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Acoustic Testing of Generator/Alternator Fans

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ACOUSTIC TESTING OF GENERATOR/ALTERNATOR FANS

by

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ABSTRACT

The intent of this project was to fill in a gap of the testing knowledge possessed for acoustics of an alternator within a generator set. The objective was to build a test fixture that would allow the user to test the acoustics of alternators without the driving force of an engine, which is a high acoustic source during testing. Eliminating the engine from the equation would allow for more accurate data of the product line, allowing for better utilization of acoustic tools when implementing sound source dampening. At the end of the project, it was found that the test fixture that was used gave useful data within certain frequencies, but will be needing modifications in order to allow for a larger range of frequencies to be more accurately measured.

ACKNOWLEDGEMENTS

Thank you to those who have helped with this project; Shashikant More, Dean Jahnz, Adam Cloutier, Ronald Pautzke, Shanti Godishala, and Martin Myers. Without your help throughout this project, it would not have been as successful as it was, and would not have issued out the learning opportunity that this brought about as well.

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INTRODUCTION

Introduction

In the field of power generators, acoustic measuring is typically completed by measuring the acoustic emissions of an entire product. A power generator typically consists of an engine (of varying fuel types), methods of engine/generator controls, engine cooling, the electrical alternator (driven by the engine), and depending on the customers' needs, could have other varying options. The engine is the largest source of acoustic emissions, from intake and exhaust sources, as well as structure-born acoustics. If the generator has a cooling system attached, the cooling fan is the next largest source of acoustic emissions. The alternator power source as an internal cooling fan as well, but the acoustic emissions of this cooling fan are minimal compared to the other sources of acoustic energy, so measuring the levels accurately are hard to accomplish.

In order to more accurately measure the acoustic emissions of the alternator cooling fan, testing must have the engine and all other acoustic sources removed. This proves difficult because the engine is normally needed in order to spin the alternator up to operating speeds of 1500 to 1800 rpm at normal operation, and up to 3000 to 3600 rpm in some cases. Along with supplying the rotational power to the alternator, the engine acts as a bearing support as well, holding up one half of the alternator's internal rotor (as it was designed to do). Along with the removal of outside sources of acoustic emissions, the test must be completed within an environment that has a low enough background acoustic level to not interfere with the test results.

Problem Statement

There is a gap in the test results of acoustic emissions' sources in power generators, having not been able to accurately measure the acoustic emissions of the main power alternator within a generator set.

Nature and Significance of the Problem

At lower speeds (1500-1800 rpm), the alternator acoustic emissions do not seem to be a significant issue. With generator operating conditions raised to 3600 rpm, the acoustic emissions of the alternator cooling fans are now believed to have a somewhat significant value. Testing done prior to this test has always included a driving source which has a higher ambient sound level than the alternator itself, so the measurements have not had a great amount of accuracy. Developing a tool in order to make this level of measurement fosters innovation within the company, geared toward improving what the company does to deliver world class product.

This project must be part of the goal tree for the engineering initiatives within the company. Without meeting the key objectives of the company, there would be no need for the company to venture into the creation of this tool. In order for the company to be the first choice of its customers, they must work toward optimizing technical productivity by creating product architectures that maximize the value to the customer. The use of a tool such as within this project will foster innovation in support of future technology and product performance. Thus, this project's objectives fall within the company's objectives and can proceed through the phases of design, construction, and validation.

Objective of the Project

The objective of this project is to develop a tool to efficiently/accurately measure the acoustic emissions of a power generator's main alternator.

Project Questions/Hypotheses

The following questions will be the goal to answer at the completion of this study:

- Is the cooling fan of an alternator giving off a significant amount of acoustic emissions?
- Can the acoustic emissions of an alternator be measured accurately, compared to background levels?

- Is there an efficient way to package the tool, to reduce setup/teardown/testing times?

The hypothesis for this project is that the output of the alternator fan will largely depend on the speed of rotation. At lower revolutions per minute (rpm), around 1500-1800 rpm, there is expected to not be a large acoustic contribution from the alternator to the overall level of a generator set. But when spinning at or around 3600 rpm, the acoustic levels are expected to be higher, and possibly a significant contributor to the overall level of a generator set.

Limitations of the Project

Once testing was completed, it was found that the limitations of the project were the speeds that could be easily obtained by the test fixture. Since the test fixture itself gave out an increasing level of sound as the speed got higher, it was deemed not possible to reach speeds higher than 1950 rpm with this test fixture.

Definition of Terms

Generator Set (Genset). Combination of an engine with an electric generator (often an alternator), in order to generate electrical energy.

Hemi-Anechoic Chamber. A room that has acoustical treatment on the walls and ceiling only and feature hard floors with no acoustic treatment.

Revolutions per Minute (rpm). A measure of the frequency of a rotation, showing the number of turns completed in one minute around a fixed axis.

ISO. International Standards Organization.

Parallelepiped Array. "A 6-faced polyhedron all of whose faces are parallelograms lying in pairs of parallel planes" [1]. In the case of this project, a Parallelepiped array is aligned according to ISO 3744 for sound power measurements.

dB. Decibel. "The bel is the logarithm of the ratio of two powers, and the decibel is 1/10 bel. The human ear responds logarithmically and it is expedient to deal in logarithmic units in acoustics" [2].

dBA or *dB(A)*. "A frequency response adjustment of a sound-level meter that makes its reading conform, very roughly, to human response" [2]. Equal to dB spectrum values with A-weighting curve applied, "simulating the human-ear response at a loudness level of 40 phons" [2].

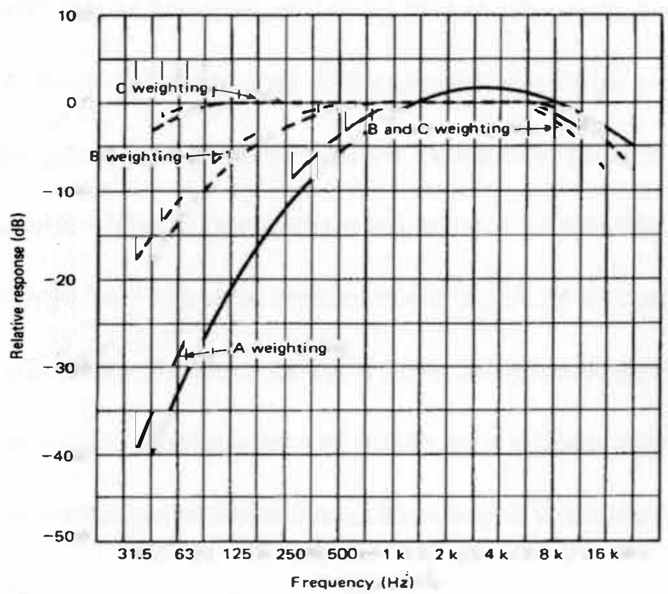


Figure 1: Spectrum Weighting Curves [3]

Sound Power. 'A measure of sound energy per time unit" [4].

Sound Pressure. "The force of sound on a surface area perpendicular to the direction of the sound" [5].

Summary

After reading this chapter, the reader should now be aware of the problem at hand, the introductory details to the background of the problem, and the eventual goal of the overall project. Keeping this information in mind, the background details of the project will now be further explained.

