The data acquisition device used for all of the experiments was the NI USB-4432 five-channel DAQ. The DAQ made it possible to interface with LabView on a portable laptop. The LabView Virtual Instrument used to collect data was developed by ARL employees to write to a custom binary format called “ICHM”. The inputs to the front panel (Fig. 4.3) that were most relevant were the sample rate, snapshot interval and snapshot length. The sample rate used to record the first few sets of data was 100,000 samples per second but then it was determined that an analysis bandwidth from 1Hz-10kHz was sufficient for the purposes of this research. The sample rate for most of the relevant data collected and used for analysis was 20,000 samples per second. The snapshot interval and length were changed based upon the experiment. The recorded data was of “.ICHM” data type and required a MatLab decoder script to extract the data, sample rate, date and time of snapshot and many other metrics concerning the collected data.
4.2 ARL FSSP Test Setup and Procedure

4.2.1 FSSP definition and operation procedures

The flow meters discussed in this thesis so far are beginning to appear in FSSP’s, or “fuel farms”. These fuel depots consist of fuel bags, 20,000-gallon rubber bags used to store fuel, fuel tanks, typically mounted onto trucks to receive/deliver fuel, and diesel pumps used to push fuel from one to the other and vice versa. Flow meters are placed in between any two entities: there is a meter between the truck and the pump and a meter between the pump and the bag. The ARL fuel farm assembly included two diesel pumps, two 20k-gallon rubber bags, two fuel tanks, six 4” diameter flow meters and one 2” diameter flow meter. Figure 4.4 below shows a flow diagram of the fuel farm setup.
Operation of the make-shift FSSP required at least two operators: one person to run the diesel pumps and the other to dictate the volume of fluid to be moved and signal the pump operator. To perform a transfer, one of the two operators would collect information about the recipient of the fluid (name, amount of fluid, vehicle, etc.) while the other started the diesel pump, if it was not already in idle. With the pump idling, the appropriate valves would be opened to dictate where fuel would flow with the valves on the pump itself being the last two to open. This would start fuel flowing at the low idle speed (1000RPM). The pump operator would then ramp up the pump speed to increase flow rate. Once the transfer approached the total number of gallons required (typically within 100 gallons of the target) indicated by the fuel meter readouts, the second operator would tell the pump operator to slow the pump back down to idle speed. Finally, the pump operator would close off the pump values once the total fuel volume was reached. The flow path would follow the blue lines in Fig. 4.4. The same procedure is used for a download but following the red flow lines rather than the blue ones. In both cases, the TRM’s acted as the “vehicles” receiving and downloading the fuel.
4.2.2 FSSP sensors and DAQ parameters

While this test site was constructed to test the flow meters’ functionality, acoustic and vibration testing occurred in tandem. Both accelerometers (352A60 and 353B16) and the microphone (378B02) were used in these experiments.

The accelerometers were placed as close to the plane of the spinning turbine as possible to get the strongest vibration signal from the flow meter moving parts. Each 4” flow meter had a divot in the outer casing in line with the turbine. This provided a good, flat location to mount one of the accelerometers, the bottom red circle shown in Fig. 4.1. Ultimately, the microphone was removed from further field-testing because it did not report any acoustic data of the flow meter and instead was saturated with noise from the diesel pump.

4.3 Pump Test Loop Setup and Procedure

4.3.1 Test Setup

In chronological order, the pump test loop was the last testing that took place in the scope of this thesis. Up until this point, data had been collected to categorize a “normally” functioning meter. The purpose of these tests was to produce failure mode data. Three main datasets were collected here: debris testing, variability testing and experimentation with internal sensor placement.
Figure 4.5 shows the flow diagram for the pump test loop. While there are three pumps shown in this diagram, only one was used in any given run (the extra pumps were there for other ARL testing). Each flow meter in this flow loop had an accelerometer attached to the divot along the outside of the meter. Three of the PCB 353B16 accelerometers were used as well as one PCB 352A60 accelerometer. The DAQ parameters for this experiment were a sample rate of 20,000 samples per second and an 18 second snapshot length.

