Prediction and Prevention of the Progressive Degradation of Mining Screens using Wireless Vibration Analysis Tools

PREDICTION AND PREVENTION OF THE PROGRESSIVE DEGRADATION OF MINING SCREENS USING WIRELESS VIBRATION ANALYSIS TOOLS

BY

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A THESIS
SUBMITTED TO THE DEPARTMENT OF COMPUTING & SOFTWARE ENGINEERING
AND THE SCHOOL OF GRADUATE STUDIES
OF MCMASTER UNIVERSITY
IN PARTIAL FULFILMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF APPLIED SCIENCE

Master of Applied Science (2015)
(Computing & Software Engineering)

McMaster University
Hamilton, Ontario, Canada

TITLE:	Prediction and Prevention of the Progressive Degradation of Mining Screens using Wireless Vibration Analysis Tools
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NUMBER OF PAGES:	x, 88

Abstract

Vibration analysis (VA) is an extremely valuable technology which has been around for decades but its application and deployment techniques continue to grow. In 2006 W.S. Tyler, an industrial screening company, approached the McMaster Computing and Software department in search of a VA strategy to be used in their industry. The massive screens they produce vibrate with incredible speed and force to sort various types of materials. Over the years this department has developed a successful wireless vibration analysis tool along with software to perform analysis.

The current VA tool can be used to tune the screen during commissioning as well as aid in troubleshooting during or after a failure. The next evolutionary step in the advancement of the system would be to perform condition monitoring.

Predictive maintenance is a relatively new concept whereby an impending machine fault or failure is detected through condition monitoring and is corrected before it occurs. Predictive maintenance is immensely beneficial and will be discussed.

The focus of this thesis is on improvements to the VA system adding longer-term, progressive data collection and analysis abilities to the current tool-set.

Acknowledgments

I would like to express my gratitude to my supervisor Dr. Martin v. Mohrenschildt for his guidance and patience throughout the process of writing this thesis. I would also like to thank our industry partners at W.S. TYLER for their continued technical and financial support; without which this project could not exist. In particular, special thanks to Markus Kopper and Dieter Takev. I would also like to thank Jay Parlar, Daniel Volante and Wisam Hussain, whose contributions to this project formed the building blocks for my research.

Notation and abbreviations

VA	Vibration Analysis
CMVA	Continuous Monitoring Vibration Analysis
PdM	Predictive Maintenance
FIVO	Fixed Installation Vibration Observer
DOF	Degrees of Freedom
TPH	Tonnes per Hour
RPM	Revolutions per Minute
FFT	Fast Fourier Transform
PDA	Personal Digital Assistant
LFB	Left Feed Bearing
LFS	Left Feed Spring
LDB	Left Discharge Bearing
LDS	Left Discharge Spring
RFB	Right Feed Bearing
RFS	Right Feed Spring
RDB	Right Discharge Bearing
RDS	Right Discharge Spring

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Chapter 1

Introduction and Problem Statement

1.1 Introduction

The vibration analysis research project funded by W.S. Tyler has been ongoing for many years at McMaster University. Over the years the project has advanced and evolved through the work of many students. The following section outlines the projects history. This will provide the reader with a better understanding of the project's goals, achievements and motivations.

1.2 Background

McMaster's involvement in this project started in 2006 when W.S. Tyler approached McMaster University for assistance. W.S.Tyler, owned by"Haver & Boecker" of Germany, is a company which sells screening technology. They produce both the woven mesh and the vibrating machinery to screen all types of aggregates. W.S. Tyler came to McMaster University with their own, in-house, vibration analysis tool. They understood that vibration analysis was an undeniable opportunity to advance their products and support business. They asked the University to help them harness more from the technology. At the time, the VA tool was a serially connected three axis accelerometer connected directly to a laptop. For all intents and purposes, the setup worked, but it was plagued with problems. For example, the laptop was big and rugged and not easily portable. The laptop and connectors were quickly gunked up by dust and debris; a common occurrence around screens in the field. This hardwire connection to the sensor meant the technician was tethered to the massive rotating equipment, a scenario generally frowned upon due to safety concerns. The VA system was limited to a single accelerometer so only one part of the screen could be analyzed at a time. McMaster University was asked to build a system that would solve these shortcomings and add some of the more complex, more powerful abilities of vibration analysis.

1.3 The Vibrating Screen

The vibrating screens produced by W.S. Tyler are the sole target of their VA project. The fixed-based machine employs rotating mechanics to produce controlled rotational accelerations. These accelerations cause vibration in the screen frame which is then translated into the screens woven mesh beds. The mesh comes in various types and sizes based on the aggregate material type and desired particle size. The vibrating screen is used in industries such as food, agriculture, pharmaceutical and mining. In the mining industry these screens are used to sort various types of aggregate and

Figure 1.1: Typical vibrating screen produced by W.S. Tyler

come in a very wide range of sizes. There are screens designed to sort anywhere between 10's - 1000's of TPH (Tonnes per Hour) of material. Some screens have multiple mesh beds to sort several different particle sizes in one pass. In general, the larger the particle size the higher the required vibrational amplitude. Some machines produce up to 7 G's of acceleration and will vibrate in either an elliptical or linear motion.

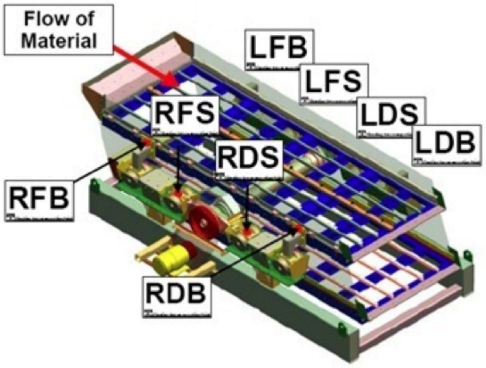


Figure 1.2: VA source nomenclature. Eight Sensors.

The nomenclature used to distinguish the various VA sample points can be seen in Figure [1.2]. The first letter 'L' or 'R' defines the left or right side of the screen. The second letter 'F' or 'D' defines the feed end or the discharge end of the screen. The final letter 'B' or 'S' defines the position as body or side-arm.

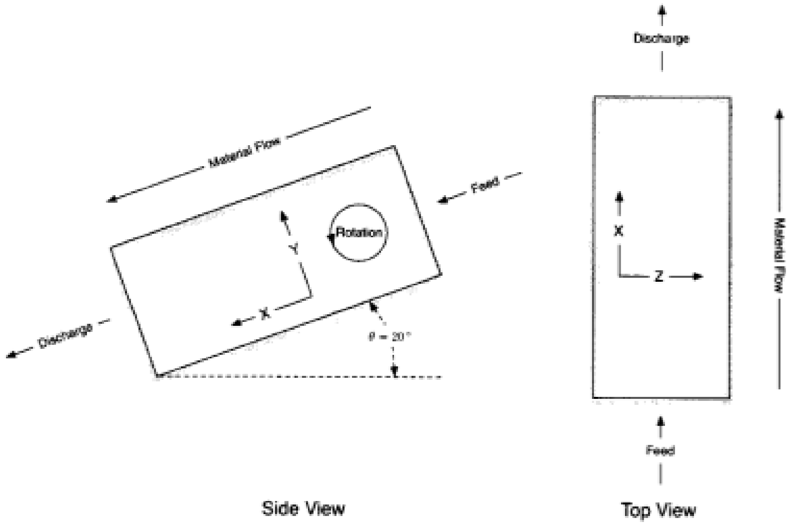


Figure 1.3: Screen Cartesian Co-ordinate Orientation

The orientation of the cartesian coordinate system can be seen in Figure[1.3]. The +x direction coincides with the direction of material flow. The +y direction is perpendicular to the x axis and points upwards out of the machine. The +z direction is perpendicular to both the x and y axis and points out of the right side of the machine. This cartesian coordinate system is used extensively in the VA. For example refer to Figure[1.4] where we can see the typical motion for an elliptical vibration screen. The machine moves in a elliptical path in the x vs. y plane and there is little to no movement in the z direction.

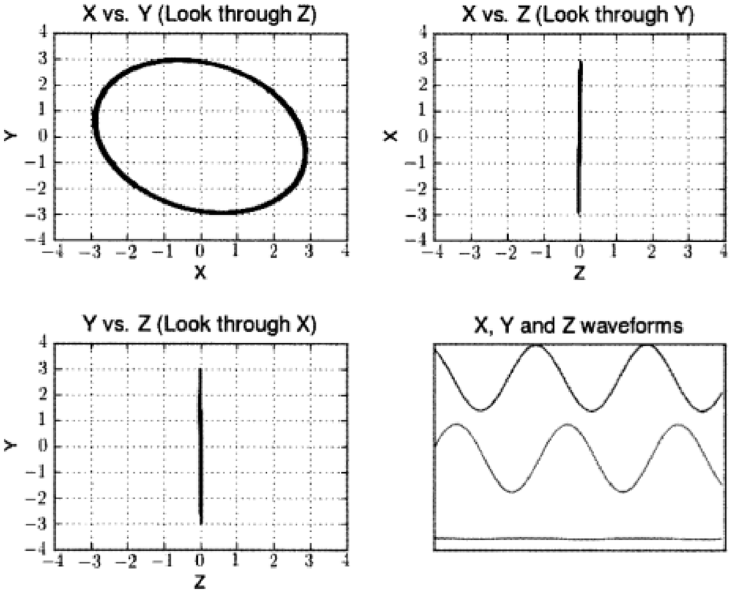


Figure 1.4: Typical vibration screen motion

1.4 Project History

When the VA project was first brought to the Computing and Software Department at McMaster University, it was assigned to the graduate student, Sahar Abughannam. Sahar laid out the requirements for the new vibration analysis tool; paving the way for years of research. Sahar developed the idea of using bluetooth technology to stream acceleration data from a sensor wirelessly. By utilizing wireless technology, technicians could work safer since they were not physically attached to the huge pieces of vibrating machinery. Sahar gave the tool the ability to perform basic vibration analysis techniques such as calculating average G-Forces, RPM, and Stroke using FFT's. The most useful tool for technicians is the Orbit Plot and Ellipse Fitting features which visually show the motion of the screens vibration. This information gives the technician some of the best indication of how well a screen is working.

Sahar made great progress but it was far from complete. With the technology built, the prototype had been proven. It now needed to be put into a package usable by W.S. Tylers technicians.

In 2010, the next student on the project was Jay Parlar. Jay took over where Sahar left off and made the system usable. Jay built the sensors, wrote the code, fought with the bluetooth to squeeze every bit of bandwidth out of it. Jay finished the system to the point where many system units were manufactured and sold commercially to W.S. Tyler's technicians and distributors. Jay also improved the vibration analysis technology by introducing cross-correlation. This feature used the vibration data from eight sensors to hone in on the more important, more interesting frequencies detected in the analysis. This feature amplified the trouble frequencies; making issues easier to detect.

Daniel Volante followed Jay's work. In addition to supporting the Vibration Analysis tool developed by Jay, Daniel improved the sensor communication technique and developed a continuous monitoring system. The original VA tool used bluetooth communication to connect the PDA to the accelleration sensors. Unfortunately there were several problems encountered using bluetooth:

1. Bluetooth supports a maximum of eight devices on a network. The tool uses eight sensors, so including the PDA made nine devices. For the system to function, an additional bluetooth receiver had to be added to the PDA in the form of a USB bluetooth module. This work-around solved the problem but it made the solution more complex.

2. The bluetooth connection protocol was fairly slow. In the presence of other bluetooth devices around the discovery time degraded considerably.

3. The bluetooth communication has limited bandwidth.

While bluetooth got the job done, it was time to move to another technology. Daniel tried several other communication techniques for compatibility and reliability.

1. Serial communication RS232 and I2C. This tied the communication to a wire which was undesirable.

2. Zigbee is an industrial standard communication technique for networks of sensors. Unfortunatly this technology does not have the bandwidth necessary to keep up with the data generated by the sensors.

3. Wifi. When the original sensors were being designed, wifi technology was relatively new, very costly, and very energy consuming. This made it a poor choice

at the time. Over the years the technology quickly improved and is now a logical choice. The power usage has greatly improved and the bandwidth exceeds the needs of the project.

Two hand-made prototype sensors were created to verify the viability of using wifi with the vibration analysis sensors and they proved to be adequate during the tests.

Daniel also worked at creating a continuous monitoring solution using the the same acceleration sensors used in the Hand-held Vibration Analysis tool. The idea behind the continuous monitoring system is to have a VA device permanently installed on the machine. It could detect anomalies in the vibration's signatures and report on them based on a set of rules determining whether the abnormality was a cause for concern.

Wisam Hussain was the next student to take up the project. Wisam, working with W.S.Tyler, moved the project in a somewhat new direction. As a result of Tyler's success with the hand-held PDA VA unit they became aware of a new problem. All the new VA units were being used in the field by their technicians and were beginning to generate a lot of data. This data was at first passed around via email but over time it became lost or misplaced and often lost it's context. The recall and trending of VA data became infeasible due to the data organization problem. A standardized dedicated filing system for the VA data was required. Besides creating online and offline VA tools which took existing vibration data and produced VA values and plots, Wisam also produced an extensive database to solve the data organization problem. This database allows W.S. Tyler to deploy a new business strategy for the VA project where by it can deliver VA information directly to its customers via the website. Taking the project online opened up a new world of technical opportunities to improve the project's effectiveness.

1.5 Problem Statement

Daniel Volante built the CMVA system and while functional, the system was not yet at a stage where it could be produced commercially. There were several major factors that prevented it from being a commercially viable tool. This is the starting point of my research.I took all the developed technology and created the Fixed Installation Vibration Observer.

The major shortcomings preventing the CMVA from being usable are as follows:

1. Lacking user friendliness. The system is operated via command line interface and is configured through various scattered, cryptic text files.
2. Industrial hardware designed to run the software. Besides the sensors, several pieces of additional hardware are required to complete the system.
3. While the mathematical analysis of the vibration data is correct, the decision making algorithm was based on oversimplified assumptions and guesses of the patterns that might be detected. For instance, the algorithm would report a 'fault' if a vibration signal was detected that was outside a set of boundaries defined by the 'baseline'. This did not take into account the 'settling' of a machine, the maintenance of a screen, or the impact of the changing presence of materials on the screen. The machine's vibrations needed to be monitored over a much wider time scale and the generated data needed to be analyzed before a meaningful algorithm could be generated. The change in the vibration patterns of the machine over time and under various conditions are simply not

known. It is therefore, impossible to tell a computer to make good decisions when not all outcomes can be predicted.