Chapter II

BACKGROUND AND REVIEW OF LITERATURE

Introduction

In this chapter, the company background will blend with the literature and tools used to complete this project. After reading this chapter, the reader should understand the background to why this project exists.

Background Related to the Problem

The company that this project takes place in is a large business unit of an even larger fortune 500 company of about 46,000 global employees. Within this business unit, the main manufacturing that takes place deals with diesel, natural gas, propane, gasoline, and JP8 powered electrical power generators. This includes the power generation system, components, and services to support them as well. These generators are meant to provide power to customers in emergency standby applications (such as a hospital or data center), prime power application (being a 90% permanent power provider to something like a mine), auxiliary power (such as a mobile application for a boat or RV), and rental generators (used to power a local state fair or similar short term events).

With many regulations around the world pertaining to power generators, acoustic levels must be met in order to not be a nuisance to the human population in the surrounding areas to a generator. Thus, a company such as this is forced to complete acoustic testing of their product in order to meet various regulations. Acoustic testing of generators was done outdoors on a large concrete pad in the woods behind the company's facilities. Being outdoors, testing was limited to when the environment would permit it. If there was rain, too much wind, or too cold of temperatures, for example, the acoustic testing could not be completed. This limited testing to about three months out of the year. In order to become a global leader in technology and innovation, the company invested in a multi-million dollar facility that would allow them to do acoustic testing year round on all sizes of generators currently in production, as well as any within future plans. The building was completed in 2011, and upon completion was the largest engine-related acoustic test cell of its kind in the world [6]. This facility is capable of running 24/7, and provides the company with a large competitive advantage in that future product will be designed with the utmost integrity, providing the customer with the best acoustic emissions possible.

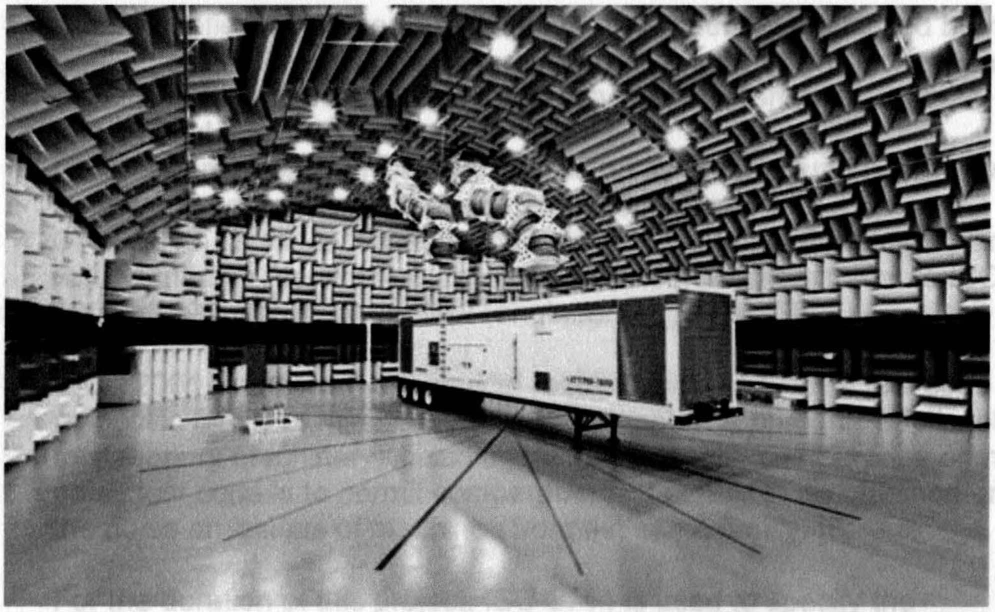


Figure 2: A Photo that Shows the Scale of the Test Cell

Literature Related to the Problem

ISO 3744:2010 specifies methods for determining the sound power level or sound energy level of a noise source from sound pressure levels measured on a surface enveloping the noise source (machinery or equipment) in an environment that approximates to an acoustic free field near one or more reflecting planes. The sound power level (or, in the case of noise bursts or transient noise emission, the sound energy level) produced by the noise source, in frequency bands or with frequency A-weighting applied, is calculated using those measurements.

The methods specified in ISO 3744:2010 are suitable for all types of noise (steady, non-steady, fluctuating, isolated bursts of sound energy, etc.) defined in ISO 12001.

ISO 3744:2010 is applicable to all types and sizes of noise source (e.g. stationary or slowly moving plant, installation, machine, component or sub-assembly), provided the conditions for the measurements can be met.

The test environments that are applicable for measurements made in accordance with ISO 3744:2010 can be located indoors or outdoors, with one or more sound-reflecting planes present on or near which the noise source under test is mounted. The ideal environment is a completely open space with no bounding or reflecting surfaces other than the reflecting plane(s) (such as that provided by a qualified hemi-anechoic chamber), but procedures are given for applying corrections (within limits that are specified) in the case of environments that are less than ideal.

Information is given on the uncertainty of the sound power levels and sound energy levels determined in accordance with ISO 3744:2010, for measurements made in limited bands of frequency and with frequency A-weighting applied. The uncertainty conforms to ISO 12001:1996, accuracy grade 2 (engineering grade). [7]

ISO 12001 Specifies the technical requirements of a noise test code for a specific family of machinery and equipment. It is primarily applicable to stationary machinery, including hand-held tools. The purpose of the noise test code is to permit comparable test results to be obtained on the noise emissions of machines from the same family. [8]

For the duration of this project, ISO 3744 is used to specify the measurement and calculation methods for the product being tested, as it falls into the category of stationary machinery components, within an approved environment to simulate a free field of measurement.

<u>Literature Related to the Methodology</u>

The methodology of this project will rely heavily on Six Sigma (6S) tools for selection and planning. "6S is a dynamic tool for industry standards and was originally developed in 1986 at Motorola" [9], and has since been expanded upon by many other companies. 6S provides a toolkit of information about the methodology of defining, analyzing, measuring, improving, and further controlling the quality of products, processes, and transactions [9]. The 6S tools within this project have been refined for use within the company that this project takes place.

Summary

With this information given within this chapter, the reader should now be aware of the literature that was used within this project. This literature gives a standard set of procedures for how to conduct an acoustic test, but not how to perform this project itself. So, with this literature in mind, the future chapters will cover the details of the project at hand, in respect to the literature that it relates to.

Chapter III

METHODOLOGY

Introduction

Using 6S as a leading process, this project will utilize planning and selection tools. Using these tools will help to lead the project to success. Success will be measured using measurement and calculation methods related to ISO standards.