4.3.2 Variability and Debris Testing Procedures

The procedure for running this test setup started with one of the three pumps being engaged. All of these tests were run with the idle speed of the pump so there were no ramp-up or ramp-down stages of the pump as with the fuel farm procedure. Flow meters 1-3 were placed in the flow loop to discover the variability between meters running simultaneously; therefore, they did not have any debris introduced into them. Flow meter 4 was the meter where debris was
introduced to attempt to induce the vibration characteristics of debris trapped inside a flow meter. The strainer was a fail-safe just in case any debris were sucked through FM4’s turbine and continued through the flow loop. Since this setup was a closed loop, unlike the fuel farm setup, the pumps could be run as long as needed without overflow. So once enough time had passed, the pump would be turned off and the DAQ would be stopped.

This was the entire procedure for the variability testing as well as the sensor comparison testing, but additional steps were required for the debris testing. There were three different methods of debris placement, the first of which was dangling larger pieces of debris in front of the turbine blades during a run. The two large pieces of debris used for this test were a piece of rubber from one of the large fuel bladders, salvaged over the summer during the FSSP tests, shown in Fig. 4.6 below. Also, shown below in Fig. 4.7 is a piece of one of the rubber gaskets used to produce the seal between joints in the hose.

Figure 4.6: Rubber debris from fuel bladder
These pieces were tied to fishing line and hung right in front of the turbine blades of FM4 without touching the blades. This was in an attempt to induce flow resistance right near the sensors without risking the debris being sucked through the turbine blades. This added an extra step of opening up the upstream connection of FM4 and placing the strung-up debris inside the meter before starting the pump and checking the strainer after the pump was turned off to verify that the piece stayed inside the meter.

The second method of debris placement was to introduce the large pieces of debris (Fig. 4.6 and Fig. 4.7) upstream of FM4 after the pump started. This was accomplished by means of a three-way valve between FM3 and FM4. The flow loop hoses were connected to two of the three openings and allowed water to pass through. The valve would open and close access to the third opening. Thirty seconds after the flow started, the debris piece was placed inside this third opening, while the valve was closed, and then sealed inside the holding area. The operator would then open the valve, introducing the debris piece into the flow loop. Finally, the operator would close the valve again after it was certain that the piece entered the flow loop. This procedure
produced data very similar to how debris would find its way into a meter in the field: it would enter upstream and would start causing problems midway through a transaction. Example results of this phenomenon were shown in Fig. 2.6.

The third and final method of debris placement involved a smaller type of rubber debris that more closely resembled long strands of grass. This debris was also a product of the openings to the rubber bladders and can be shown in Fig. 4.8. This debris was wrapped around the shaft of the turbine blade assembly, as shown in Fig. 2.7. This step involved taking FM4 out of the loop to insert the debris and placing it back in the loop before starting the pump. FM4 would also have to be removed again from the loop after the pump was turned off to locate the debris and verify it stayed inside FM4. Ultimately, this debris never stayed wrapped around the turbine shaft after a transaction and would be found in the strainer downstream of FM4.

Figure 4.8: Small rubber "stringy" debris
Chapter 5

Analysis Techniques and Fault Testing Results

One goal of this research was to develop techniques that can detect fault conditions affecting flow meter operation and accuracy using measured acoustic and/or vibration signals. Several analysis and processing techniques were required to interpret the large amounts of data collected from the flow meters. Different techniques were required for the different testing conditions. An in-depth analysis into the repeatability of frequency characteristics between flow meters as well as identifiers for the two failure modes are included in this chapter. Data collected on flow meters in a series flow loop show similar vibration characteristics. Analysis into the failure mode data revealed identifying traits of faults in the flow meters. Details on preliminary automated detection methods are also discussed.

5.1 External Microphone Effectiveness

During the course of this thesis, there has been plenty of field-testing of flow meters to ensure an accurate representation of the operational and failure acoustic and vibration characteristics of the flow meter. This testing involved many different sensors as well as sensor placements. This section reviews the utility of the external microphone used in field data collection.

The accelerometers had the advantage of being mounted in the plane of the spinning turbine and therefore picked up a large amount of signal from the flow meters’ moving parts. The microphone was not directly coupled to the structure of the flow meter and while it was much
closer to the flow meter than the diesel pump, the pump noise dominated the response of the microphone.