4. Acquire periodic vibration samples over a large time frame in order to show progressive changes to the vibration signature. The current system does not have the support systems and archiving automation to support such a long term installation.

1.6 System Improvements

Throughout the duration of the research term, several major improvements where made to the existing vibration analysis system. This section describes the improvements, difficulties encountered and the solutions generated for each.

1.6.1 Battery Upgrade

The original (Version 1) VA sensor design used a 2 AA battery pack. While this power supply arrangement works flawlessly in many other applications it's operation in the vibration analysis sensor was plagued with problems, such as:

1. Due to the loose housing of the AA battery in its battery compartment, a correctly angled bump or vibration of the sensor would briefly disconnect the battery and cause the sensor to reboot. Since these sensors were expected to endure lengthy intense vibrations, this was a serious problem. Any slight interruption in the power caused the sensor to fail which in turn would interrupt the analysis.

2. Most of the devices on the sensor Printed Circuit Board (PCB) required 3.3V to work properly. Because a 2AA source only produces 3V a capacitor pump charger circuit was required to bump up the voltage. The pump charger was inefficient and quickly drained the battery. The pump charger was problematic and was suspected of causing so much noise in the system that extra effort was required to arrange it properly on the PCB.

The AA batteries were replaced by a 9V battery, which using a snap-on connector greatly mitigating the chances of power loss due to bumping or vibration. The pump charger was no longer required as the 9V source was more than enough to drive a 3.3V power regulator as a stable power source.

Figure 1.5: Bluetooth VA Sensor with AA Batteries

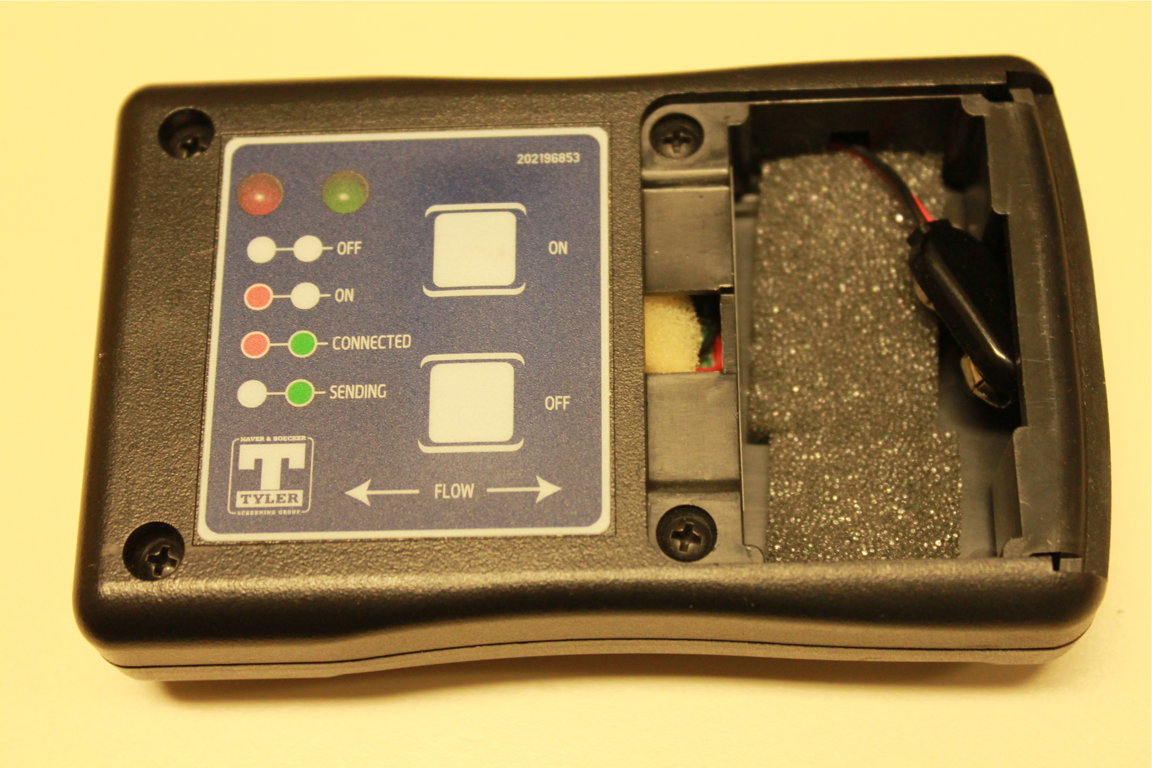


Figure 1.6: Wifi VA Sensor

Included in the driver for the VA sensors is a battery health indicator which simply reports that the battery level is low, typically giving the operator about ten minutes of time before the device fails. When using the AA battery pack system, this battery level was particularly difficult to determine because of the pump charger and the limited 3V range. The 9V battery design gives a much larger voltage range to monitor and no voltage boosting is required; just a consistent regulator. Consequently, battery warnings are now more accurate. Unfortunately, due to the differing voltage drop characteristics of alkaline and rechargeable batteries it is still somewhat difficult to produce accurate results without knowing the type of battery.

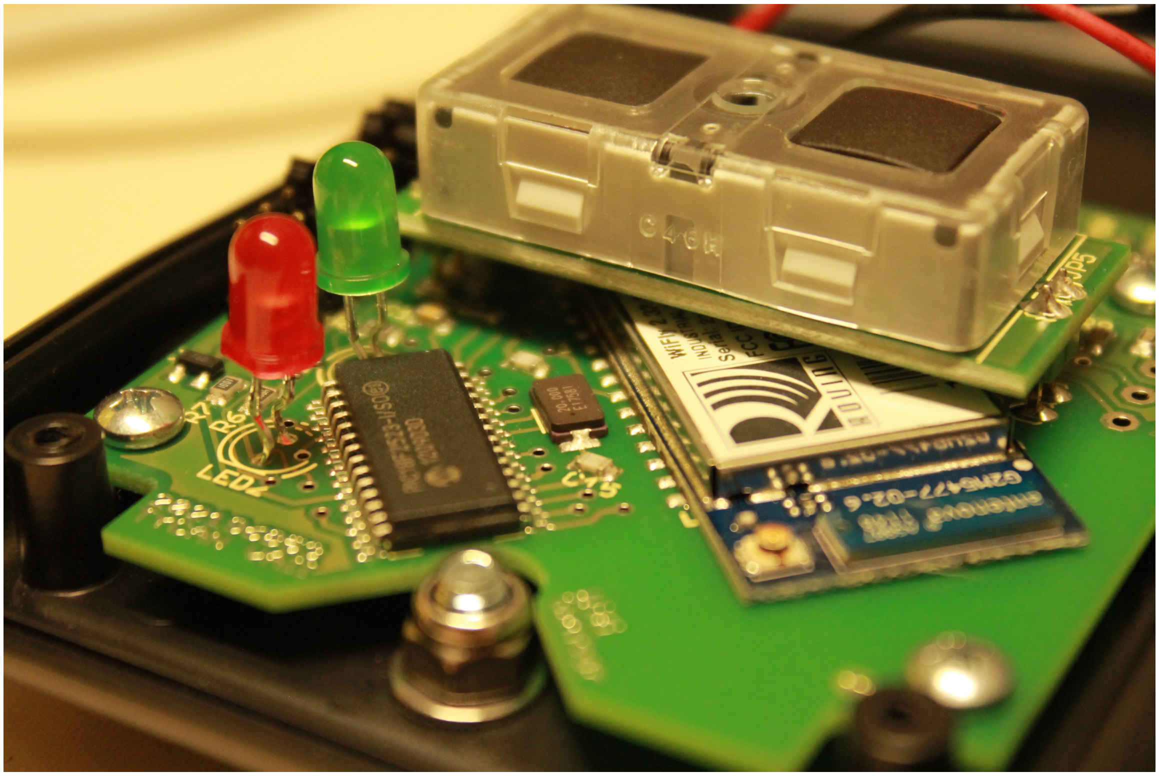


Figure 1.7: Inside the Wifi VA Sensor

1.6.2 Wifi Update

Thanks to the work performed by Daniel on a pair of prototype sensors the wifi chip was deemed a viable replacement and improvement to the bluetooth model. The first batch of wifi based sensors were manufactured and needed to be integrate into the existing PDA.

- A new PDA was purchased. It came with a built in Wifi antenna rather than bluetooth. It also came with a slightly upgraded operating system.
- A Wireless router was purchased and configured to allow for communication between the PDA and the sensors. Ideally the system should be able to run without this additional hardware but the setup of an Ad-Hoc network was

Figure 1.8: Replacement WiFi (Roving - WiFly) Chip

never tested. The network is organized through a range static ip's, manually configured for each of the sensors. The wifi SSID is configured and WPA2 encryption is enabled for added security. The same security must be configured on each of the sensors.

- WIFI chip (Whyfly) takes an RS232 serial connection and transmits the data over a TCP network stream. They are configured via ASCII commands which can either be transmitted through the TCP stream, for example a telnet connection, or they can be configured over their RS232 connection sourced by the microcontroller. It was decided that the configuration be done over the network due to its relative simplicity. The development time required to make the necessary modification to the assembly code executing on the microcontroller enabling it to configure the wifi chip was too great. The issue is that the wifi chip must first be put into a configuration mode. This requires that two pins on the wifi chip be shorted for a given number of seconds. The custom PCB manufactured for this project is modified to exposed these pins through on-board jumpers. To put the sensor into configuration mode you must take the sensor face plate off, move the jumper to the correct location and cycle the power. Once this is set, the wifly chip puts itself into an Ad-Hoc server mode. The operator then simply connects their computer to the wifly Ad-Hoc network and runs the configuration script. The script opens a TCP connection, runs the necessary commands and restarts the chip. It is at this point where the operator must be conscious of the specific IP given to the sensor. Each sensor must have a unique network address so that the controller software can later determine which sensor the data came from. This configuration may have been a bit simpler through DHCP but provides less control. A DHCP server and a way of differentiating the sensors, likely via MAC address, would be required. In this way more time is spent setting the sensor up initially but sequential ip addresses for differentiating the sensors are easier to understand than obscure, random un-configurable MAC addresses associated with the hardware. This decision makes the sensor easier to use in the field.

1.6.3 Sensor Synchronization

For the best results during the analysis of the vibration data, synchronized data from the vibration sensors is recommended. That is to say, each sensor logs a g value at the exact same moment of time. To achieve this, the acquisition on all of the sensors must be synchronized. The data being transmitted doesn't have to be synchronized as long as it comes in the order it was digitized. When the data gets to the analysis software it is re-combined, each recording from each sensor contains a digitized value from the exact same moment in time. Their only difference is the location on the vibrating screen.

There are a few ways required to achieve this:

1. A synchronization algorithm can be built into each microchip and into the PDA, analysis software which maintains a common, correcting clock source. This option can become quite complex.

2. Start each of the sensors at exactly the same time. This option is simplest but it does not correct for timing error entirely. For instance, the error between the clocks on the microchips remains as, they don't all run at exactly the same frequency. This method also assumes that the communication signal used to start each of the microchips arrives at exactly the same time. While the time difference between the arrival of this signal can be designed to be very low, it still exists.

The original sensors still operating with the bluetooth chips did not employ any sort of synchronizing efforts. When acquisition was started, each sensor was commanded to start one after the other in sequence, albeit very quickly. Luckily the timing error was still so low that it did not appear to affect the data. There is still room for improvement.

Now that the sensors are moved over to a wifi network solution there is the option of using a broadcast method not previously available on the bluetooth modules. This broadcast method allows the controller to send out a single start command packet which is received by each of the sensors at the same time. This is an ideal way to start each of the sensors synchronously, in theory. Unfortunately one of the caveats of using the broadcast packet was that it has to be a UDP packet. A UDP packet is optimized for simplicity and speed. It does not utilize any handshaking to confirm that the message arrived. TCP has its own handshaking and is able to retry and confirm a communication packet. This adds some extra overhead but makes communication far more reliable. Unfortunately in the case of our start message being broadcast out over UDP, the frequency of communication failure was too high. Approximately 50% of the time a start acquisition broadcast was sent out, at least one sensor didn't receive the message. If one sensor doesn't run then there's no point in running the rest because you have lost synchronization.

Regrettably, the broadcast message design was removed and the sensors are started the same way the bluetooth sensors were started using the reliable, but sequential TCP message.

Chapter 2

Literature Review

2.1 Vibration Analysis

It is a well known fact that experienced car mechanics can literally hear the development of certain faults in car engines. The sounds or “signatures” detected indicating a fault have even become fairly common terms. Examples include “piston-slap”, “bearing knock” or “pinging”. Randall (1974) This ability to detect a fault by recognizing a certain sound is, in principal, a form of vibration analysis. When operating normally a machine will vibrate in a certain way, with setting a base-line “signature”. Deviation from this “base-line” may indicate the development of a fault. An experienced mechanic can recognize that there is a problem because something doesn’t sound right. Often, time problem details can be pinpointed because the particular “signature” sound before. Traditional Vibration Analysis works in much the same way.

While the study of vibration dates back centuries, the vibration analysis techniques used today began in the 1950’s with the advent of high speed computers.

(Rao, 2010) Computers gave engineers the ability to perform powerful signal analysis using algorithms such as the Fast Fourier Transform.

In modern VA it is common to use accelerometers to read time-discrete samples of acceleration. Accelerometers are preferred because Randall (1974):

- They have a wide frequency / dynamic range
- They have small mass and dimensions
- They are rugged, no moving parts.
- They can be electronically integrated to give velocity displacement.

The application of vibration analysis can be broken down into two categories:

- Maintenance and Tuning.
- Fault Detection.