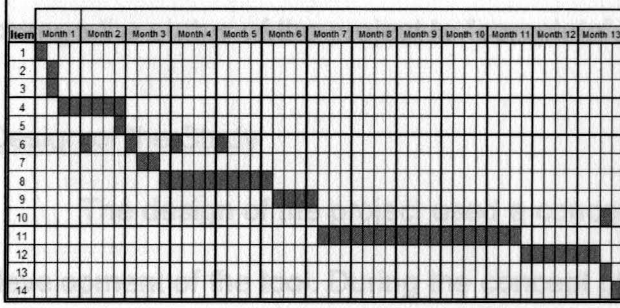
Timeline

In order to better plan throughout this project, A RACI diagram was developed to show the timeline of the project, and the resources used within each milestone. 'Planning provides a method of identifying objectives and designing a sequence of programs and activities to achieve these objectives" [9]. Defined more simply, the planning stage of a project is meant to decide what to do in advance, how to do it, when to do it, and who is going to do the work. The RACI diagram is similar to a Gantt chart [10], except that it has additional information beyond timeline, but also resource allocation, and status of the tasks, all on the same diagram. This RACI diagram covers a majority of the planning with which the rest of the project will be gauged against:

Table 1: RACI Diagram

DFSS High Level Project Flow
Resource Matrix and Milestone Plan - RACI
Acoustic Alternator/Generator Fan Test Rig

R = Responsible
A = Accountable
C = Must be Consulted
I = Must be Informed



Item	Task or Milestone Definition	Jacob Kriesel	Shanti Godishala	Shashikant More	Adam Cloutier	Ronald Pautzke	R-Y-G
		Resources					
1	Define requirement for fan test rig.	R		A	C	C	
2	Submit charter for approvals	R	A	C	I	I	G
3	Charter Fully Approved	A	R	I	I	I	G
4	Plan team meetings and hold kick-off.	A	I	C	C	C	G
5	Launch Charter (make an active project)	A	I	C	I	I	G
6	Attend training	R	A	I	I	I	G
7	Develop fan rig concepts	R	I	A	C	C	G
8	Select Concept	R	I	A	C	C	Y
9	Complete design optimization	A	I	C	C	R	Y
10	Contract	R	I	A	I	I	Y
11	Construct test rig	R	I	A	C	I	Y
12	Validate test rig performance	R	I	A	C	C	Y
13	Submit project for final approval.	R	A	C	I	I	Y
14	Project Fully Approved and Completed.	I	R	I	I	I	Y

This timeline takes place over about thirteen months. In the initial months, the project must be defined. A team was chosen, the product goals were laid out, and a problem statement was chosen to guide the entire project. Resource allocation is a key aspect in the scheduling process [9]. The project was then approved by management, as well as the 6S black belt as an acceptable 6S project. Upon approval, the project team kicked off the project with a meeting to discuss future plans and workloads. Concepts were developed initially, with a final selection sometime near the end of the fifth month of the project. Once a final concept was selected, it had to be optimized in order to achieve the best results upon completion, and this task took about a month to complete for this project. Finally, real parts started to be constructed. The company's in-house machine shop did the majority of the construction, but with varying levels of priority and other workloads throughout the company, this project had a construction phase of about five months. Once constructed, the test fixture was tested within the acoustic test cell to measure the performance of the tool. After data had been collected and analyzed, the project team then submitted their findings to the 6S black belt for approval to change the status of the project to "complete".

Design of the Study

The design of the project used a concept phase to work through the development of the tool. During the concept phase, the following questions should be asked:

- What are the desired functions of the project?
- What is the project supposed to accomplish?
- What criteria must the project meet?
- Are there any constraints to the final solution? [9].

The project utilized some 6S tools in order to effectively design the project in the best way possible, and hopefully answer the above questions. The 6S tools were to be used to come up with a concept design, able to come up with the correct parameters and tolerances within the design[11]. Initially, the project team conducted a Kawakita Jiro (KJ) investigation. This KJ showed the thoughts of the team as to what is believed to be the major requirements for the project when making a tool to measure the acoustic emissions of an alternator. A vote took place to show the importance of each characteristic of such a tool. A sample set of questions is located in the Appendix on page 51.

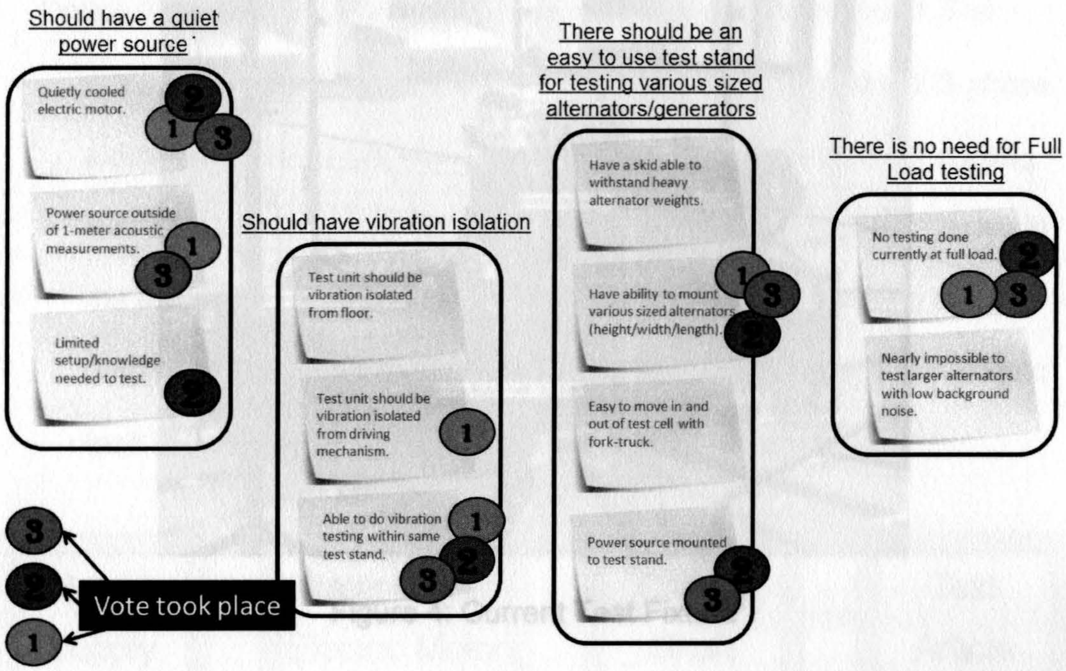


Figure 3: 6S KJ Tool

Concept generation took place using a Pugh matrix. The Pugh matrix was a good method of breaking down the design into many characteristics, giving ratings to each, in order to show which concept met the goals of the project's requirements. The concept generation phase brought about the following options for how to construct the tool for the project:

Option 1. Use a pre-existing tool to perform testing. This tool was beneficial because it already existed, but was the reason for the start of this test because of the inability of the tool to give accurate acoustic results at prime speeds for a generator without inducing resonances into the tool during operation. All testing with this option was to be done with no electric load induced on the test unit.

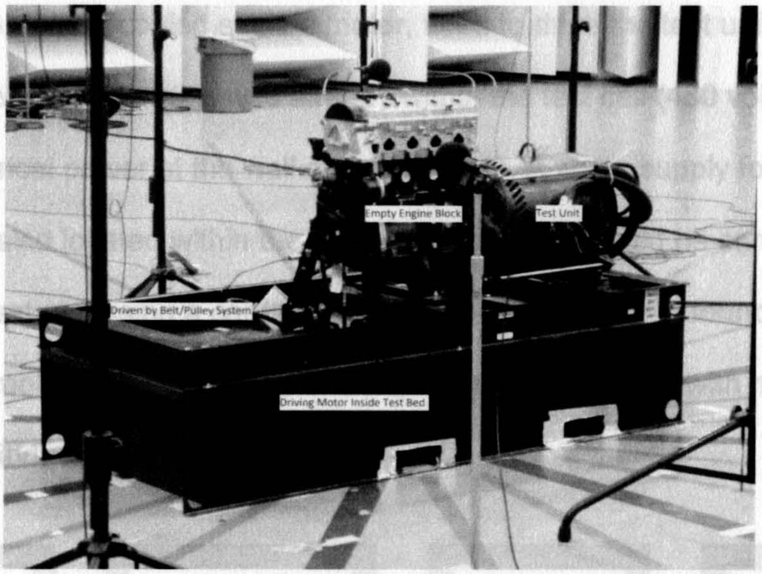


Figure 4: Current Test Fixture

Option 2. Air cooled electric motor, used to drive the test unit. The power supply for this was already within the test cell (480 volt 3-phase electrical power at the wall of the test cell). The motor would be connected to the test unit using a cardan shaft, similar to driveshafts found in automobiles. All testing with this option would be done with no electric load induced on the test unit.