Figure 5.1: Example of averaged FFT signal from divot-mounted accelerometer

Figure 5.2: Example of averaged FFT signal from external microphone
Figure 5.1 shows an example of the averaged FFT of the divot-mounted accelerometer. Figure 5.2 in contrast shows an example of the averaged FFT of the microphone response for that same dataset. Both of these plots are representative of the typical responses from each sensor collected at the ARL FSSP. Figure 5.1 shows the mid-range frequency (1kHz-4kHz) information representative of the vibration of the turbine blades during fuel flow while Fig. 5.2 predominately shows the low-frequency (<500Hz) diesel pump noise. Shown below, Fig. 5.3 is the mean-squared coherence of the two signals used to create Fig. 5.1 and Fig. 5.2. The red line shows the amplitude boundary between incoherent (below 0.9) and coherent (above 0.9) frequencies. The only coherent information between these two measurements is the low-frequency pump noise, which is unimportant to the scope of this thesis, so the microphone was ultimately removed from field measurements. It is important to note that when debris got caught in the turbine blades of the flow meter, it could sometimes be heard from someone standing nearby the flow meter. While not always audible, the characteristics of debris caught in the flow meter turbine, discussed later, might be detectable by an external microphone.
5.2 Processing Techniques

Several basic processing methods were used to extract useful information from collected data. These methods include averaging FFT’s, Finite Impulse Response (FIR) filtering, spectrogram analysis and Frequency Response Function (FRF) construction. The simplest method was an FFT calculation used to determine the frequency response of collected data. For standard field data analysis, the time series was divided up into 100 blocks and each FFT was averaged together. Since much of the relevant frequency information from the flow meter was tonal; averaging many responses together would reduce the effects of broadband noise on the results and make them easier to interpret. When used to extract frequency information from modal analysis, often the vibration amplitude decay of the turbine blades was too fast to divide up the time series into sections to average together. To still incorporate averaging and reduce broadband noise, several turbine blade strikes were performed and those responses were averaged together in the frequency domain. For most of the data types collected in this research, an averaged FFT alone was not enough to extract the necessary information and other techniques had to be employed.

Data analysis often requires filtering to remove unwanted frequency information in order to better see relevant data. The data collected for this research utilized filtering for two main functions: to remove unwanted environmental noise and to isolate tonal amplitudes for detection purposes. As previously mentioned, a diesel pump was used to move fluid from one location to another during field testing. The pump was the source of a significant amount of low-frequency noise (<200Hz) that would propagate down the hoses and saturate the accelerometer responses. Since this particular noise source was stronger in amplitude than the desired signal, a high-pass filter was utilized for much of the field data. A cutoff frequency of 200Hz ensured the pump noise would not dominate the response and that the blade-passage frequency (250Hz-350Hz) would
remain untouched. This filtering was also useful for laboratory testing to eliminate HVAC and other equipment noise present in the lab. Band-pass filters were also used to isolate the relevant turbine blade modal frequencies for detection purposes. Details on the filtering used for detection is described later on in this chapter. For both cases, a Kaiser FIR filter was used to accomplish these tasks.

A typical fluid transaction has three main stages: 1. ramp up, 2. main flow, 3. ramp down. The resulting variability of the frequency content of the signals during the different stages of the flow, makes time-frequency analysis techniques good for analyzing the characteristics of a fluid transaction. Using the short-time Fourier transform, or spectrogram, it was possible to visually identify the three stages of the fluid transaction and determine their characteristics. Through trial and error, it was determined that a 1024-point Hanning window and zero overlap were the best spectrogram parameters to visualize the three main frequency components identified in Chapter 3. The spectrogram also proved to be a powerful tool in determining the frequency characteristics of the two failure modes. The identifying markers for each failure mode were easily seen in a spectrogram, which led to creating preliminary automated detection algorithms.

During the modal analysis of the turbine blades, a force hammer was used for much of the testing, as described in Chapter 3. Collecting data on the input source as well as the response made it possible to produce frequency response functions (FRF). When applicable, this technique proved useful to reduce the amount of noise that entered into the results. While not always possible, in the case of the water-filled flow meter, using a force hammer provided additional data making results that much easier to extract.
5.3 Flow Analysis Results

Much of the data presented up until this point has been used to characterize the “normal” functioning flow meter. The data analyzed in this section was collected to show two things. First, the response of one flow meter is similar to that of another flow meter and that the frequency response of a fluid transaction is easily repeatable. Second, the results of inducing the two failure modes in the flow meter are shown as well as discussion of the preliminary detection algorithms developed. Much of this data was collected at the ARL pump test loop facility, described in detail in Chapter 4.