Maintenance and Tuning is currently the most common use of VA. During commissioning or routine maintenance a technician will perform VA to ensure the machine is running at its designed specifications. This will ensure that the machine is running efficiently and optimally and will prevent future failures. Parlar (2010)

If the machine begins to fail it may result in a loss of productivity or perhaps an unusual sound or vibration. These symptoms are not always visually or audibly discernible so a technician may perform another vibration analysis in the form of fault detection, to determine the source of the problem. Some of the common faults that modern VA can detect are: unbalance, misalignment, looseness, bent shaft, gear problems, bearing problems, motor internal faults, electrical grounding faults, structural noise excitation. Weir (2013)

There are three main ways in which to use Vibration Analysis Randall (1974):

- Field measurement with portable equipment

- Detailed laboratory analysis involving recordings made in the field
- Continuous monitoring with permanently installed sensors

The first two methods have been implemented and are currently being used by W.S. Tyler. The third method is the focus of current research. The data generated by the continuous monitoring set-up (third option) will help improve the effectiveness and advancement of laboratory analysis (second option).

There is no one correct way to perform VA, it depends greatly on the nature of the problem. J.D.Smith (1989) Therefore, many different techniques are used to extract meaningful, usable information from generated vibration data.

RMS Velocity: In this technique, the RMS velocity (mm/s) of a machine in good condition is known as a standard. When the measured RMS velocity begins to move beyond the range of that known velocity it may indicates machine deterioration. Randall (1974) This is a very basic form of vibration analysis and excels because of its simplicity. It requires little to no computing power and has been around for a long time. It is limited however, because it only provides a rough estimate of the condition of the machine. This technique provides very little information in the way of fault diagnosis and will miss faults that do not present with large amplitudes.

Waveform / Time Domain Analysis: The waveform analysis is simply a plot of the vibration data in a single axis vs time. Generally the vibration of the machine should produce a smooth sine wave. A misshapen sine wave may indicate a machine fault. This technique is useful for detecting impulsive vibration excitation that would not show up in spectrum analysis or averaging techniques.Randall (1974)

Spectral Analysis Modern VA makes use of the FFT (Fast Fourier Transform). The FFT is an technique which allows us to convert time domain data into the frequency domain in real time. Real time analysis is advantageous because it allows us to see conditions change as they occur. In some faults its the transient events that contain the most information. Randall (1974) When the data is viewed in the frequency domain it shows which frequencies exist in the data and at what magnitude. Analysis will show the relative strength of certain frequencies in the signal which can indicate a variety of things. Randall Randall (1974):

The type of faults which can be detected and perhaps diagnosed from a frequency analysis include unbalance (at shaft speed, primarily radial), misalignment and bent shafts (shaft speed and low harmonics, radial and axial), oil whip (just less than half shaft speed) and developing turbulence (blade and vane passing frequencies). Changes in natural frequencies can indicate crack growth or build-up of fouling. Local faults in rolling element bearings manifest themselves at frequencies corresponding to the rate of impact of the fault but also at higher frequencies (typically 20 - 60 kHz) corresponding to component natural frequencies.

Cepstrum Analysis This method is an effective way to detect periodic components in a signal. It is effectively taking an FFT of an FFT.

Orbit Analysis Orbit analysis is a plot of the waveform data between two axis. The x vs. y plot should be a smooth ellipse representing the path of the machines vibration. The x vs. z and y vs. z should be a straight line because there should be no movement in the z direction. Any abnormalities in these plots may indicate a fault.

DC Filters A DC filter is used on the data to remove the impact of gravitational acceleration. It is advantageous to remove the DC component for many types of analysis, but the gravitational acceleration may be an important component for calculating certain values, such as screen tilt.

Butterworth Filters Butterworth filters are powerful bandpass filters used to focus the analysis on certain frequency ranges. This filter is extremely useful for zoning in on known frequency spectrum's for a focused analysis. That said, the filter is removing all the frequency content outside the targeted band. These areas may contain important system condition information, so filter should be use very consciously.

There is no one correct way to perform VA; it depends greatly on the nature of the problem. J.D.Smith (1989) For example, for the purposes of maintenance and tuning, VA will generally focus only on the operating frequency of the machine. The VA tool will remove all other frequencies using a bandpass filter in order to generate the useful information required by the technician. Unfortunately this technique will not work for all problems because in some situations the useful information is in other frequencies; frequencies currently being filtered out. Sometimes the problem can be diagnosed simply by looking at the raw vibration wave form but other problems may require a series of complicated filters, frequency analysis and time averaging. Parlar (2010)

2.2 Condition Monitoring

Condition monitoring is the process of measuring machine parameters to estimate the machine's 'health'. In this case, the machine's vibration is monitored but condition monitoring parameters include temperature, oil quality etc. Condition monitoring uses the fault detection abilities of VA at much more frequent intervals in an attempt to detect a fault or developing fault sooner.

Unfortunately, despite a large body of research, the use of VA in the field is typically still performed by expert technicians. Parlar (2010) These technicians are expensive, and take a long time to train. In order for VA based condition monitoring to be successful, the analysis performed by these technicians must be automated. Using the experience of field technicians, researchers and engineers continue to experiment with expert systems. Ebersbach and Peng (2008)Chen and Mo (2004)Bo-Suk Yang and Tan (2005)

The typical model-based techniques S. Edwards and Friswell (1998) Chuei-Tin Chang and Tsai (1993) are inadequate for VA because they require extensive knowledge of the system under study. The detailed mathematical models of the systems required for the models are typically infeasible due to system complexity.

In order to successfully automate the VA of mining screens large amounts of vibration data from the machines needs to be collected. The machine needs to be monitored frequently and machine failures and failure mechanisms must be noted. Once all this data is collected it can be analysed to determine what changed in the vibration signature in the lead up to and advent of the failure. The particular deviation from the base-line in the time leading up to the fault can then be monitored in the future to predict the development of the fault.

So far, vibration-based condition monitoring of a rolling element bearing has been mostly studied from a signal processing point of view. Very little attention has been paid to the effects of the fault on the bearing's vibrational behaviour. Therefore, the first step in successfully implementing of bearing health monitoring is to establish the base-line behaviour of a healthy bearing. Furthermore, although a number of rotary machines operate under variable speed and load conditions, very few researchers have proposed robust techniques for the fault diagnosis and prognosis of such systems. Ghafari (2007)

The Trade-off. Intermittent detailed analysis can provide information about the normal wear process where as continuous monitoring can provide advanced warning of sudden failure. Randall (1974)

2.3 Predictive Maintenance

Unscheduled downtime of critical equipment in an industrial process can be very costly. It is estimated that the global process industry looses $20 billion a year (plant services). Today's plant managers generally have three options when it comes to machine management. Deciding which option to go with can be a bit of a balancing act.

On one end of the spectrum they have the option to "run to failure". This method allows companies to reduce short-term running costs because it requires little to no labour. When a machine goes down, they fix it. Unfortunately this also means they have no idea when the machine will fail so every time it does they will experience unscheduled down time.

On the other end of the spectrum there is the option of "preventative maintenance". With this method, maintenance of machinery is periodically scheduled in order to maintain the reliability of the machinery in an attempt to thwart unscheduled down time. PM's are relatively expensive short-term and can be wasteful. They often require scheduled down time and are labour intensive. During a PM, maintenance personnel will performs some sort of inspection of the machine and often replace parts that are prone to failure, even if it is still functioning normally. This can be wasteful especially when these parts are very expensive. PM's can greatly reduce unscheduled down time, but at a significant cost, without knowing if they prevented an impending failure.

By utilizing modern technology plant managers may decide to implement "Predictive Maintenance" or PdM. With this method, machines are monitored for various characteristics such as temperature, oil quality or in our case, vibration. PdM is able to predict an impending failure. This method reduces maintenance labour and material costs needed for PM's. By fully utilizing the information gathered from PdM energy consumption is minimized, product quality and production capacity availability are increased, spare parts inventory is reduced, consistent equipment performance and reliable production is provided, down time and over-hauls are reduced, asset life is extended, maintenance overkill and maintenance collateral damage is prevented, staff time allocation, repair scheduling is improved and overtime costs are saved. Weir (2013) By knowing when and why a machine is going to fail two of the greatest challenges in machine maintenance are removed. While PdM enables huge savings it does have its own costs. The technology required to monitor the machine can be a substantial added cost at set-up time and may required its own maintenance over time which adds complexity. PdM also requires highly trained technicians to interpret the data and to maintain the system.

Table 2.1: Maintenance Comparison

Technique	**Benefits**	**Drawbacks**
Run to Failure	inexpensive	highest potential for unscheduled down time
Preventative Maintenance	reduced potential for unscheduled down time	labour intensive expensive required periodic maintenance downtime
Predictive Maintenance	reduces potential for unscheduled down time reduces unnecessary maintenance and labour	high set-up cost more complex requires highly trained technician

2.4 Industrial Controller Design

Control panels are a typical sight at any industrial operation. They provide a way to power, organize and protect electrical equipment necessary for the process. The environments surrounding mining screens can be particularly harsh for electrical equipment. This section identifies these hazards and present solutions to them.

As mentioned by Randal Randall (1974), the most important features of a permanently installed vibration analysis system are:

1. extreme reliability
2. ruggedness
3. noise avoidance
4. cannot produce false alarms from electrical spikes or mechanical shocks e.g. a material dump.

Most failures of electronics equipment, instruments or sensors are mechanical in nature. Almasi (2009) Due to the complexity, small size and intricacy of electronics it is very difficult to track down the cause of the failure. It is especially difficult when all it takes is a hairline crack in a PCB trace or solder joint. Mechanical failures will most often occur to electrical equipment when it is subject to variable dynamic and vibrational loading from large rotating equipment; such as mining screens. The dynamic behaviour of a thin plate, a model used to represent a PCB as well as many other devices, has been studied fairly extensively due to its frequent occurrence in application. The system will experience the most damaging dynamic loading when it is vibrating (resonating) at its natural frequency. This undesirable frequency can be determined experimentally or by using the thin plate model and thus steps can be taken to avoid it. Unfortunately, in the application of a control panel there are many other components interact dynamically. The plate has a natural frequency, the enclosure has a natural frequency, and when combined, the plate-enclosure system has its own natural frequency which can also cause damage to the electronics and should be avoided. To make matters worse, it is standard in the industry for the manufacturers of rotating equipment to install control panels onto the same skid as the machine. This adds yet another element to the system of dynamically interacting components. The only way to accurately model the vibrational dangers to a control panel is for it to be modelled with the entire system, accounting for all the components' interactions.

Given the complexity of the model and the various sources of the dynamic and vibrational loading steps can be taken to defend against it. First, it is highly recommended that the the control panel not be installed on the same skid as the rotational equipment. This reduces the magnitude of the transferred vibration and decreases the complexity of the system, therefore reducing the number of resonant frequencies. Ideally, the control panel would have a separate foundation. This is not always feasible as mining screen are often installed in towers where the vibrations are transmitted through the tower structure itself. Second, it is recommended to stiffen the control panel components and fastening hardware. Stiffening will increase the k constants and effectively increase the resonant frequencies hopefully to levels much higher than those reached by the system. This is especially relevant in mining screens as their operating frequencies are relatively low as compared to most rotating equipment. Utilizing ribs, locking fasteners and supporting brackets will all help stiffen the system. The mounting of the enclosure box is an important consideration to avoid damaging bending and torsional modes of vibration. It is preferred to keep the box's centre of gravity low and centred between stiff supports. Almasi (2009)

Other environmental dangers that should be considered are high humidity, water, extreme heat or cold, corrosive liquids or gasses. High humidity may cause water to condense on or in the electrical equipment and cause short circuit failures. A common solution to this is to keep the equipment slightly warmer than the surrounding environment. The electrical equipment should be kept in an air tight container to limit its exposure to corrosive chemicals.

Another important consideration is that the systems HMI (Human Machine Interface) be intuitive, and easily usable by the typical operator. For example, it should be easy for the machine operator to test the validity of an alarm to make sure the system working properly Randall (1974). Using a couple of red and green indicator lights makes for a very simple way of communicating important system status information.

The VA Unit should be easily integrated into the target system infrastructure. This implies it should have a standard power requirement, e.g. 120/240VAC and 50 or 60Hz. The system should also use standard industrial parts so that replacement or repair parts are easily accessible.

Chapter 3

FIVO - the Fixed Installation Vibration Observer

The FIVO is the practical realization and continuation of Daniel's work on the continuous monitoring vibration analysis project. The observer is a complete and working system designed to be permanently installed along side a screen. It utilizes the project's newer wifi VA sensors to monitor the screen over a long time period to generate long term vibration data. The system completes many of the features lacking in the original fixed system and is a strong base for future development.

3.1 Introduction

A continuous monitory vibration analysis system is an advanced data logger. The system periodically collects vibration data from acceleration sensors placed around a vibrating screen. This data can then be analysed and logged to provide insight into the heath of the mechanical screen. The CMVA system can capture a history of the machine as well as interact with local control systems in the event of a detected failure. Ideally all the recorded data will be logged to a centralized database where further data analysis and trending can be performed. The system will alert local systems of detected failures and log the screen's vibration signature over time to provide the necessary information for predictive maintenance and troubleshooting.

3.2 System Requirements

To be successful to FIVO system must be capable of providing the following features:

- Long term vibration analysis recorder
- Industrial Environment Ready
- Web synchronization
- Integration with current VA system
- User friendly interface.

These basic requirements are broken down even further in the table below.

Function	**Description:**
Start at Power On	The system should start-up automatically once the power is restored.
Vibration Recording	Save vibration recordings locally.
Transmit Data to Server	Send locally saved (backlogged) data to the server as well as up to date recordings.

Configurable data storage/transmit method	Allow users to configure how much data is stored locally. When and how much to transfer to the server.
Local data processing	To detect vibration faults
System Status Indication	To indicate basic system faults. AOK, WARN, FAULT. Indication should be communicated locally, to the server, and to the PLC.
Online Configuration	Configuration of the system through a web application accessible online. Configuration file can be downloaded or synced to system
LAN Configuration	Provide the ability to configure the system through the browser, just as you would on the website. without an internet connection.
XML Configuration File	All configuration settings will be saved in a single XML file.
XML Data File	All vibration data will be stored in XML format.
Automated Server Sync	Configurable automated server data/setting synchronization technique.
Log PLC Signals	Provide the ability to configure and log PLC Control Signals (Run/Stop), (Feed/None).
Watchdog	Subsystem to restart the application and/or computer hardware in the case of a system ‘freeze’.

3.3 Design

3.3.1 Overview

FIVO Consists of only a few sub-modules as depicted in 3.9.