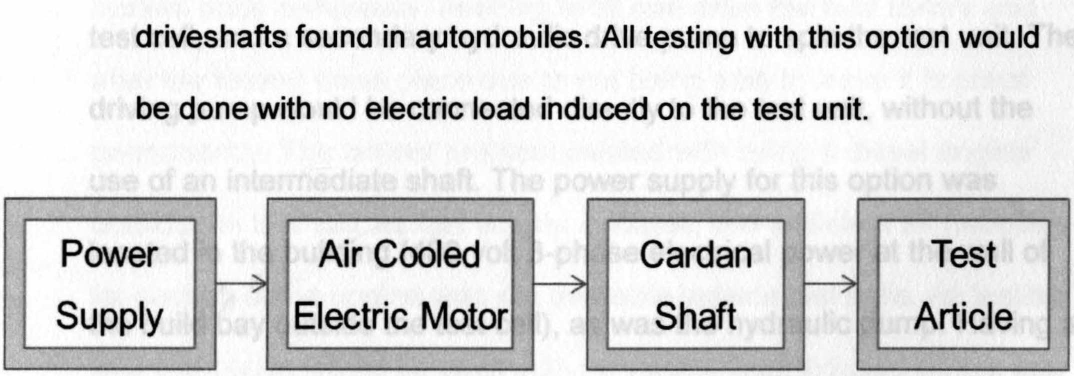


Figure 5: Air Cooled Electric Motor Concept Diagram

Option 3. Water cooled electric motor, used to drive the test unit. The power supply for this was already within the test cell (480 volt 3-phase electrical power at the wall of the test cell). A water supply for cooling was also located within the test cell. The motor would be connected to the test unit using a cardan shaft, similar to driveshafts found in automobiles. All testing with this option would be done with no electric load induced on the test unit.

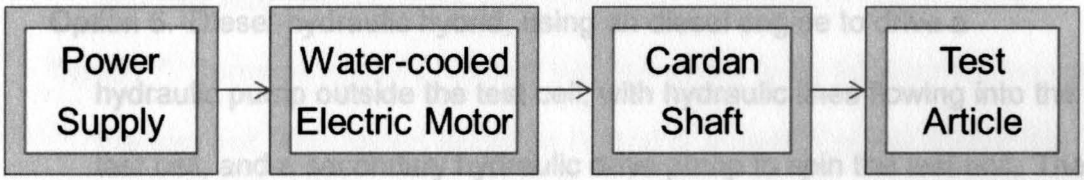


Figure 6: Water Cooled Electric Motor Concept Diagram

Option 4. Electric-hydraulic hybrid, using an electric motor to drive a hydraulic pump outside the test cell, with hydraulic lines flowing into the test cell, and a secondary hydraulic drive pump to spin the test unit. The driving pump would be connected directly to the test unit, without the use of an intermediate shaft. The power supply for this option was located in the building (480 volt 3-phase electrical power at the wall of the build bay outside the test cell), as was the hydraulic pump. Having a hydraulic system adds complexity, needing to fill and drain the fluid before and after the testing takes place due to not being able to leave it in place permanently. All testing with this option would be done with no electric load induced on the test unit.

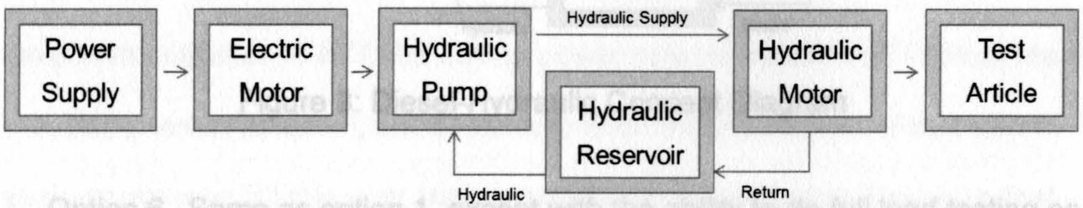


Figure 7: Electric-Hydraulic Concept Diagram

Option 5. Diesel-hydraulic hybrid, using an diesel engine to drive a hydraulic pump outside the test cell, with hydraulic lines flowing into the test cell, and a secondary hydraulic drive pump to spin the test unit. The driving pump would be connected directly to the test unit, without the use of an intermediate shaft. The power supply for this option was already available, as was the hydraulic pump. Having a hydraulic system adds complexity, needing to fill and drain the fluid before and after the testing takes place due to not being able to leave it in place permanently. The largest problem existed with using a diesel engine outside the test cell, as fuel supply, exhaust, and sufficient air handling for cooling of the engine was not available outside test cells. All testing with this option would be done with no electric load induced on the test unit.

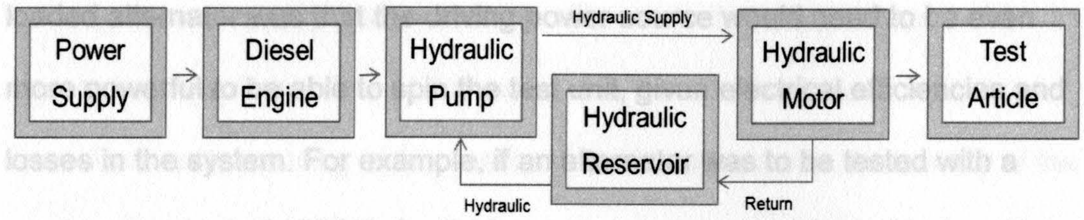


Figure 8: Diesel-Hydraulic Concept Diagram

Option 6. Same as option 1, except with the ability to do full load testing on the test unit. This option would be limited to a certain power output due to motor size needed to be able to spin an alternator to higher loads.

Option 7. Same as option 2, except with the ability to do full load testing on the test unit. This option would be limited to a certain power output due to motor size needed to be able to spin an alternator to higher loads.

Option 8. Same as option 3, except with the ability to do full load testing on the test unit. This option would be limited to a certain power output due to motor size needed to be able to spin an alternator to higher loads.

Option 9. Same as option 4, except with the ability to do full load testing on the test unit. This option would be limited to a certain power output due to motor size needed to be able to spin an alternator to higher loads.

Option 10. Same as option 5, except with the ability to do full load testing on the test unit. This option would be limited to a certain power output due to engine size needed to be able to spin an alternator to higher loads.