5.3.1 Flow Meter Similarity and Repeatability

While most of the initial field data showed the same frequency trends between different fluid transactions and different flow meters, further testing was conducted to verify these findings. As described in Chapter 4, accelerometers were placed on several meters running on the same flow loop and data was collected simultaneously for all flow meters used in the same fluid transaction. It is important to note that the diesel pump used in this experiment was run at idle speed (1000RPM or 16Hz) and not ramped up as in a typical fluid transaction. When the pump is run at a slower speed, the amplitudes of vibration also decrease, resulting in lower signal amplitudes in Fig. 5.4 when compared to Fig. 3.1. Figures 5.4 and 5.5 show accelerometer spectrograms from two separate flow meters that were a part of the same flow loop measuring the same fluid transaction. Both responses have the same three frequency components as do the data presented in Chapter 3, as well as the blade passage frequency (~150Hz), and they both show similar amplitudes of these frequencies across the eight minutes of data. Even though these measurements were taken on two different flow meters, the responses are almost identical.
Figure 5.4: Flow meter #1 spectrogram in series flow loop testing

Figure 5.5: Flow meter #2 spectrogram in series flow loop testing
5.3.2 Air Entrainment Testing Results

Air is introduced into the flow at the end of a fluid transfer, when the last of the water from the truck-mounted tanks drains into the hose. The last stage of the flow contains the remaining water and air from the tank. Due to the fact that air was typically found to interfere with flow rate measurements towards the end of a transaction, the three stages of flow had to be identified in the data before any detection could take place in an attempt to isolate the ramp down stage. Figure 5.6 shows the blade-passage frequency as a function of time for a typical transaction (shown in blue) with the three stages of flow labeled with black, red and green squares.

![Figure 5.6: Blade-passage frequency versus time for fluid transaction](image)

The ramp up stage of flow is the point in time where the pump starts moving fluid at idle speed, note the first increase in blade-passage frequency during the ramp up stage shown in Fig. 5.6. This stage ends when the pump has reached its maximum speed (typically 1700RPM, or...
28Hz) and increases no further. Note the second increase in blade-passage frequency during the ramp up stage shown in Fig. 5.6. The main flow phase is defined as the portion in the fluid transaction where the blade-passage frequency has stopped increasing and remains constant at the pump’s maximum speed. This is the portion of the transaction where the most fluid is transferred. This stage ends, and the ramp down stage begins, when the pump speed begins to decrease. The ramp down stage ends when the blade-passage frequency returns to zero, indicating that there is no more fluid flow.

With the ramp down stage of the data identified, the next step was to analyze the spectrum during this window in time. This time series was identified and isolated by means of detection algorithm that was developed, which is discussed in more detail later. After filtering out pump noise and averaging several smaller FFT’s together, it was determined that the 4kHz tone that presented itself in a normal dataset would significantly decrease in amplitude when air entered the flow meter. Figure 5.7 shows the averaged FFT of the ramp down stage of a normal fluid transaction (blue) as well as the averaged response of the ramp down stage of an air entrained transaction (orange). While this figure only shows one example of this phenomenon, the data from all but one of the air entrainment runs showed this same behavior. This unique trait of air entrainment was exploited in developing a preliminary detection algorithm.
5.3.3 Air Entrainment Detection

The ultimate goal of studying flow meter failure modes was to be able to automatically detect them, so an automatic detection algorithm was developed to detect air entrainment using a similar approach as the analysis procedure. Since the detection of air entrainment relied so heavily on knowing the stage of flow, the test procedure for testing for air entrainment also included tapping the magnetic pickup as one of the DAQ sensors. This way, the algorithm could use the blade-passage frequency to identify the different stages of flow and start analysis once the ramp down stage was reached. To mimic a real-time fluid transaction, the algorithm analyzed 2000 point sections (0.1 second) of blade passage frequency data at a time, as if it were processing the data in real time. The algorithm used different thresholds to determine flow stage from this loop calculation. The end of the ramp up stage, and therefore the beginning of main flow, was identified once the blade passage frequency rose above 300Hz, or 585GPM. The
leftmost red circle in Fig. 5.6 shows the location of the end of the ramp up stage that the algorithm automatically determined. The ramp down stage began when the current blade passage frequency fell 20Hz, or 40GPM, below the average of the ten previous data points. The leftmost orange circle in Fig. 5.6 shows the location of the beginning of the ramp down stage. The fluid transaction ended when the blade-passage frequency fell below 100Hz, or 196GPM. The end of the ramp down stage in Fig. 5.6 is shown by the rightmost orange circle. The detection algorithm used these thresholds to automatically identify the three stages of flow and isolate the ramp down stage for further analysis.