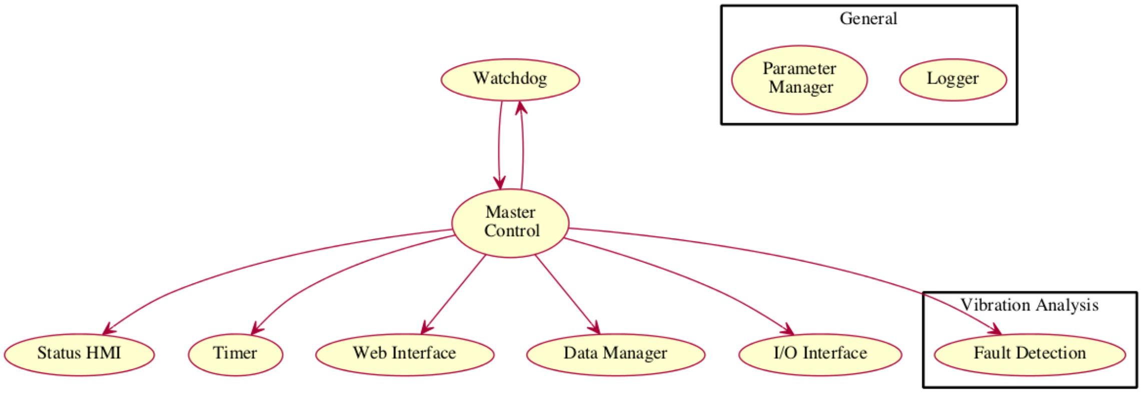


Figure 3.9: Overall Architecture

The diagram 3.10 illustrates how the FIVO system communicates internally.

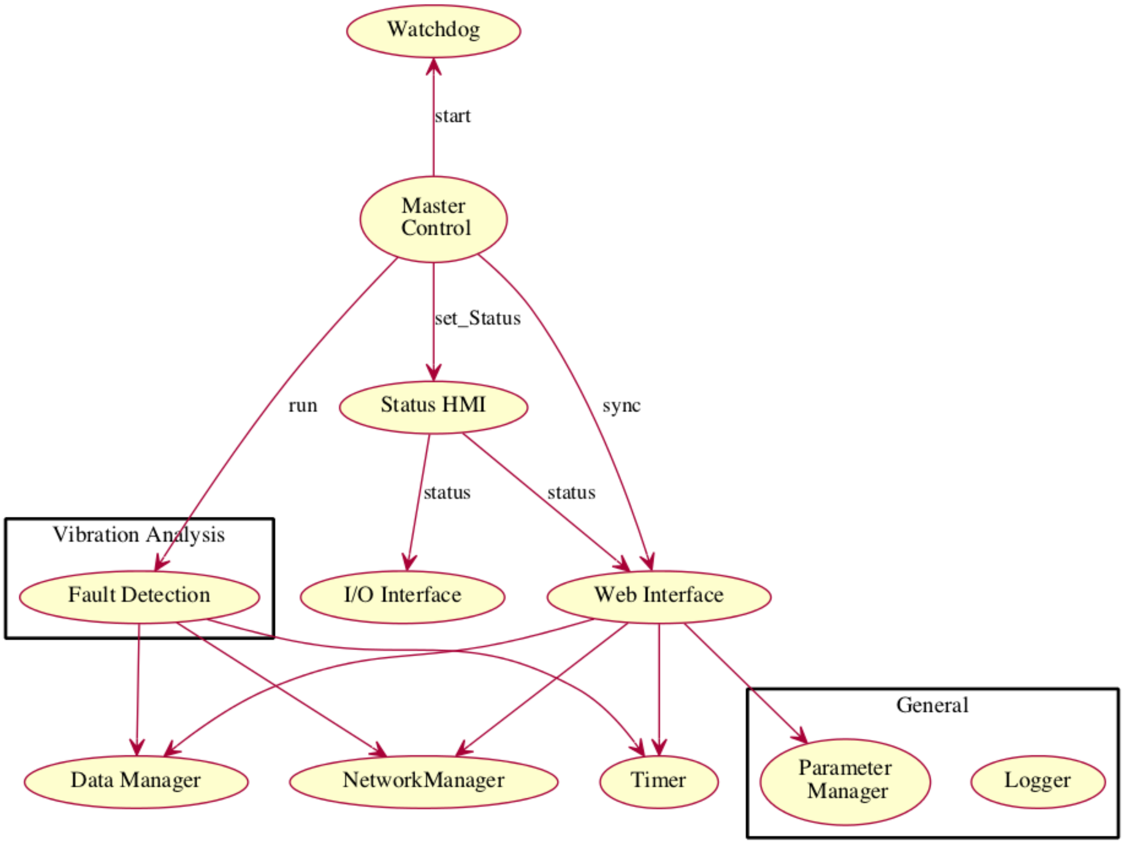


Figure 3.10: FIVO Running

The diagram 3.11 illustrates how the FIVO system starts up.

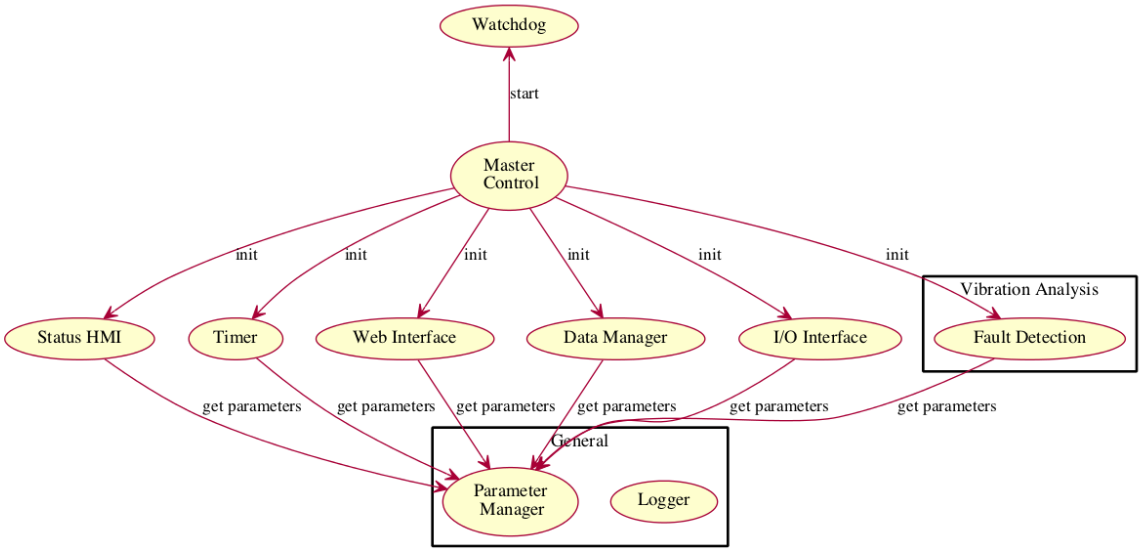


Figure 3.11: FIVO Startup

The diagram 3.12 illustrates how the FIVO system communicates with a VA sensor.

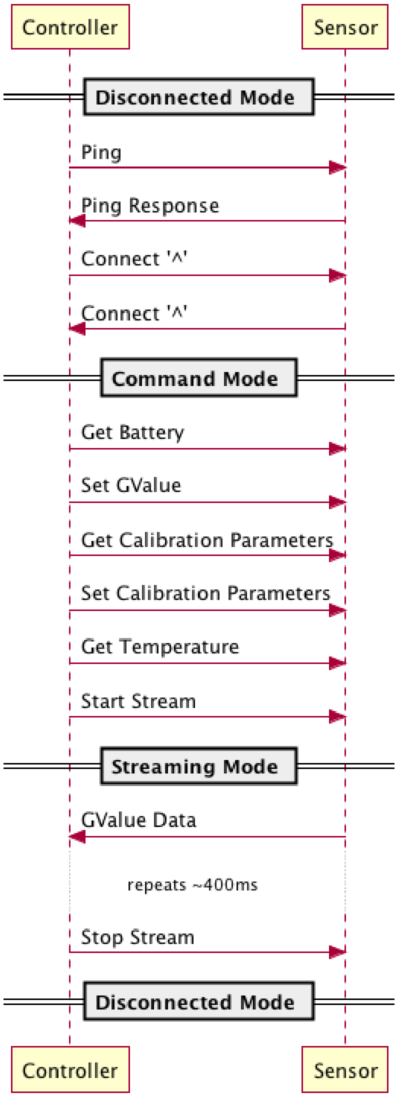


Figure 3.12: FIVO Sensor Communication

The following sections detail out a few of the common, high level objects in the FIVO system.

Parameters (Saved as XML)

Name	Description
Record Duration	specifies the length of time a recording should run
Customer Data	details about the customer such as name, email address, etc.
Machine Data	details about the machine such as model number, serial number etc.
I/O Select	configuration enabling or disabling some of the IO options used to communicate with other systems such as PLCs or plant networks.
Debug Mode Select	Allows the FIVO to operate in debug mode. This debug mode more detailed log files are generated. This mode should only be used when attempting to troubleshoot a problem in the system.
Record Frequency	The frequency at which the Vibration Analysis is performed
Start-up Delay	The time delay, from start-up of the vibrating screen, that a VA Acquisition can be performed.

Sensors and Addresses	Configuration of the VA sensors in the system. Each sensor has a unique address and here it must be configured so that the FIVO can communicate with it. The physical mounting location of the sensor on the vibrating screen is also specified here.

Errors

Name	**Description**
No Network	Occurs when a network connection cannot be established. If there is no network connection the FIVO cannot be configured.
Parameter File Corrupt or Missing	If the parameter file is corrupt of missing the FIVO may be missing critical configuration. In the event of this error the FIVO cannot acquire data.
Failed Internet Access	If there is no internet access the FIVO cannot upload the acquired data to the centralized server. Data can be stored locally temporarily.
X # of Sensors Fail	Occurs when a failure is detected on 1 or more VA sensors. The FIVO can still operate with the loss of a few sensors but the quality of the analysis quickly degrades.
All Sensors Fail	If all sensors have failed something has gone critically wrong. No acquisition can be performed.

Vibration Warning Triggered	Occurs when the FIVO detects vibration levels that cross the configured warning threshold.
Vibration Fault Triggered	Occurs when the FIVO detects vibration levels that cross the configured fault threshold. When this fault occurs the vibrating screen should stop operating as it has reached vibration levels that are self-damaging. This error can be tied to a IO output capable of communicating with the controlling PLC, triggering an automatic shut-down.
Screen Stopped during Recording	This error occurs if the screen operation was stopped while the FIVO was performing an acquisition. Because the vibration characteristics change so much when the screen is started and stopped the data collected becomes incomparable. The data file is flagged as failed.
Watchdog Time-out	Occurs when the FIVO software becomes unresponsive. The PC contains a hardware watchdog which will reset the PC when this error occurs in an attempt to resolve the problem.

Status

Status information will be communicated via panel LED's, 4-20mA PLC connections, and internal IPC.

Name	**Description**
AOK	all systems running nominal
Warning	vibration warning, sensor failure, other ...
Fault	No connection, not recording, vibration fault

IO Uses

Name	**Description**
System Status	Indicates the FIVO run status. 4mA = AOK. 10mA = Warn. 20mA = Fault.
System Control	Allows an external device (eg. PLC) to control the acquisition intervals. When this signal is high, the FIVO will acquire VA data.
Run Signal	Provides the vibrating screen run signal to the FIVO. This allows the FIVO to observer whether or not the vibrating screen is running.

States

Name	**Description**
power on	
start-up OS and application	PC automatically launches the FIVO application
initialize	Application loads essential systems and initiates communication with associated hardware.

verify	verify configuration
make recording	perform VA Acquisition
save data to local database	
systems health check	
transmit data to server with system status	Push to server. If configured to do so.
check for new parameters on server	Pull from server. If available.
repeat at make another recording	

3.3.2 Components

Name	**Description**
MasterControl	Main Component. Organizes and maintains high level operation.
StatusHMI	Manages all the of STATUS displaying.
Timer	Manages the acquisition interval.
Logger	Manages the system log.
DataManager	Manages the acquired data.
VibrationAnalysis	Performs Local Vibration Analysis
Watchdog	Manages the hardware watchdog
WebInterface	Manages the network interface. LAN Config and Data uploads.

Master Control

Purpose

Control and execute the high level system logic tree. This is the highest level of the process tree, the entire system is executed by the logic in this module. This module will control the system process and deal with the high level failure resolution.

Public Functions:

init(...)	Initialize the system. Run vitality checks. Make sure system is operational.
run(...)	Run the main loop of the program.

init(...):

Description:	Initial start-up routine which performs system vitality checks.
Uses:	WebInterface, IOManager, ParamMan.
Inputs:	debug
Outputs:	returnval = {status, network, web, parameters} status (bool) - False if error setting status. network (bool) - False if error testing network. web (bool) - False if error testing web connection. parameters (bool) - False if error checking parameters.
Design:	initialize watchdog start watchdog initialize all other modules. Modules will return their success. verify all modules initialization return successful. resolve any failures and retry get / check / update parameters log errors / actions performed return success / failure

Running This begins the main loop of the program. However, there are a few things that must be done prior to starting the main loop which should not be done in the initialization function. They are as follows:

1. Set the status indicator to AOK. This will indicate the system run signal has been given and there are no known errors. It cannot be done in the initialization step because to indicate running, the run function must be called.

2. Start the necessary timers. All of the timers should be set to their correct

starting values when they were initialized however they will need to be started when the run signal is given.

Now that the main loop is ready to run, the program can begin. The basic loop to the system is as follows:

- Run the VA routine
- Perform a web synchronization
- Reset the watchdog

Design:

The sequence of the system start-up is very important for proper operation. The design and order of operations will be discussed below. In many situations it is crucial to maintain the designed operational order or the system will fail. The reasoning behind certain design decisions will be discussed when possible and appropriate.

1.	ParamManager	Parameter Manager module should be the first to be initialized. All other modules are depend on it.
2.	Watchdog	In order for the watchdog to work as a fail-safe, it must started before a failure occurs. Starting it as early as possible will maximize its effectiveness.
3	System Logger	
4	Timer	
5	I/O Interface	
6	StatusHMI	
7	WebInterface	
8	DataManager	
9	VibrationAnalysis	

run(...)

Description: Start main application loop.

Uses: Everything. This either directly or indirectly uses all modules of the system.