Options 6 thru 10 are the same as option 1 thru 5, except that they are for testing with load on the test unit. The problem with trying to test with a loaded alternator was that the driving power source would need to be even more powerful to be able to spin the test unit, given electrical efficiencies and losses in the system. For example, if an alternator was to be tested with a maximum output of 10 KW, the driving power source would need to be at least that size in order to spin it, but would only need to be a fraction of that size to spin with no load. At this size, the cost of the motor needed to overcome that higher load would not be significant. But, if the load required would be near 100KW, than the power source cost goes from tens of thousands to hundreds of thousands of dollars in cost. This complexity and cost for the full load options of six thru ten is shown as a negative within the Pugh matrix selection criteria. For these reasons, it was ultimately decided that the acoustic testing of an alternator with any amount of load on the alternator was not within the scope of this tool project.

Upon further discussion with alternator professionals, the critical sound levels of an alternator should be the acoustic emissions emitted from the cooling fan of the alternator. This sound level would not change with load on the alternator, and therefor was another reason for not pursuing any full load testing for acoustics.

The project team was made aware of the critical parameter tree compared to the final concept design. This critical parameter tree was the key to understanding which characteristics may have the greatest effect on the accuracy of the test results. This data was used when constructing the tool, so as to be sure of quality craftsmanship in the areas that were critical to the success of the project. The critical parameter tree looks as such, with three tiers of criticality, relating to the quality of the 3-phase motor, the quality of the cardan shaft and its effect on vibration induced acoustics, and ultimately that the entire package of the tool had a small acoustic signature overall. These critical paths were highlighted with red arrows, vs. the black arrows that were deemed to be not as critical:

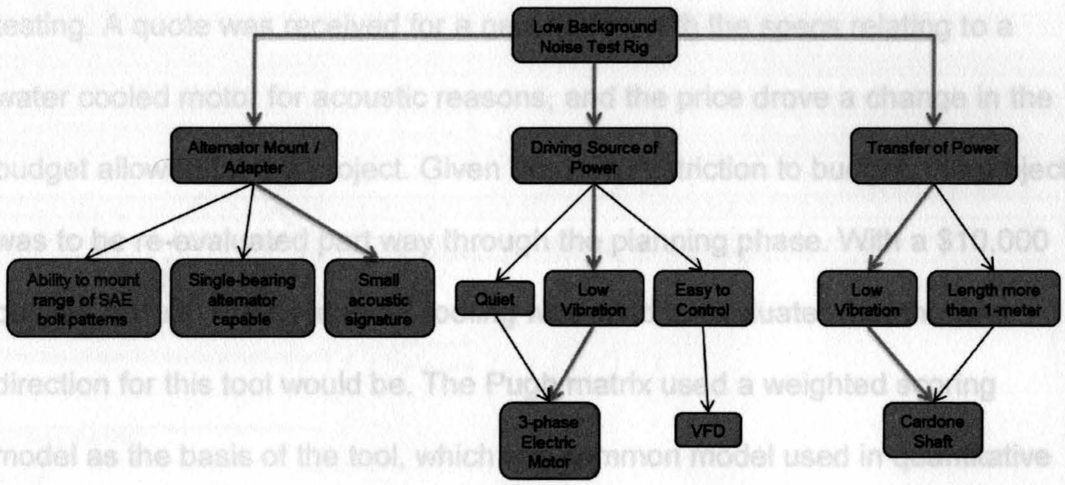


Figure 9: Critical Parameter Tree

The tool was constructed within the company's machine shop. This allowed the project team to hold control over the process to ensure quality through the construction phase. Throughout the design phase, the tool was optimized to be able to be used on a wide range of conditions, or in this case, a wide range of alternator platforms. This was important so that the project had a good level of quality as well as being able to reduce the cost of the total project [11].

<u>Budget</u>

The company initially gave this project control over the budget. The budget was soon changed to spending below $10,000, due to economic concerns. Another factor that changed the budgeting was the availability of an electric motor that would meet the acoustic demands to be quiet during testing. A quote was received for a new motor, with the specs relating to a water cooled motor for acoustic reasons, and the price drove a change in the budget allowed for the project. Given this new restriction to budget, the project was to be re-evaluated part way through the planning phase. With a $10,000 budget, a Pugh matrix from 6S tooling was used to evaluate what the best direction for this tool would be. The Pugh matrix used a weighted scoring model as the basis of the tool, which is a common model used in quantitative selections within R&D projects [9]. Each item of the criteria within the tool was given a weight value, and the user scored each item. The multiplication of the weight and score gave the weighted score:

Table 2: Pugh Matrix Diagram

Alternator/Generator Acoustic Testing

Concept										
Criteria/Concept	No Load Testing					Full Load Testing				
	Arrow Test Rig - Power Source Inside Test Cell - Belt Driven	Air Cooled Electric Test Rig - Power Source Inside Test Cell - Driveshaft Connection	Water Cooled Electric Test Rig - Power Source Inside Test Cell - Driveshaft Connection	Electric Hydraulic Test Rig - Power Source Outside Test Cell - Direct Connection	Diesel Hydraulic Test Rig - Power Source Outside Test Cell - Direct Connection	Arrow Test Rig - Power Source Inside Test Cell - Belt Driven	Air Cooled Electric Test Rig - Power Source Inside Test Cell - Driveshaft Connection	Water Cooled Electric Test Rig - Power Source Inside Test Cell - Driveshaft Connection	Electric Hydraulic Test Rig - Power Source Outside Test Cell - Direct Connection	Diesel Hydraulic Test Rig - Power Source Outside Test Cell - Direct Connection
1. Performance 1800 RPM	-	S	S	S	S	-	S	S	S	S
2. Performance 3600 RPM	S	S	S	-	-	S	S	S	-	-
3. Background Noise	-	-	+	+	+	-	-	+	S	S
4. Acoustic Reflections	-	-	S	+	+	-	-	-	S	S
5. Maintenance	-	S	S	-	-	-	S	S	-	-
6. Target Product cost ($10,000)	+	+	S	+	+	+	-	-	-	-
7. Storage	S	+	+	-	-	+	+	+	-	-
8. Use on various sized tests	-	+	+	+	+	-	-	-	-	-
9. Safety/Environmental	-	+	S	-	-	-	+	S	-	-
10. Power Source Outside Sound Chamber	S	S	S	+	-	S	S	S	+	-
11. Ease of Installation in Sound Chamber	-	+	+	-	-	+	+	+	-	-
12. Drive source outside of 1-meter measurements	-	+	+	-	-	-	+	+	-	-
13. User knowledge needed for power source	-	+	+	-	-	-	+	+	-	-
14. Fulfillment of needs of other departments	-	+	+	+	+	-	+	+	+	+
15. Fulfillment of needs of future potential projects	-	+	+	+	+	-	+	+	+	+
16. Cost	+	+	-	-	-	-	-	-	-	-
Total Σ +	2	10	8	7	6	3	7	7	3	2
Total Σ –	11	2	1	8	9	11	5	4	10	11
Total Σ S	3	4	7	1	1	2	4	5	3	3
Total	-9	8	7	-1	-3	-8	2	3	-7	-9
Rank	5	1	2	3	4	#N/A	#N/A	#N/A	#N/A	5

Add Row | Add Column

Use the Add Row and Add Column to retain the formulas
Note, new columns will be inserted at Column D

Note: Ranking is color coded
1— Green
2— Yellow
3— Red

Using the Pugh matrix, without the budget concern, the water cooled motor was the best choice. But, with a refined budget, the Pugh matrix showed that a fan cooled motor would be the best option. This option was also already available, and did not need to be purchased.