After the ramp down stage time series was automatically identified, it was filtered with a Kaiser FIR bandpass filter to isolate frequencies between 4kHz and 4.1kHz. Both the unfiltered and filtered time series were divided up into 2000 point windows and the RMS amplitudes were calculated for all of the windows of time in both signals. The amplitudes of the filtered signal were compared to the amplitudes of the unfiltered signal. For a normal fluid transaction, the ratio of the two would fall anywhere between 20% and 50% of the overall amplitude. For an air entrained fluid transaction, the ratio would be anywhere between 1% and 12%. Figure 5.8 shows the ratio of the unfiltered RMS ramp down stage time series versus the filtered RMS ramp down stage time series for a normal fluid transaction (blue). Figure 5.8 also shows the ratio of the unfiltered RMS ramp down stage time series versus the filtered RMS ramp down stage time series for an air entrained fluid transaction (orange). Both time series in Fig. 5.8 were determined automatically by the blade-passage frequency detection process described above. The ratio of the filtered versus unfiltered signals is a strong indicator of whether there is air entrained in the flow because it shows the relative strength of the 4kHz tone compared to the overall vibration level.
Debris testing took place at the pump test loop and involved a different test setup than the makeshift fuel farm. As described in Chapter 4, a closed flow loop was utilized rather than an open one to insert debris into the flow loop. In addition, a three-way valve was placed upstream of the flow meter and provided a means of introducing the debris pieces into the flow loop. The debris piece was inserted into the flow loop well after the fluid transaction had started to ensure a noticeable difference in the data would be detectable. While three types of debris were used (large rubber bag debris, rubber gasket piece, smaller rubber string debris), only the first two actually provided any detectable results and therefore this chapter only includes data from the large rubber debris and the gasket piece.
Figures 5.9 and 5.10 both show the accelerometer response to fluid transactions when debris was introduced into the flow loop via the three-way valve part-way through the transaction. It is important to note that the diesel pump was run at its idle speed (1000RPM) rather than the speeds used in the fuel farm testing, because of limitations due to the short overall length of the loop. This accounts for the smaller amplitude in the three characteristic frequencies before the debris piece interacts with the flow meter. The first spectrogram shows the results of using the gasket piece in the flow loop and the second spectrogram shows the results of using the large rubber debris in the flow loop. Each spectrogram has a section in time where the response amplitude is relatively low (blue-light blue). This is the normal response of the flow meter, before the piece of debris impacts the turbine blades. The second section in time is represented by an overall rise in amplitude (green-yellow) and a significant rise in the amplitude of the frequency band from 1.6kHz-1.8kHz (red). This window of time is when the piece of debris has reached the turbine in the flow meter and is impacting the turbine blades. The debris piece is impacting the turbine blades and causing the turbine assembly to rattle between the two bearings. This accounts for the overall rise in vibration amplitude. The large increase in the 1.6kHz-1.8kHz band suggests that this particular modal frequency is excited when repeatedly impacted by the debris piece. It is expected that a similar increase in overall vibration amplitude as well as a drastic increase in amplitude in the 1.6kHz-1.8kHz frequency band would also be present in debris testing conducted with the same pump speeds used in normal fluid transactions. All of the debris-induced flow meter testing utilizing large debris pieces presented with similar results as the two example datasets shown in Fig. 5.9 and Fig. 5.10.
Figure 5.9: Spectrogram response of fluid transaction with rubber gasket piece introduced

Figure 5.10: Spectrogram response of fluid transaction with large rubber debris introduced
5.3.5 Debris Detection