Function Parameters:

Name	**Description**
exit_status (bool)	True if clean exit. Since the run function is the main loop, there is no reason for it to exit, let alone return anything.

StatusHMI

Purpose:

This module will manage the status outputs. Through various forms of HMI, it will indicate the overall status of the system in a simplified manner. There are 3 individual methods for communicating the system status: local visual (indicator light's), PLC interface, and through online interface. Each method will communicate the same message and at the same time. Each method can be enabled or disabled in the system parameters.

There are three main system status states:

AOK	All-OK will indicate that there are no present issues and that the system is running normally.
Warn	Warning will indicate that the system requires attention but it is still functioning.
Fault	The Fault status indicates that there is a critical problem and it requires immediate attention.

The three HMI indication methods are:

Local Visual: The local visual method will simply display the status through LED's mounted on the main control panel. There are 3 indication lights on the front of the control panel it indicate the status.

Colour	**Indication**
RED	Fault
YELLOW	Warn
GREEN	AOK

*When the system is shut-down, all three lights will be dark.

*When the system is starting, all three lights will be active.

PLC Interface: One of the most common ways of communicating data with a PLC is through a 4-20mA analogue channel. This method will make use of this channel to communicate the system status.

Signal	**Indication**
15 mA	Fault
10 mA	Warn
5 mA	AOK

Web Interface: Under normal operating conditions the system will be in regular communication with a centralized server. Utilizing this connection, this method will communicate the system status to the centralized server where it can be logged and displayed online.

Parameters:

Name	Type	Description
HMI_visual	Bool	Toggle the use of the visual HMI method. True = Use Visual HMI indication
HMI_plc	Bool	Toggle the use of the PLC HMI method.
HMI_web	Bool	Toggle the use of the Web Interface HMI method.

Public Functions:

init(...)	initialize the module.
set_status(...)	set the HMI status.
get_status(...)	get the HMI status.

---

init(...)

Description: Initialize the StatusHMI module.

Uses: ParamMan, IOIface

Parameters: none

Design: Get the parameters. Set-up the connection to the web module and the IO module. Initial conditions: status set to Fault.

---

set_status(...)

Description: The set_status function sets the status of all three indication techniques, if they are enabled in the parameters.

Uses: ParamMan, IOIface

Parameters: status - {AOK, WARN, FAULT }

Design: Check that the given status is an acceptable request. If so, save the status internally. Set the visual HMI if enabled. Set the PLC if enabled. Set the web if enabled.

---

get_status(...)

Description: Returns the current status of the system.

Uses: None

Parameters: status - {AOK, WARN, FAULT }

Design: Return the current status.

Timer

Purpose:

The timer module will handle the delays and timing events as they are configured in the parameters. By keeping the timing separated from the rest of the system it will make it much easier to adjust the timing technique later if required. The timer module will simply be a countdown timer, designed around the system it is running on. It can be set, started, stopped, and reset. When the countdown has finished, the timer will be checked by the routine using it, and will indicate the status of the countdown.

Uses: none

Public Functions:

init(...)	initialize the module.
set_time(...)	set the time limit of the clock. Default is 0.
get_time(...)	get the time left on the clock
is_finished(...)	check to see if the clock has finished. Return True for countdown complete.
reset()	restart the clock. To start the clock, this must function must be called.

Logger

Purpose:

This module will serve as an interface for the rest of the system to log their activities. All of the debug messages will be passed through the logger. This allows us to collect and organize all the system messages into one location. The logger will determine whether or not to display the debug messages based on the parameters. The log can also be saved to file. This module will help in debugging any issues that arise in the system. The data can also be used for advanced vibration analysis where the extra data may be required.

Uses: ParamMan

Parameters: debug, **Public Functions:**

init(...)	initialize the module.
msg(...)	create a new message in the log.

DataManager

Purpose:

To maintain the storage location and availability and processing status of the data files produced by the vibration analysis routine. The modules maintains a list of data files that still need to be transferred to the centralized databank.

Uses:

System Parameters: debug

Public Functions:

init(...)	initialize the module.
add(...)	add the datafile to the datamanager repository
get(...)	get the datafile(s) that are being held by the datamanager, ready for transmission.

WatchDog

Purpose:

The watchdog modules does not perform any functions that assist the systems main goal, however it indirectly adds reliability. This module will interface with and manage the watchdog subsystems in order to minimize system hangs.

Uses:

System Parameters:

Public Functions:

init(...)	initialize
check-in(...)	reset the watchdog time-out

WebInterface

Purpose:

The web interface module will handle all communications to the centralized server.

It is designed to simplify the web syncing process. This module serves to provide the following features:

1. Transfer data files generated by the vibration analysis modules to the centralized database.
2. Communicate the current status of the system to the web.
3. Download and update the system parameters from the W.S. Tyler VA server.

The WebInterface module will only connect to the main server every so often to reduce network traffic. This time-out is handled using a timer and is configured using the parameters.

Parameters:

WebInterface_Interval	time to wait in between web communications
WebInterface_Enable	toggle the use of the Web interface. The other WebInterface parameters will be ignored if the Web Interface is disabled.
Server_Authentication	Toggle server authentication.
username	the username required to connect to the server.
password	the password required to connect to the server.
ServerAddress	The address of the centralized server and database.

Uses: ParamMan, Timer, NetworkMan

Public Functions:

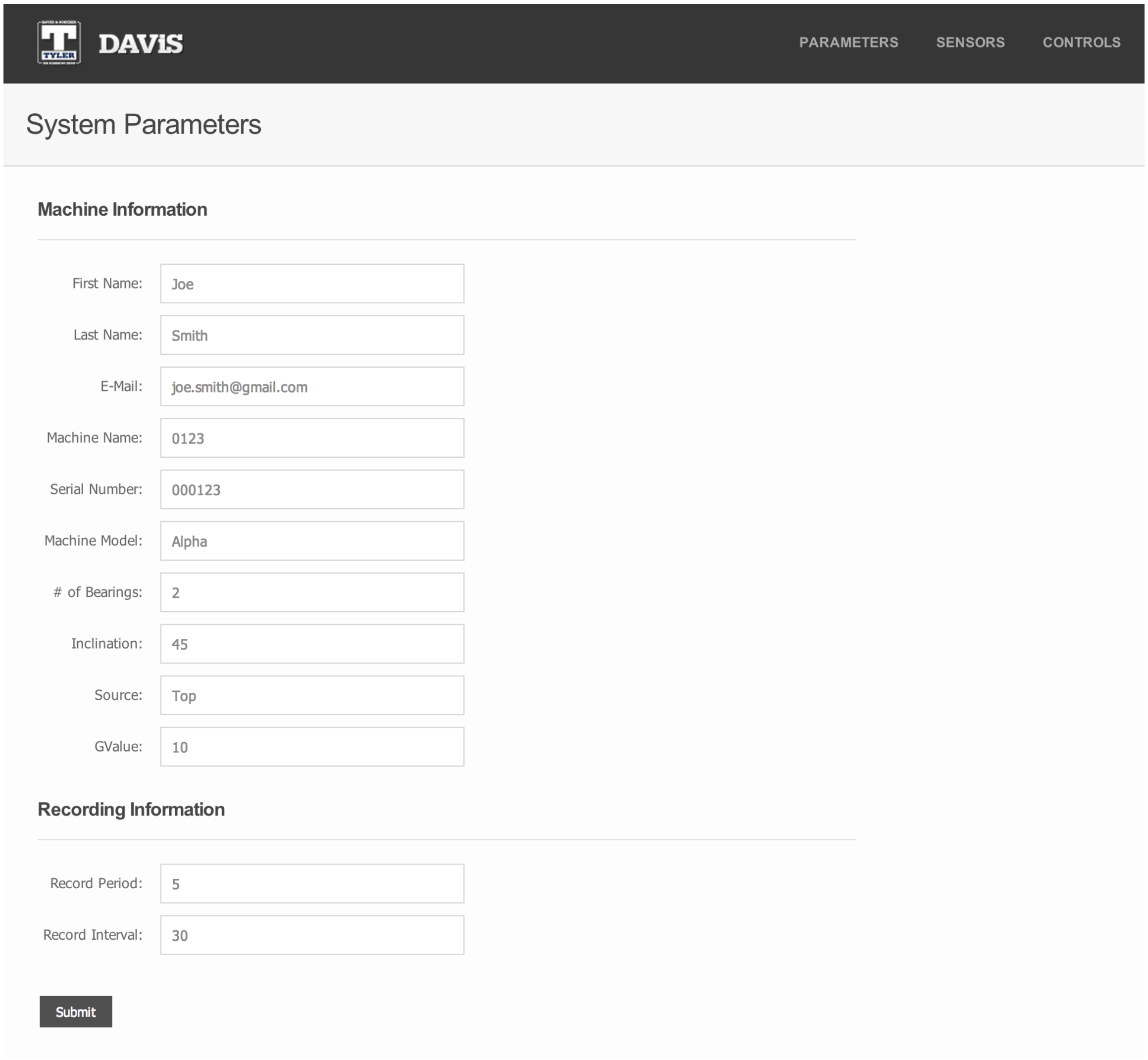
init(...)	Get parameters. Initialize subsystems.
set_status(...)	Sets the system status to be transmitted to the server.
get_webparam(...)	Get any updated parameters from the server.
send_message(...)	Send a text message to the server.
send_data(...)	Upload data file(s) to the server
sync(...)	automate the communication of status, upload of data and download of para

VibrationAnalysis

Purpose:

To connect to the sensors, collect the data and produce a data file. To analyse that data file and report its acceptability.

Hardware Selection



System Parameters

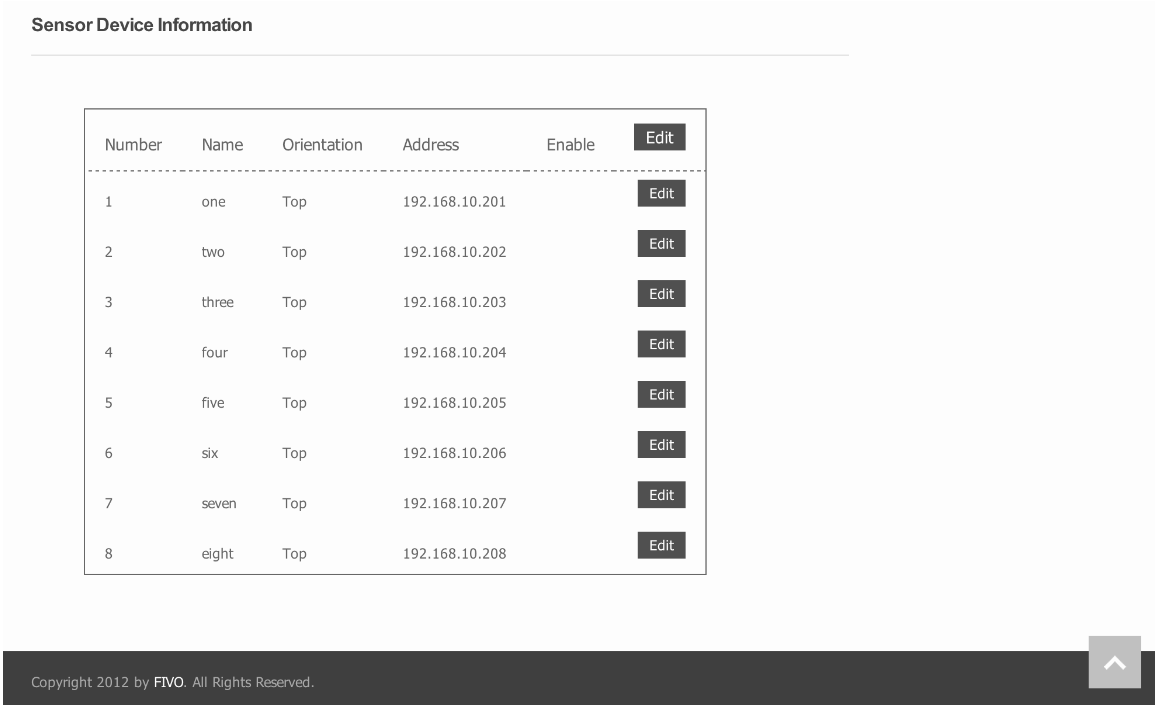
Machine Information

First Name: Joe
Last Name: Smith
E-Mail: joe.smith@gmail.com
Machine Name: 0123
Serial Number: 000123
Machine Model: Alpha
# of Bearings: 2
Inclination: 45
Source: Top
GValue: 10

Recording Information

Record Period: 5
Record Interval: 30

Figure 3.13: Web Parameters



Sensor Device Information

Number	Name	Orientation	Address	Enable	Edit
1	one	Top	192.168.10.201		Edit
2	two	Top	192.168.10.202		Edit
3	three	Top	192.168.10.203		Edit
4	four	Top	192.168.10.204		Edit
5	five	Top	192.168.10.205		Edit
6	six	Top	192.168.10.206		Edit
7	seven	Top	192.168.10.207		Edit
8	eight	Top	192.168.10.208		Edit