The options within the Pugh matrix were the options provided from the concept generation phase of the project.

<u>Construction Phase</u>

A 3D computer model was used to fashion the parts on a CNC mill. This mill was located within the company's internal machine shop, and so the budget was not affected by the labor as much as the sourcing of materials. Once all the parts were either machined or purchased, assembly began. The tool was meant to be able to accommodate a large range of alternator sizes, and as such, had many different bolt patterns on the same tool. The tool comprised of an electric motor, connected to a double-cardan drive shaft, connected to the bearing adapter assembly, which then was attached to the test unit. The entire driveline rested upon a test bed table, which was solid enough to eliminate unnecessary vibration induced acoustics.

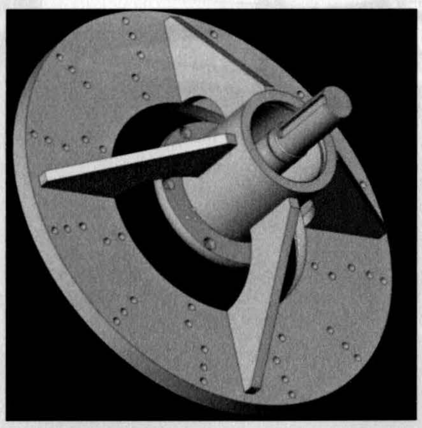


Figure 10: 3D Model of a Sub-Component of the Tool, the Main Piece of the Bearing Adapter

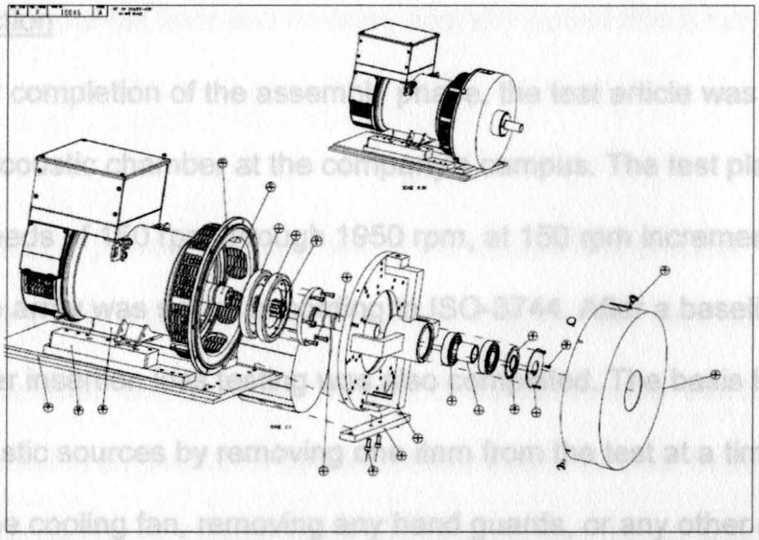


Figure 11: CAD Drawing of a Sub-Component of the Tool, the Bearing Adapter

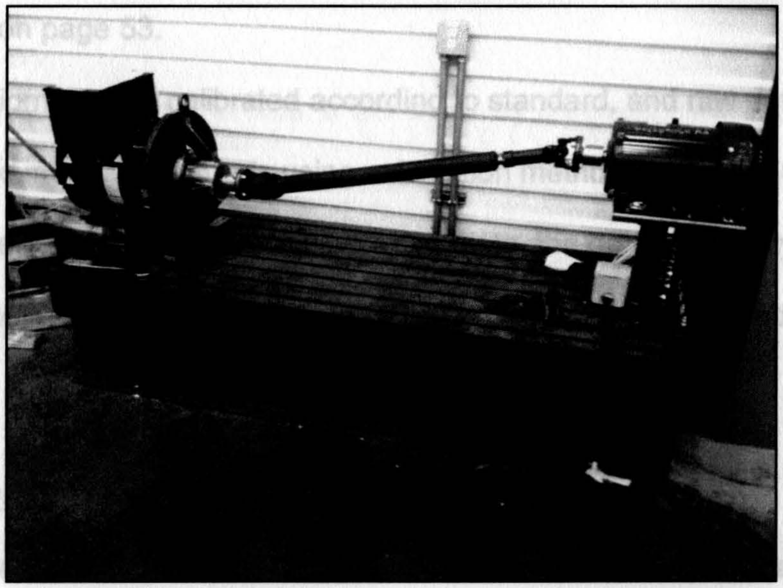


Figure 12: Finished Assembly of the Entire Test System

Data Collection

After completion of the assembly phase, the test article was placed within the acoustic chamber at the company's campus. The test plan covered rotating speeds of 150 rpm through 1950 rpm, at 150 rpm increments. The microphone array was set up according to ISO-3744. After a baseline test was done, further insertion loss testing was also completed. The basis for this was to find acoustic sources by removing one item from the test at a time, such as removing the cooling fan, removing any hand guards, or any other example, to find out if any of these objects hinder, alter, and/or add to the airflow in a way to change the acoustics of the test. A sample test plan is located in the Appendix, on page 53.

Equipment was calibrated according to standard, and raw data was transformed into useful reports using calculation methods from the ISO standard as well. Once the testing was complete, the data was analyzed to see if the deliverables were met, and to find out any lessons learned for future tests.

Data Analysis

After recording the data, it must be converted to a number that would be used to see the sound power of the test unit. The sound power number is calculated by multiplying by ten times the base-10 logarithm of the ratio of the measured values. The formula looks as such for converting a recorded sound pressure (L_P) level into a sound power (L_W) level, when measuring a sound source that is on a flat floor and emitting acoustic sound into a hemi-anechoic space [12]:

$$L_W = L_P - 10 \log_{10} (2 / 4\pi r^2)$$

The sound power measurement is the measure of acoustic energy compared to a time unit, over a certain area. This number then pertains to the sound source itself, displaying the amount of acoustic power that is capable of being produced in all directions by the specific sound source. In this way, the sound source can be more easily compared to another sound source because the sound power measurement doesn't depend on the environment it is within. The sound source will always give off that specific amount of energy at the source.

In order to record the data, a tool made by Siemens LMS was used in conjunction with PCG microphones. The entire setup was calibrated before testing to ensure the equipment was working correctly. After recording the data, the LMS hardware transferred the data to the computer that it was connected to, and within the software from LMS all the calculations were be done. "The software helps accelerate measurement setups and delivers correctly formatted results" [13]. LMS software can be used to output the sound power calculations, and is able to display the data in a number of visual formats, such as line graphs or octave bar charts.

Utilizing graphs is the best way to look at the data for this project. The point of this project was to validate that the tool being developed can be used for future acoustic tests. Therefore, the data from this test will be a comparison between the acoustic emissions of the test unit and driving motor combined, versus the acoustic emissions of the driving motor alone. If the acoustic levels of the driving motor are low enough compared to the test unit, then the tool is a success.