Since debris entering the flow loop is independent of the fluid transaction stage, unlike air entrainment, the detection algorithm does not require knowledge of the flow stage. Debris can enter the flow loop at any time, so an automated detection algorithm must constantly check the amplitude of the overall response as well as the amplitude of the frequency band between 1.6kHz-1.8kHz. As with the previous method, the current detector filters the incoming data with a Kaiser bandpass filter between 1.6kHz-1.8kHz. Then, it splits the time series data into 2000 point windows and processes them one at a time via a for loop to simulate a data buffer analyzing incoming data in real-time. An RMS calculation is performed every loop iteration for both the original and the filtered signal. Rather than comparing the two RMS values to each other, they are compared to past RMS values to see whether a dramatic increase in amplitude is detected. As shown in both Fig. 5.9 and Fig. 5.10, the change in frequency response is immediate and severe. One of the challenges to this method of detection is the fact that during the ramp up stage of fluid flow, the amplitude of vibration also increases, though not as drastically. Knowledge of the fluid transaction stage could possibly prevent this issue. Another potential pitfall is the fact that the vibration levels increase when the pump speed increases. Since the pump noise is mainly low-frequency noise, the 1.6kHz-1.8kHz frequency band amplitude shouldn’t drastically increase due to increased pump speed. Checking both the unfiltered and the filtered versions of the signal and ensuring that they both drastically increase should prevent pump noise from inducing a false positive. Future versions of the automated detection algorithm must take these into account when attempting to determine whether there is debris caught in the flow loop.
Chapter 6

Conclusions

6.1 Discussion of Results

The focus of this research was to determine the fluid-borne acoustic and structure-borne vibration properties of failure modes present in tactical flow meters. The United States Army is beginning to use turbine flow meters to accurately measure large-volume fluid transactions that take place in fluid distribution centers called Fuel System Supply Points (FSSP), or “fuel farms”. The Penn State Applied Research Laboratory (ARL) has already conducted research into improving the accuracy of the flow meter by means of embedded temperature and density correction algorithms as well as advanced reporting technologies. Of the several failure modes experienced in field testing, the two failure modes explored in this thesis were air entrainment in the flow loop and debris caught in the flow meter turbine. Both of these events resulted in flow rate measurement error greater than the allowable 0.5% of total volume.

Data was collected from flow meters at a makeshift FSSP facility via externally mounted sensors in an attempt to better understand the acoustic and vibration properties of the flow meter. For environmental and safety reasons, water was used in all field testing rather than fuel. Several frequencies were discovered to be common to all fluid transactions in the flow meter and were later determined to be modal frequencies of the turbine blades. Further testing was conducted to intentionally induce both air entrainment and debris into the flow meters to better understand the characteristics of these failure modes.

Due to the amount and variety of data collected, several processing techniques were required to properly analyze the data: frequency analysis, spectrograms, time-domain filtering
and others. Failure mode testing revealed unique identifiers of both air entrainment and debris that could be consistently found in the datasets. Air entrainment was found to occur at the end of a fluid transaction so analysis was restricted to the ramp down phase of fluid transactions. The data suggested that the energy in the 4kHz tone significantly decreased when air was mixed in with water during a transaction.

Figure 6.1 clearly shows the absence of the 4kHz tone in air entrained vibration data when compared to normal flow vibration data. When debris was caught in the flow loop and interacted with the turbine blades, two identifiers appeared in the data. First, the overall vibration amplitude increased and second, the amplitude of the 1.6kHz-1.8kHz frequency band significantly increased. Figure 6.2 is a spectrogram of an example dataset where debris interacts with the flow meter turbine midway through a transaction run at an idle pump speed.

![Figure 6.1: Frequency response comparison between normal and air entrained end flow](image)
The ultimate goal of researching the failure modes in the system was to detect conditions affecting the accuracy of the flow meter and to then implement Condition-Based Maintenance (CBM) technologies. This motivated the development of preliminary automated algorithms to detect the presence of air entrainment or debris in the flow meter. The detection method for air entrainment involved using the variable blade passage frequency to determine when the ramp down stage occurred. Then the data was filtered with a Kaiser 4kHz bandpass filter and its amplitude was compared to the amplitude of the unfiltered signal. If the ratio of the two fell below 10%, the algorithm determined that air was entrained in the flow. For debris testing, the incoming data was filtered with a 1.6kHz-1.8kHz Kaiser bandpass filter and the amplitude of both the filtered and unfiltered signal were constantly checked, since this failure mode can occur at any point during a transaction. If both amplitudes dramatically increased in amplitude in a short amount of time, the algorithm determined that there was debris caught in the turbine blades.
6.2 Future Work