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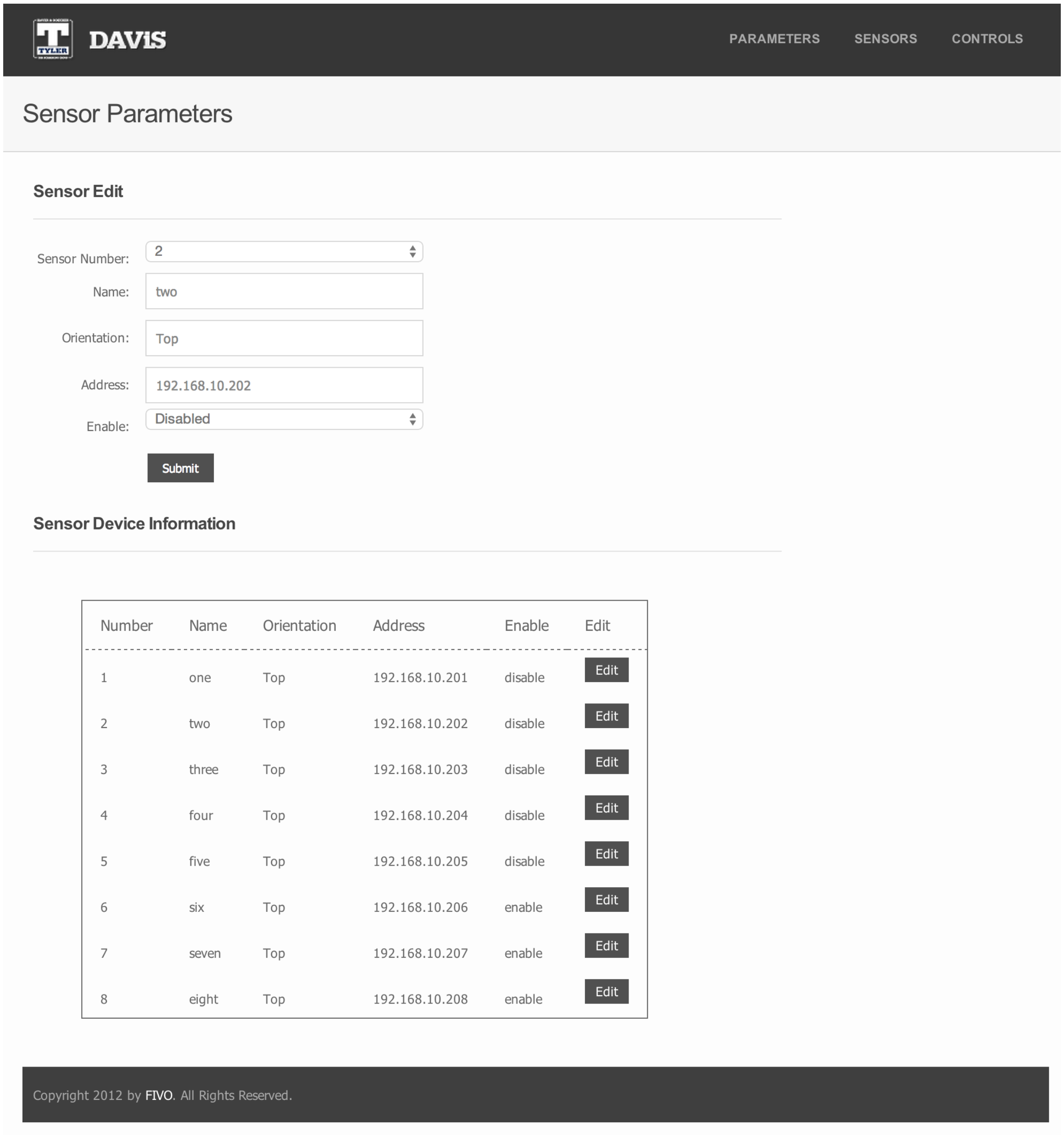
Figure 3.14: Web Sensor List



Sensor Parameters

Sensor Edit

Sensor Number: 2
Name: two
Orientation: Top
Address: 192.168.10.202
Enable: Disabled

Sensor Device Information

Number	Name	Orientation	Address	Enable	Edit
1	one	Top	192.168.10.201	disable	Edit
2	two	Top	192.168.10.202	disable	Edit
3	three	Top	192.168.10.203	disable	Edit
4	four	Top	192.168.10.204	disable	Edit
5	five	Top	192.168.10.205	disable	Edit
6	six	Top	192.168.10.206	enable	Edit
7	seven	Top	192.168.10.207	enable	Edit
8	eight	Top	192.168.10.208	enable	Edit

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Figure 3.15: Web Sensor Parameters

Figure 3.16: ADAM IO Module

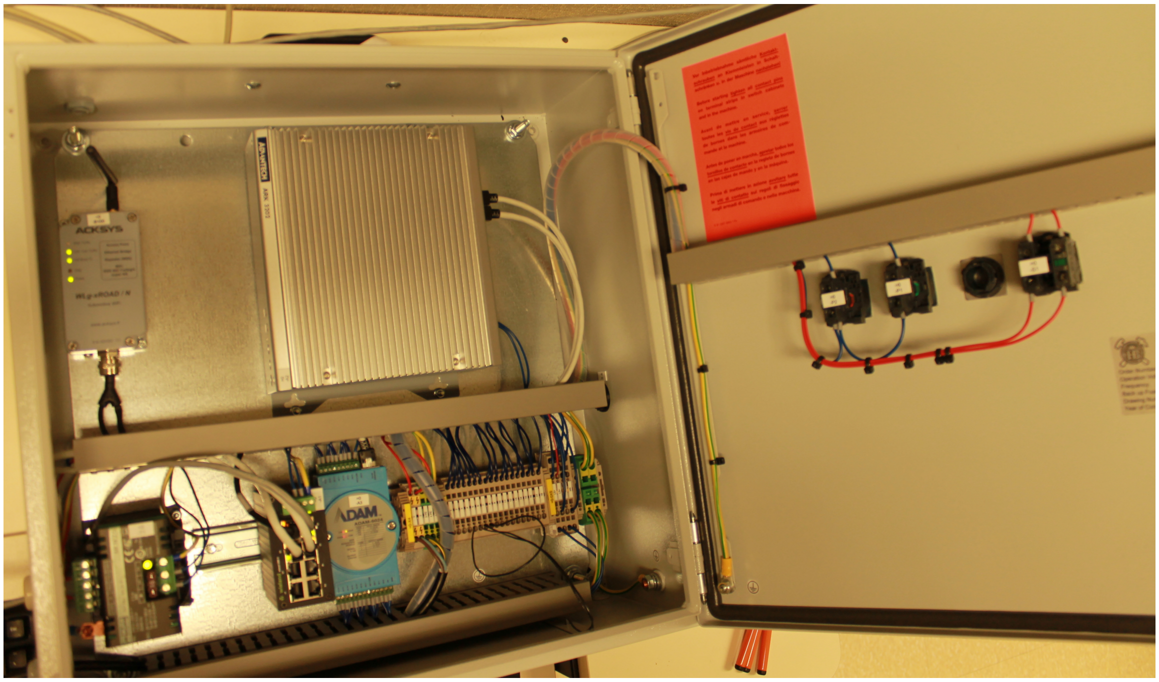

Figure 3.17: Inside the FIVO Enclosure

Figure 3.18: The FIVO Enclosure

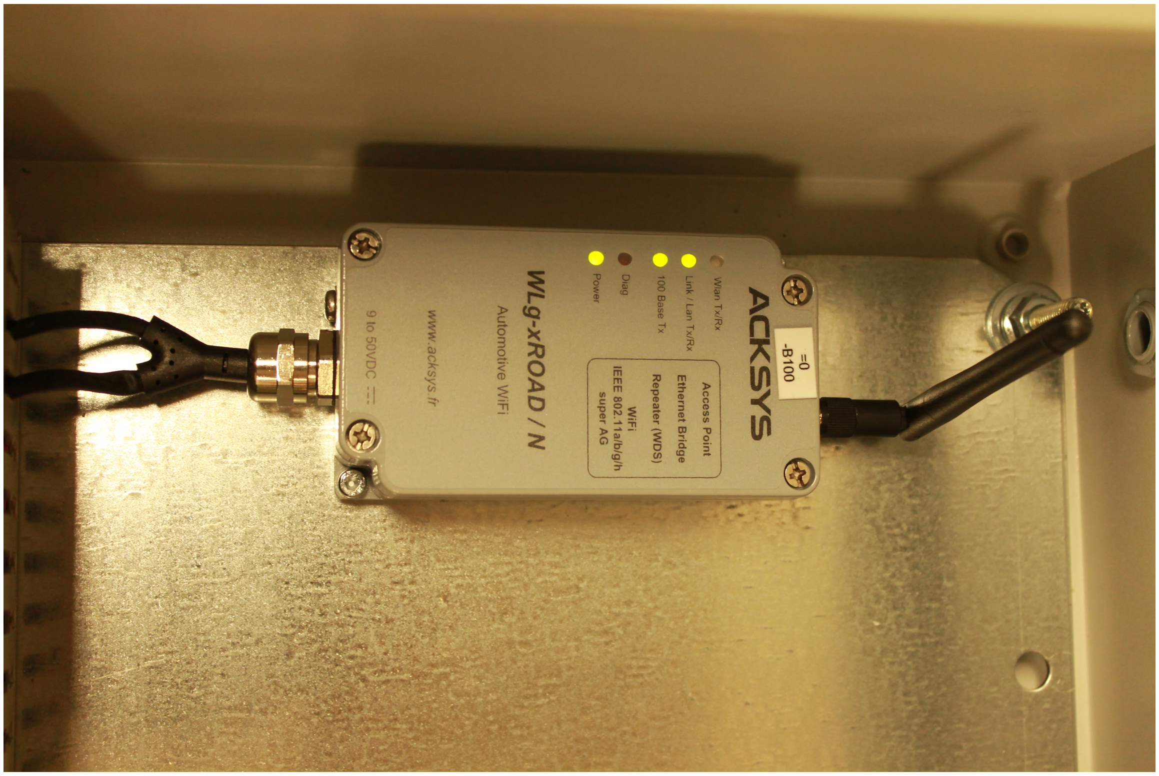

Figure 3.19: FIVO Wifi Module

Chapter 4

Conclusion

4.1 Discussion

This thesis presented the design and implementation of a fixed installation vibration analysis system for mining screens. The proposed system is designed to overcome many of the shortcomings of the previous generation VA system. The discussion below will evaluate.

The W.S. Tyler VA Sensor has undergone two upgrades. The first being the switch in power source, from a pair of AA batteries to a 9V battery. The connection on the 9V battery is far more secure than the AA's which greatly reduces the occurrence of intermittent power loss while subject to vibration. The second upgrade was the replacing the Bluetooth with Wifi communication. Wifi is easier to use, allows for higher data throughput and has proven to be a more reliable medium.

For the past several years, W.S. Tyler has been focusing on taking their vibration analysis suite to the next level. The existing analysis system allowed the technician to perform a short term analysis and almost instantly generate information which allowed them to tune or troubleshoot problems with their screens. The next step in the evolution of the system was to enable the prediction of problems before they happened. In order for the system to be able to perform predictive maintenance it must to be able to:

- Perform long-term, periodic, VA data acquisition.
- Organize and archive data for processing and data mining.
- Be easy to use, install, and configure.
- Be resilient, built of industrial hardware to survive its environment.
- Process and trend data to produce useful and meaningful results.

The FIVO uses existing W.S. Tyler VA Sensors to perform VA Acquisition. The system is designed to provide an acquisition scheduler which allows for configurable, periodic acquisition. This system is deployed on a PC instead of a PDA. Much more storage space is available for long-term acquisition. The system can upload scan data to a centralized server which effectively enables unlimited acquisition.

The organization and archiving of data for long term analysis is only partially covered in this thesis. This requirement is completed through the combination of this thesis and the work of Wisam Hussain. This thesis covers data collection, saving to the updated XML format, and the uploading the data to a centralized server. Wisam goes on to explain how the data is then archived and catalogued.

The web interface is a simple and effective way of interacting with the user. It can be accessed from anywhere on the network; making it very flexible for the end user. Most people today are familiar with webforms and configuring accounts through their web browser so by using this method, little training is necessary. It also means additional software does not need to be installed on the technician's or end user's computer, alleviating a many potential issues.

As is described in the hardware section 3.3.2 the prototype has been built into an industry standard industrial enclosure capable of withstanding the harsh, dusty, corrosive environment typical around mining screens. All of the internal components have been selected to be industrial grade.

The algorithm proposed in the previous system (CMVA) was oversimplified and limited in its application. While the work in this thesis does not generate an improved algorithm it provides the stepping stones required to generate a far more powerful algorithm. By combining the FIVO and the work on the centralized server researchers can generate a much larger set of vibration data over far greater periods of time. This opens the door for far more advanced vibration analysis techniques such and predictive maintenance as described in section 2.3.

4.2 Future Work

1. Vibration Power Generation. W.S Tyler now requires their VA sensor operate wirelessly. It is too dangerous for an operator to be physically connected (through a cable) to an operating vibrating screen. This is why the VA sensors use wifi communication and batteries. Unfortunately these batteries don't last very long; especially during constant use. If the FIVO system is to succeed, the VA sensors cannot be solely powered by batteries. Replacing batteries on a daily basis to continue analysis just isn't feasible. Plugging the sensors into a fixed power source would require cables effectively tethering the vibrating screen to

the infrastructure around it is not desirable. Another option is to somehow use the operation of the screen itself and harness the vibrational energy to power the sensors.

2. Greater VA Resolution. Upgrading the VA sensors to use Wifi instead of Bluetooth provides much greater communication bandwidth. The VA sensors limited their acquisition frequency in order to accommodate the bluetooth technology. With the bandwidth restriction now removed, the sensor is now open to using its full acquisition rate which may lead to more useful results.

3. Deploy the FIVO. The FIVO system discussed in this thesis is still an early prototype. It requires testing, revisions and production in order to progress.

4. Long Term VA Data. As discussed, the generation of more powerful analysis algorithms and more useful VA results, more VA data is required. The FIVO system is capable of generating this data over long periods of time. Once the data is generated, researchers can process it and generate algorithms that are capable of supporting predictive and preventative maintenance. Even longer term this data can be mined. For instance, if we compare data from screens of the same model it may result in the observation of recurring design flaws which then supports product improvement.

Appendix A

A Mathematical Model for the Vibrating Screen

The purpose of this section is to:

1. describe the mathematical equations which govern the motion of the vibrating screen.
2. demonstrate how each of the parameters impacts the system response.
3. explain how to control the system by adjusting these parameters.

The plots and parameters used in the models have been chosen to explain the concepts of the system. The example values may not represent a typical mining screen however, the concepts they demonstrate are still valid.

Figure A.20: Mining Screen produced by W.S. Tyler

A.1 The Exciter

The exciter is the mechanism used to add an oscillating force to the screen in order to make it shake. While there may be several way to create a oscillating force, the simplest method is to use a rotational imbalance. A rotational imbalance is the one of the most typical sources for unwanted vibration and designers will go through great lengths to remove/counteract them. In the case of a mining screen however, we will use the rotational unbalance to our advantage. For the remainder of the model this will be represented simply as a unbalanced rotating mass.

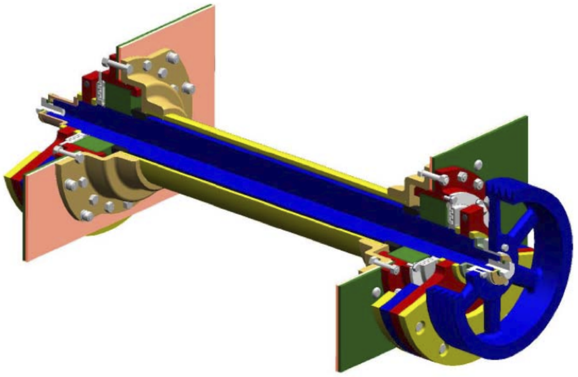

Figure A.21: Shaft Assembly produced by W.S. Tyler. A typical design for a Rotational Imbalance Exciter

A.1.1 Rotating Imbalance

To start, we will simplify the model by observing only one degree-of-freedom and then expanding later. Equations governing a 1-D unbalanced rotation mass are as follows:

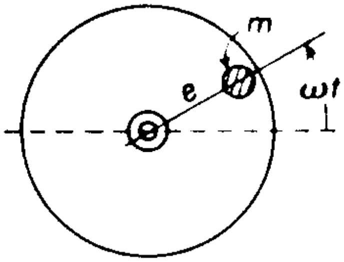

Figure A.22: Rotating-Imbalance

$$F = ma \tag{A.1}$$

$$a_c = v^2/r \tag{A.2}$$

$$v = \omega r \tag{A.3}$$

$$a_c = r\omega^2 \tag{A.4}$$

$$F_c = mr\omega^2 \tag{A.5}$$

Typically the distance the mass is from the centre of rotation is known as the 'eccentricity' so in this case the 'r' will be represented as 'e'.

$$F(t) = me\omega^2 \sin(\omega t) \tag{A.6}$$

The force generated by the rotational unbalance can be described using Equation A.6.

A.1.2 Parameters

A number of parameters can be manipulated.

Mass Eccentricity

Typically a combined parameter known as mass-eccentricity (me). Increasing or decreasing the mass or the eccentricity or both will increase or decrease the amplitude of the force respectively.

Rotational Velocity

The rotational speed in radians/second (ω). Increasing ω will increase the speed of the system but it will also increase the the amplitude of the force quadratically. In order to increase speed without increasing amplitude adjustment of me is also necessary.

A.2 The Screen

The vibrating screen sifts materials/aggregate by passing it over various sizes of wire mesh. This mesh by itself is not designed to support the mass of the material placed upon it, therefore it requires external support. The structure that supports the mesh is designed fairly stiff in order to support the load of materials across the span of the mesh without it deforming. Deformation reduces the amplitude and the control of the vibrational motion. Deformation is also very hard on the structure and leads to material stress failure. In an attempt to keep the structure rigid it is designed with large pieces of steel. As a result the supporting structure is a very large mass that must now also vibrate in order to vibrate the mesh. To give this structure the room and freedom to vibrate it is placed on large springs.

A.2.1 Rotating-Imbalance Mass-Spring-Damper System

Inherent to just about any system we must include damping due to friction. Putting all the parameters together we are now able to make simplified but representative model for further study.

$$m\ddot{x} + c\dot{x} + kx = me\omega^2 \sin(\omega t) \tag{A.7}$$

The system we are studying is now a generic mass spring damper system combined with a rotational unbalance, as seen in Figure A.23.

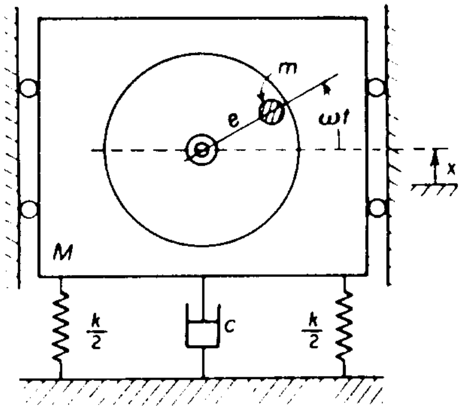

Figure A.23: Simplified 1D Rotating-Imbalance Mass-Spring-Damper System

The movement of our system can be described using the following equations:

$$x(t) = X\sin(\omega t - \phi) \tag{A.8}$$

where:

$$X = \frac{me\omega^2}{[(k - M\omega^2)^2 + (c\omega)^2]^{1/2}} \tag{A.9}$$

$$\phi = \tan^{-1}\left(\frac{c\omega}{k - M\omega^2}\right) \tag{A.10}$$

A.2.2 Parameters

This section will describe each parameter and how it impacts the response of the system. Many of these parameters can be modified to get to get a more desirable system response.

me	mass eccentricity
ω	rotational velocity
k	spring constant
M	total mass of the system
c	damping constant.

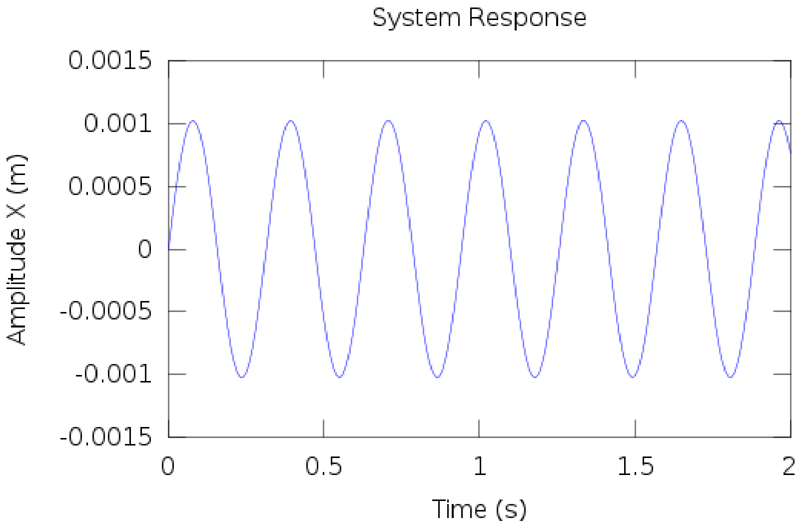

Figure A.24: This is an example of a typical system response with constant parameters.

Mass Eccentricity

You can see from Figure A.25, when you increase the mass eccentricity, the the amplitude of motion increases linearly. This characteristic provides us with a simple and controllable way to increase or decrease the amplitude of the vibration. Simply adjust the parameters of the exciter to get the desired amplitude.

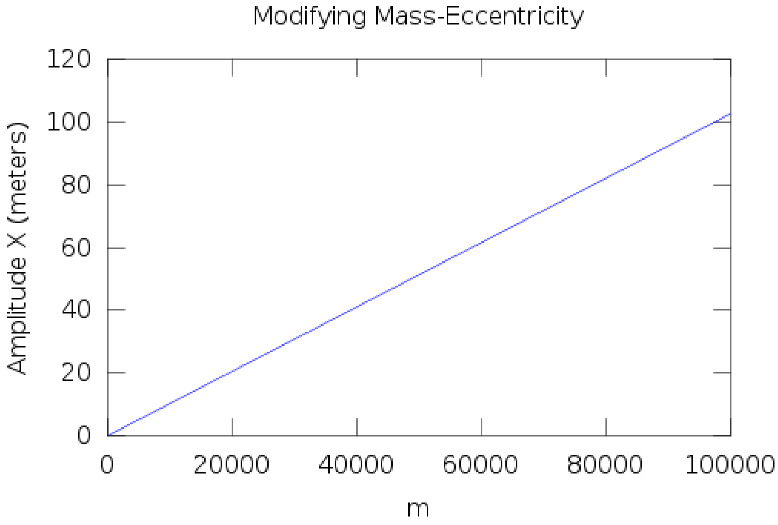

Figure A.25: Response when modifying Mass-Eccentricity

Rotational Speed

In Figure A.26, the amplitude of the system has a somewhat complex response to changes in operating frequency. The amplitude climbs non-linearly towards some a peak as the speed increases. After the peak the response amplitude decreases non-linearly to some non-zero steady state value.

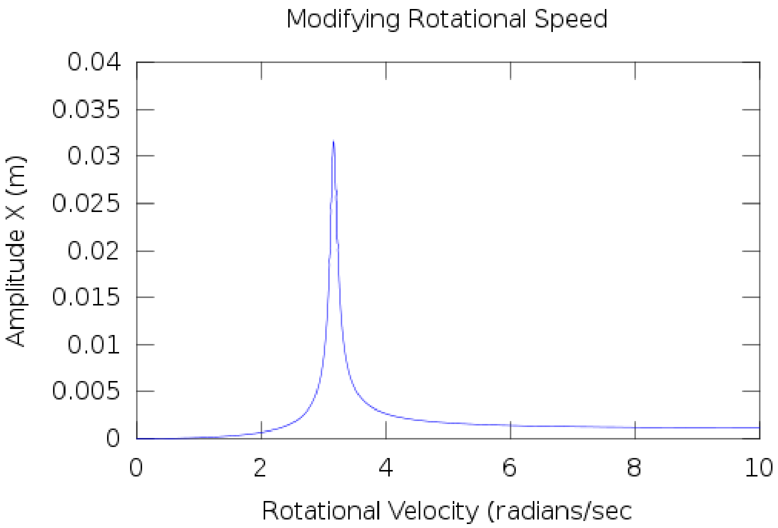

Figure A.26: Response when modifying Rotational Speed

Spring Constant

In Figure A.27 a response similar to Figure A.26 where the amplitude rises to a peak and then settles down again non-linearly. In this case however, the amplitude diminishes to 0.

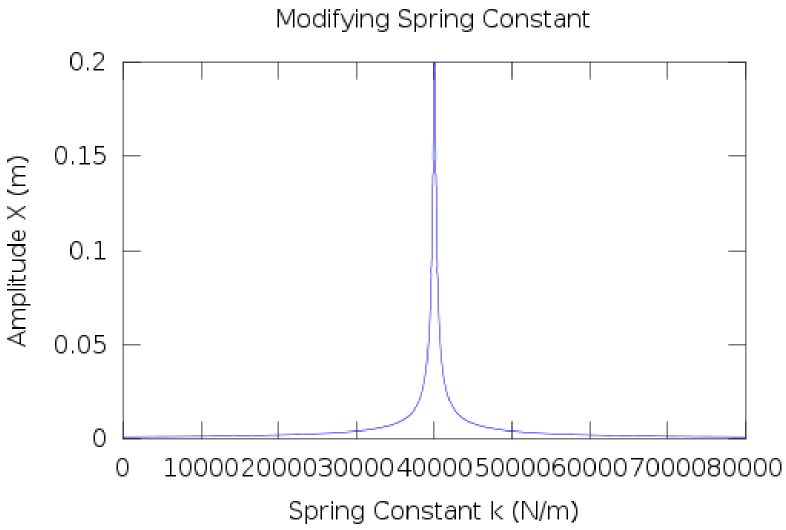

Figure A.27: Response when modifying the Spring Constant

Total Mass

In Figure A.28 the amplitude of motion changes as the total mass changes. The response is similar to the one seen in Figure A.27. The amplitude rises non-linearly to the same peak value and then settles to 0 as mass is increased.

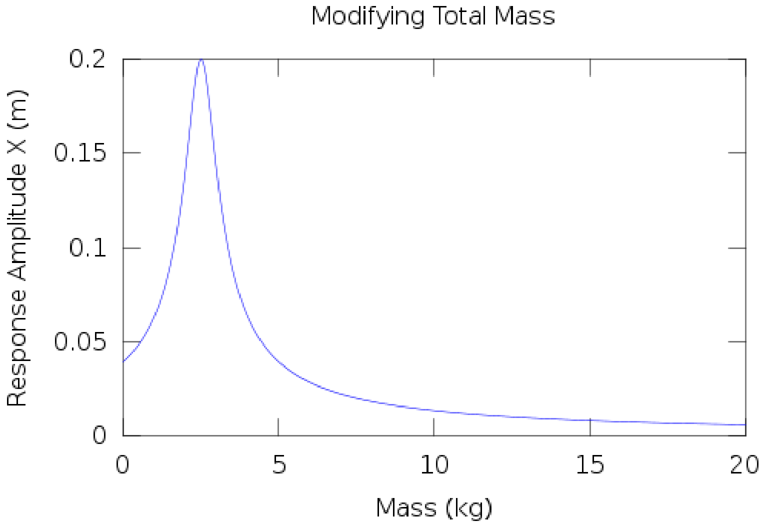

Figure A.28: Response when modifying Total Mass

Damping

Figure A.29 shows how the amplitude of motion changes as the systems damping constant increases. The amplitude decreases non-linearly as the damping increases. This can be a useful characteristic for tuning purposes if a reduction in amplitude is required.

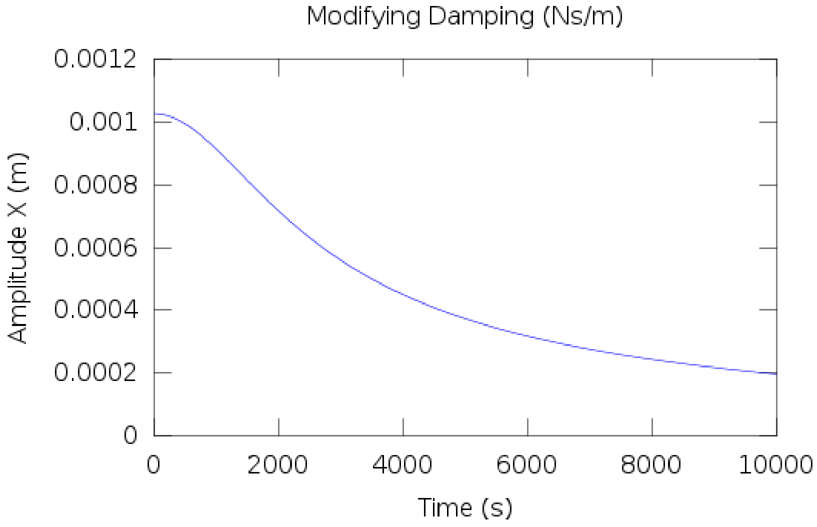

Figure A.29: Response when modifying Damping

A.2.3 The Natural Frequency

The undamped natural frequency is the frequency that the system would vibrate at if left uninfluenced by external forces and damping. It is the frequency that the system best responds to and where it will experience its greatest amplitudes of vibration. The equation for the undamped natural frequency can be written as:

$$\omega_n = \sqrt{\frac{k}{m}} \tag{A.11}$$

From Equation A.11, the natural frequency depends only on the spring constant and the mass, both of which can be controlled.