While only two failure modes were researched for this thesis, the Failure Modes and Effects Analysis (FMEA) performed and described in Chapter 2 included additional failure modes that could potentially be explored with acoustic methods. Aside from just failure mode exploration, there are other avenues of future research involving the tactical flow meter and improving its accuracy. Two possibilities for future work that are discussed in this section: exploring ideal internal sensor placement in the context of CBM, and researching the effects of calibration drift on the acoustics and vibrations of the flow meter.

It is also important to note that the detection methods for both air entrainment and debris, discussed in Chapter 5, only detect possible measurement error but do not quantify it. Future study could explore the impact of the two failure modes on the allowable 0.5% measurement error for a fluid transaction. A potential method of determining error for air entrainment is to measure the total time of a fluid transaction and compare it to the amount of time the fluid transaction had air entrained. Comparing these two could perhaps quantify the potential transaction error in gallons rather than simply detecting an error.

6.2.1 Internal Sensor Placement

Ideally, any sort of condition monitoring processes would be performed by the microprocessor already on-board the flow meter. This eliminates the cost of adding more electronics. The simplest way to incorporate the sensors into this system would be if they could be mounted internally, eliminating the need for external sensors and wires. The last phase of
testing at the pump test loop explored the effectiveness of mounting an accelerometer and a microphone inside the flow meter and comparing their responses to the response of an accelerometer mounted in the divot outside of the meter.

The sensors used in this experiment were two PCB 353B16 accelerometers and the WM7121PE analog silicon microphone. Figure 6.3, shows the placement of the two internal sensors with the accelerometer circled in red and the microphone board circled in yellow. The DAQ parameters were a sample rate of 20,000 samples per second and a snapshot length of 18 seconds. The procedure for running these tests was the same as the procedure for the variability testing described in the previous section with the exception that only FM3 had any sensors attached to it. The pump would start, pass water through the flow loop for as long as required then shut off at the end.

![Figure 6.3: Internal sensor placement inside flow meter electronics casing](image)

This testing revealed that the sensor placement shown in Fig. 6.3 was unsuitable for collecting data comparable to the sensors in the standard method shown in Fig. 4.1. Figures 6.4 and 6.5 show the frequency responses of both the internal accelerometer and internal microphone respectively. While they do share similar frequency peaks, 732Hz and 974Hz, neither of them show any of the frequency peaks that are characteristic to the flow meter. Figure 6.6 is the mean-

squared coherence between the accelerometer externally mounted in the divot and the accelerometer internally mounted inside the electronics casing. It is clear that there is very little frequency information that crosses the coherence threshold (red line). Figure 6.7, which shows an example of the mean-squared coherence between the external accelerometer and the internal microphone data, shows a very similar result where very little surpasses the coherence threshold.

Figure 6.4: Internal accelerometer averaged FFT’s frequency response
Figure 6.5: Internal microphone board averaged FFT’s frequency response

Figure 6.6: Example mean-squared coherence between external and internal accelerometers
6.2.2 Calibration Drift

A second area of future research is detecting calibration drift. Calibration drift is a term that describes how a piece of equipment’s calibration data will slowly become inaccurate over normal usage. The tactical flow meters in this research depend on calibration data (as shown in Fig. 2.5) to properly infer flow rate from the blade passage frequency of the turbine blade. As mentioned in Chapter 2, the flow meter is recalibrated once every calendar year to ensure that the calibration curves are accurate. As is often the case, it is possible that the flow meter experiences calibration drift well before the yearly recalibration and therefore reads incorrect flow, or may experience no drift at all. Future study could potentially go into acoustically determining when a flow meter requires recalibration. Due to the amount of wear a flow meter receives in a year’s time, a long-term study must be conducted to measure the flow meter characteristics right after it is calibrated and again right before it is due to be calibrated. This transition from calendar-based maintenance to CBM would decrease the cost of operation by limiting the number of times a flow meter...
meter must be pulled from service or storage to be calibrated, eliminating the need for unnecessary calibration appointments.
Bibliography

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