The peaks seen in Figure A.26, Figure A.27 and Figure A.28 can be explained now. When the force of the exciter is being generated near the natural frequency of the system, the amplitude grows. The system is ‘good’ at operating at its natural frequency so when the frequency of the external force and the natural frequency of the system are close, the force and the system work together.

Typically in the design of machines, steps are taken to stay away from this natural frequency because of the negative effects of vibration. In the case of a mining screen however, it is desirable to move closer to the natural frequency in order to increase the amplitude of vibration.

A parameter typically used to show the operating speeds ‘closeness’ to the natural frequency is r, Equation A.12.

$$r = \frac{\omega}{\omega_n} \tag{A.12}$$

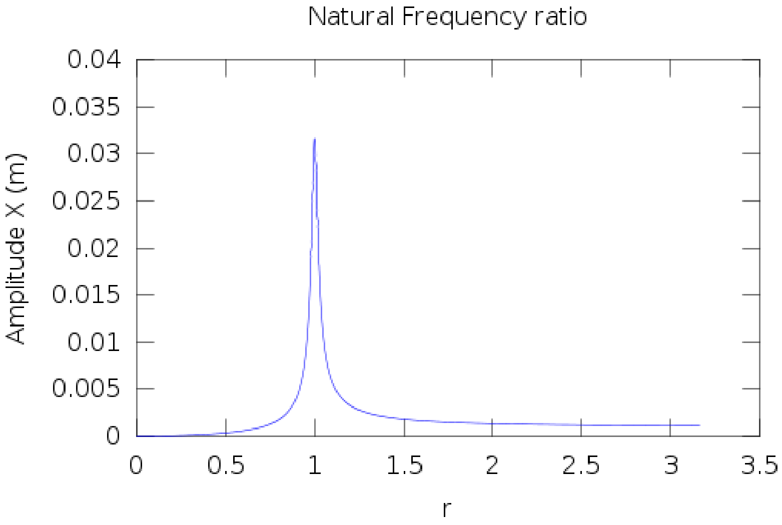

Figure A.30: Repeat of Figure A.26 using the term r.

As you can see in Figure A.31, the peak response is generated when the frequency is equal to the natural frequency.

A.2.4 The Steady State

In Figure A.31 a peak is reached when the frequency ratio r is equal to 1 meaning the operating frequency is equal to the natural frequency (Equation A.12). After this peak the amplitude of vibration settles down to some steady state value as the operating frequency increases. The steady state amplitude X_{ss} can be described by Equation A.13.

$$\text{for } r >> 1 \qquad X_{ss} = \frac{me}{M} \tag{A.13}$$

This means that for operating frequencies many magnitudes greater than the natural frequency, the amplitude of operation will only be affected by the mass eccentricity and the total mass of the system. This steady state region is essentially unaffected to slight changes in operating frequency, as long as it stays well above the natural frequency of the system.

A.2.5 2-DOF Problem

This report has now covered the equations governing a 1 DOF vibrating screen. When we move to the 2 DOF problem, the equations remain the same but now there is an additional set for the new DOF. The system will now be modelled in the x and y direction as seen in the following figure.

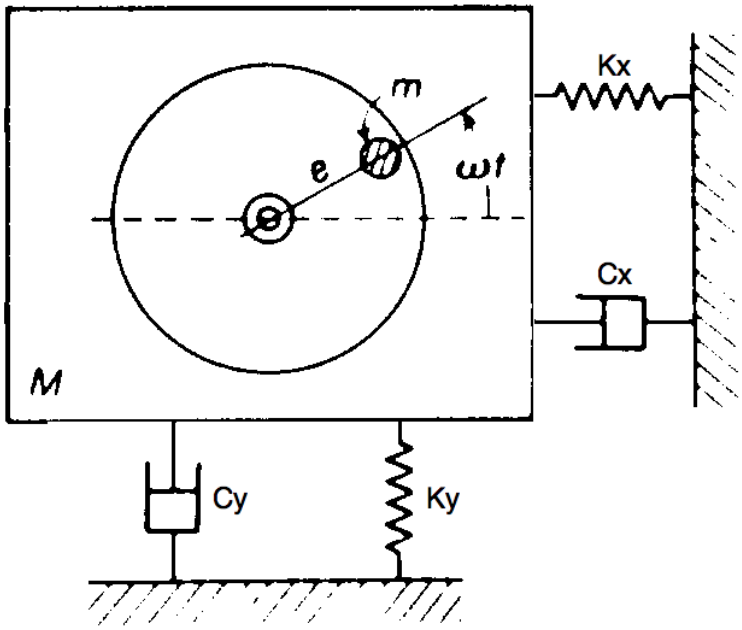

Figure A.31: Illustration of our 2DOF Rotational Imbalance Mass-Spring-Damper Model

Equations of Motion

$$m\ddot{x} + c\dot{x} + kx = me\omega^2 \sin(\omega t) \tag{A.14}$$

$$m\ddot{y} + c\dot{y} + ky = me\omega^2 \sin(\omega t - \pi/2) \tag{A.15}$$

The movement of the 2D system can be described using the following equations:

$$x(t) = X \sin(\omega t - \phi_x) \tag{A.16}$$

$$y(t) = Y \sin(\omega t - \pi/2 - \phi_y) \tag{A.17}$$

where:

$$X = \frac{me\omega^2}{[(k_x - M\omega^2)^2 + (c_x\omega)^2]^{1/2}} \tag{A.18}$$

$$Y = \frac{me\omega^2}{[(k_y - M\omega^2)^2 + (c_y\omega)^2]^{1/2}} \tag{A.19}$$

$$\phi_x = \tan^{-1}\left(\frac{c_x\omega}{k_x - M\omega^2}\right) \tag{A.20}$$

$$\phi_y = \tan^{-1}\left(\frac{c_y\omega}{k_y - M\omega^2}\right) \tag{A.21}$$

You can see from the equations that they are very similar to the 1D approach. The total mass of the system and the mass eccentricity are unchanged because the exciter works both in the x and y direction when unconstrained.

Parameter Impact

The following plots are produced x vs y. This gives us a view of the orbital path the machine moves in 2D space. The ideal orbit of a machine is a circle, where the amplitudes in the x direction and y direction are equal because the spring and damper components are balanced. In each of the figures, the modification to the parameters was done in the y-dimension.

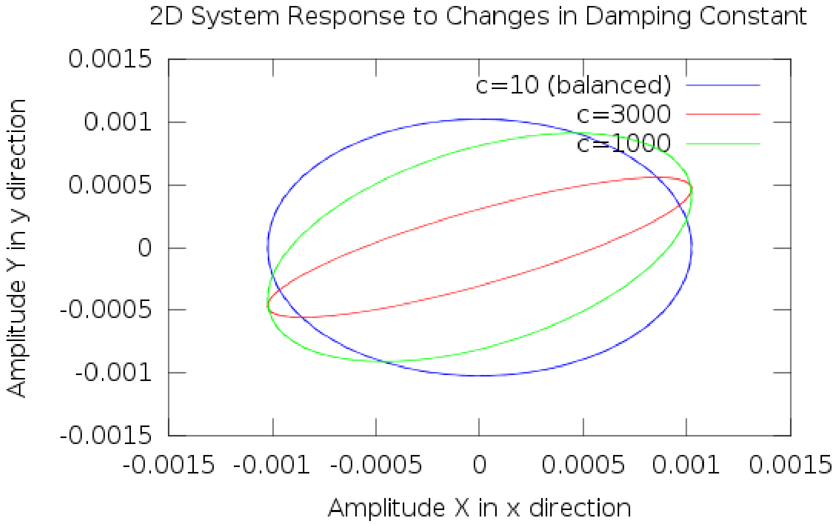

Figure A.32: Demonstration of how the 2D orbit changes with damping constant c.

The orbits in Figure A.32 become increasingly narrow as the damping constant is increased. Also note that the orbit is increasingly twisted as the damping constant is increased. This response can be explained by Equations A.19 and A.21. If you refer to Figure A.29 where we changed the damping constant in the 1D model you see a non-linear decline in displacement amplitude. The same response is happening in this situation. As the damping constant is increasing, the amplitude in the y direction is decreasing. The twist is caused by Equation A.21. As c_y changes, the resulting ϕ_y is changing causing a phase shift in the response in the y direction. This shows up as a twist in the 2D plot.

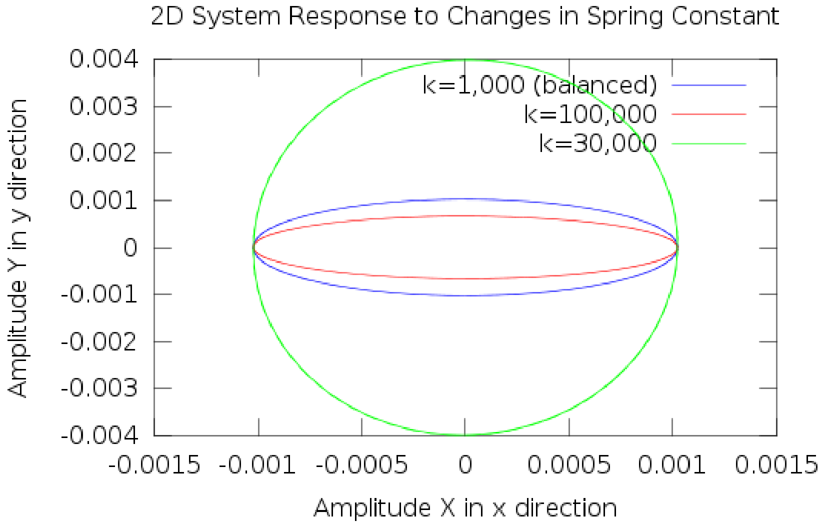

Figure A.33: Demonstration of how the 2D orbit changes with spring constant k.

The orbits in Figure A.33 grow wider and thinner as the spring constant k is increased. This response can be explained by Equations A.19 and A.21. In reference to Figure A.27 the response rises to a peak and then diminish as the spring constant k was increased. The peak appeared at a spring constant of approximately 40,000 N/m. In Figure A.33 when the damping constant is set to 30,000 (close to the peak) the amplitude in the y direction becomes very large. When the spring constant is set to 100,000 (far past the peak) the amplitude decreases from its balanced value. The rising and falling of the displacement amplitude correlates to the results of the 1D model. This tells us that the concepts we learned about the impact of the parameters in the 1D model are also applicable in the 2D model. Note also that there is little visible twisting of the plots. You would expect to see a change in phase because the spring constant k is in both equations, little is apparent because of the parameters we have chosen. In the balanced case, the spring constant already dominates the other terms so when it is increased, there is little change.

A.2.6 More Degree's of Freedom

To keep the model simple we made the assumption that the supporting structure was completely rigid and could be modelled as a point mass. In reality of course this is not the case. It is impossible to make a perfectly rigid mining screen, especially because we want to try and keep the mass down while keeping a large span. During normal operation the screen will twist, bend and deform. This motion will introduce additional unwanted harmonics into the system so minimizing this deformation is important to the longevity and efficient of the machine. Unfortunately the equations of motion behind this kind of motion are beyond the scope of this report.

A.2.7 Application Concepts

This report has now covered the basic equations governing the motion of a simplified mining screen. We have made several assumptions to keep our model simple which may skew real world results from our mathematical calculation but the concepts shown regarding the impact of the system parameters remain the same. We can use our understanding of these concepts and adjust some of the system parameters to get the type of system response required for the application.

Running at Steady State

In application, the typical vibrating screen is run at a frequency much higher than the systems natural frequency. There are several advantages to doing this:

1. As seen in Section A.2.4 , when $r >> 1$ the systems displacement operates

in a flat region, refer to Figure A.26. As we have seen, this steady state displacement value is only effected by the mass-eccentricity (me) and the total mass (M) making it relatively easy to control. The fact that we can adjust the displacement value without worrying about adjusting the spring constant or damping constant in this region is very convenient. Also, running in the steady state region means the system will be more stable.

2. The actual sifting operation of the screen does not necessarily operate better with greater displacement amplitude. Displacement of only a couple millimetres is typically enough. The higher operating frequency means the system will shake faster, not harder, increasing the efficiency of the machine.

A.2.8 Start-up and Shut-down

We have seen in Figure A.26 how the response amplitude spikes at a particular frequency known as the natural frequency. Running the system at steady state keeps us far away from this peak zone minimizing the risk of the vibration becoming unstable. Unfortunately, in order to get to this high rotational velocity you must pass through the natural frequency zones. If the system spends too much time passing through this critical phase it may produce in excess of what the machine can handle. There are two ways to avoid this problem:

1. Pass through this critical speed region very quickly. Generally the eccentric mass is powered by an electric motor. If the motor is sized properly, it should be able to accelerate the exciter through this critical phase before any major vibrations build up. Unfortunately this does not help us when shutting down the system. If we allow the exciter to coast to a stop it will pass through this

critical region much slower. If the motion being generated on shut-down is too large a breaking system may have to be used.

2. Temporarily change the parameters of the system. If you are unable to pass through this critical region quickly enough to avoid damaging amplitudes of vibration, change the position of the critical region by adjusting the correct parameters. Start-up and shut-down would be done in two acceleration phases. First, speed the machine up to a certain speed below the natural frequency. Second, quickly add mass to the screen to decrease the natural frequency of the system below the current operating condition. Now that you have added the mass you are currently operating above the natural frequency. You can now continue accelerating until you meet designed operating speed. Lastly, remove the mass and begin screening. The same process can be used for shut-down only, in reverse. Using a removable mass we can essentially jump the natural frequency over the operating frequency and never have to pass through it.

3. Use a spring loaded eccentric mass. If the eccentric mass is designed in such a way that it has no eccentricity under a certain rotational velocity it may be possible to accelerate the system past the natural frequency before the rotating mass becomes unbalanced. In this case, no force would be produced at the natural frequency of the system and you would not have to worry about large amplitude building up.

A.2.9 Forces Transmitted to the Base

The base structure supporting the screen springs must be able to hand the forces that are generated by the vibratory motion of the main screen. Simply supporting the structure's mass is not enough. Also, if the base structure experiences has any significant movement it will have its own equations of motion, with its own natural frequency which may impact the operation of the screen. Extra consideration should be taken in the design of the base and base foundation of the screen.

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