Testing Phase

With the tool completely assembled, the entire system could be moved inside the hemi-anechoic test cell. Once placed in the center of the cell, a parallelepiped array of microphones was arranged around the tool to be able to capture 1-meter sound power related acoustic measurements, according to ISO 3744. Along with 1-meter measurements will be eight microphones placed at the 7-meter distance from the unit, encircling the entire test at 45° angles. A tachometer was also used to measure the exact speed of the spinning assembly of the tool. All of this data was recorded using LMS SCADAS hardware. The microphones were aligned in the following parallelepiped method, as referenced by ISO 3744:

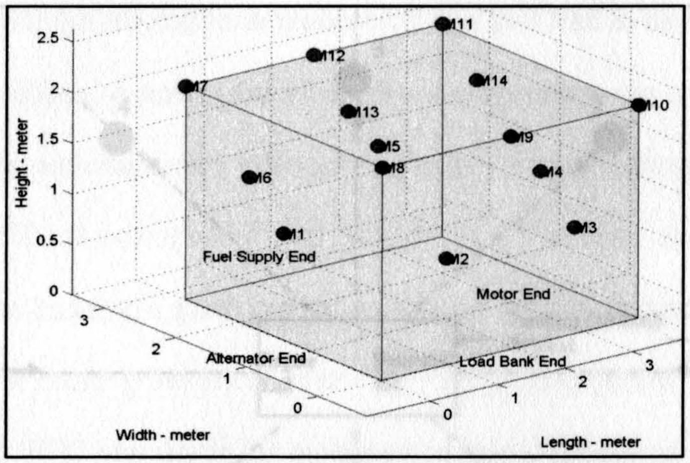


Figure 13: 3D Parallelepiped Model of Microphone Array

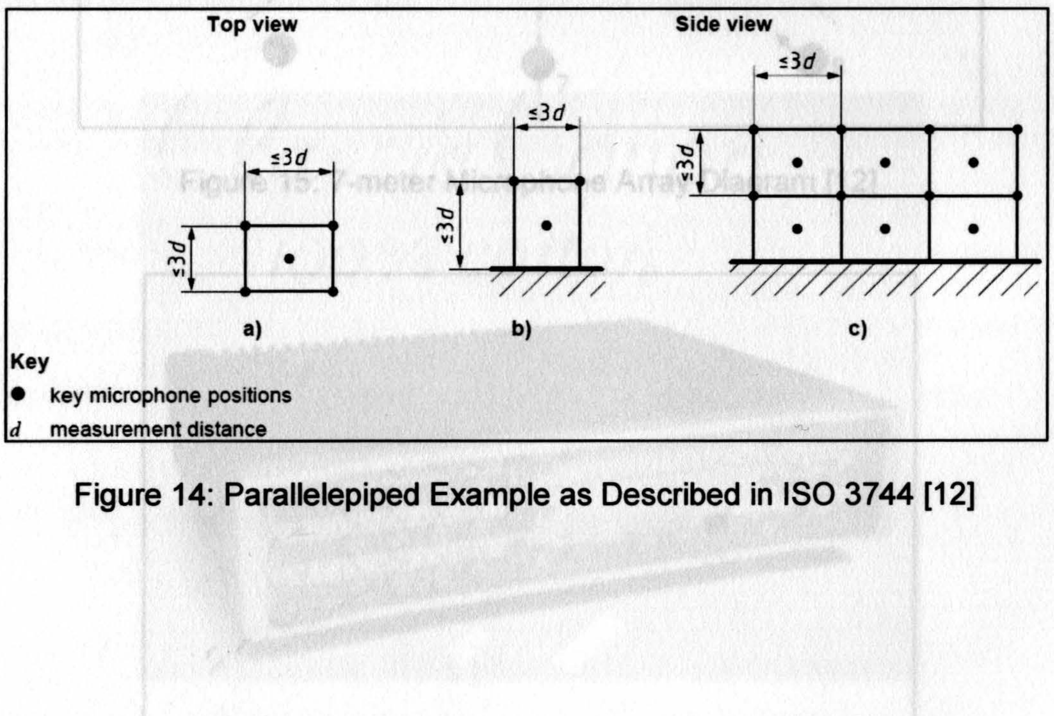


Figure 14: Parallelepiped Example as Described in ISO 3744 [12]

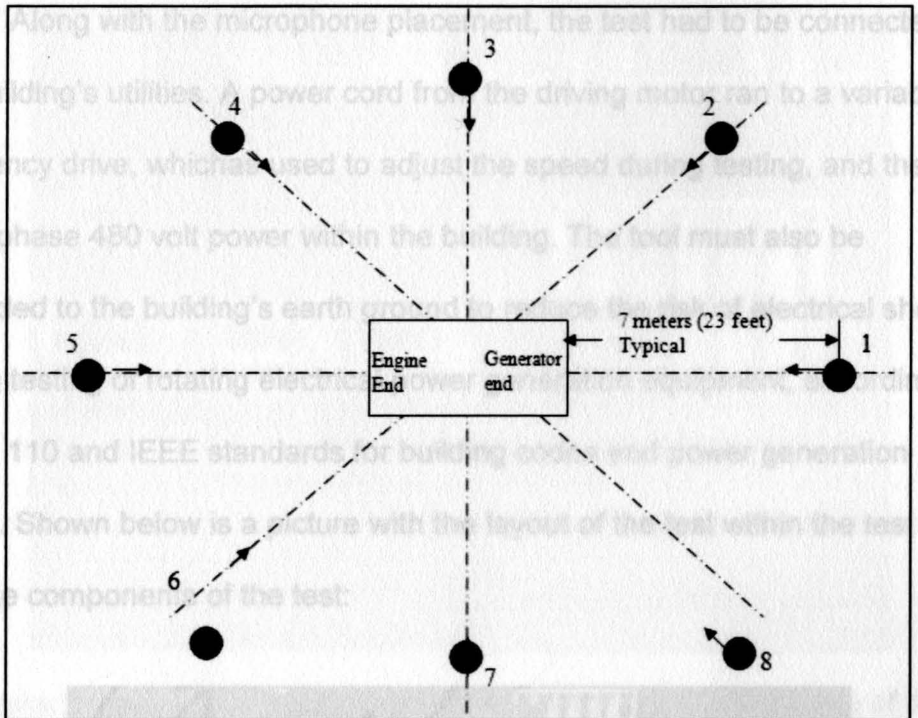


Figure 15: 7-meter Microphone Array Diagram [12]

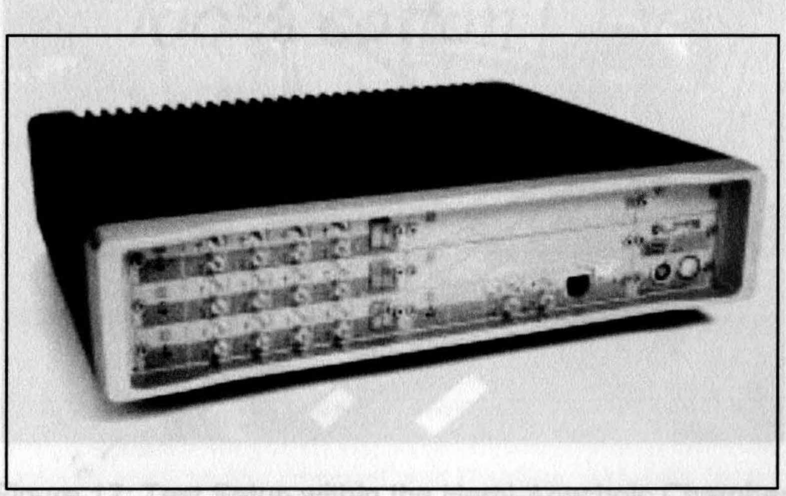


Figure 16: LMS SCADAS Mobile used for Acoustic Data Recording

Along with the microphone placement, the test had to be connected to the building's utilities. A power cord from the driving motor ran to a variable frequency drive, whichas used to adjust the speed during testing, and then to the 3-phase 480 volt power within the building. The tool must also be grounded to the building's earth ground to reduce the risk of electrical shock during testing of rotating electrical power generation equipment, according to NFPA 110 and IEEE standards for building codes and power generation codes. Shown below is a picture with the layout of the test within the test cell, and the components of the test:

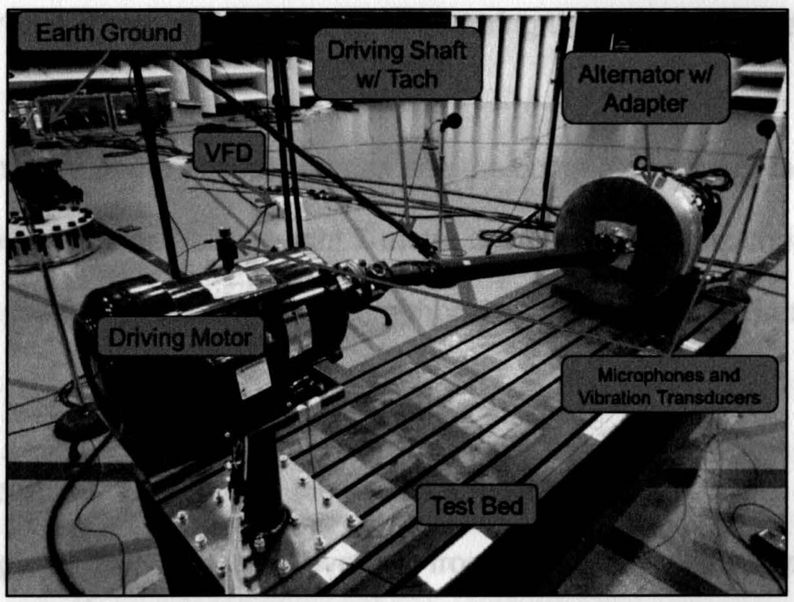


Figure 17: Test Setup within the Hemi-Anechoic Chamber

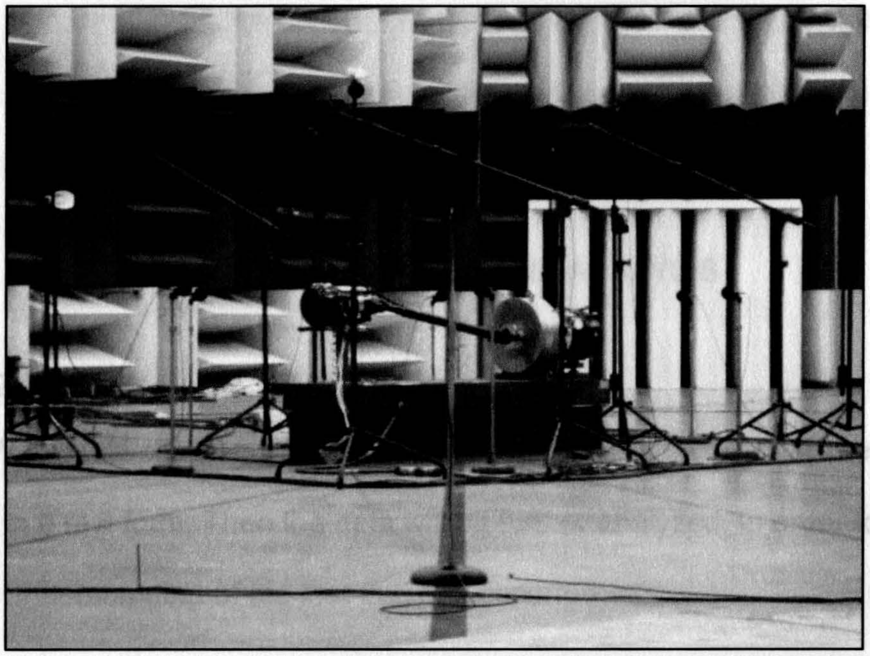


Figure 18: A Photo of the Finished Tool during the Testing Phase of this Project

Within the photo above, one can see the complete setup of the test. In the foreground was one of the eight 7-meter microphones. Surrounding the test fixture itself were the 1-meter microphones in a parallelepiped array.

Summary

Throughout this chapter, the reader should have learned the methodology for how the project evolved, from concept to construction. 6S tools were used to analyze the concept and timeline, acoustic tools used to analyze the data, and in-house machine shop used to procure the parts for the tool itself, and a brief introduction to the test setup within the hemi-anechoic chamber.

Chapter IV

DATA PRESENTATION AND ANALYSIS

Introduction

Within this chapter, the reader will first see the acoustic data presented to them in a raw form. Then the data will be further analyzed, in order to have a better understanding of the test that has occurred.

Data Presentation

The data was output to the following format for all the speeds tested, but here are two main target speeds of 1500 rpm and 1800 rpm. The data shows multiple tests on one graph, followed by calculated data as well. First, the red line shows the combined acoustic output of the drive motor and alternator being tested at the same time. Secondly, the blue line shows the test with the alternator disconnected at the same speed. This test gave the background acoustic levels without the alternator spinning. Thirdly, the green line shows the calculated output of the alternator by itself. This number was calculated by subtracting the logarithmic acoustic output of the entire test setup (red line) by the logarithmic background levels (blue line) to come up with the output of the alternator alone. Doing so across the entire frequency domain gave the green line for display. On the left side of each graph is the axis for the A-weighted Sound Power levels and on the bottom axis is the acoustic frequency at each octave:

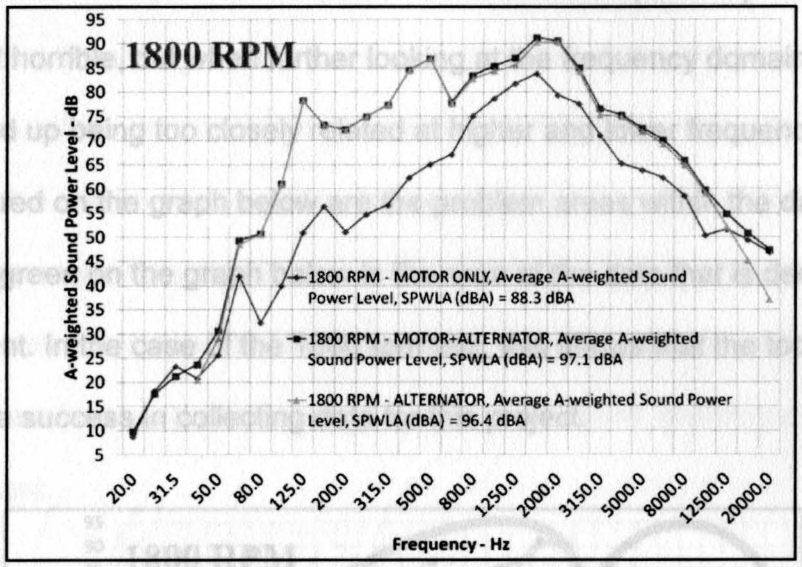


Figure 19: 1800 rpm Line Chart

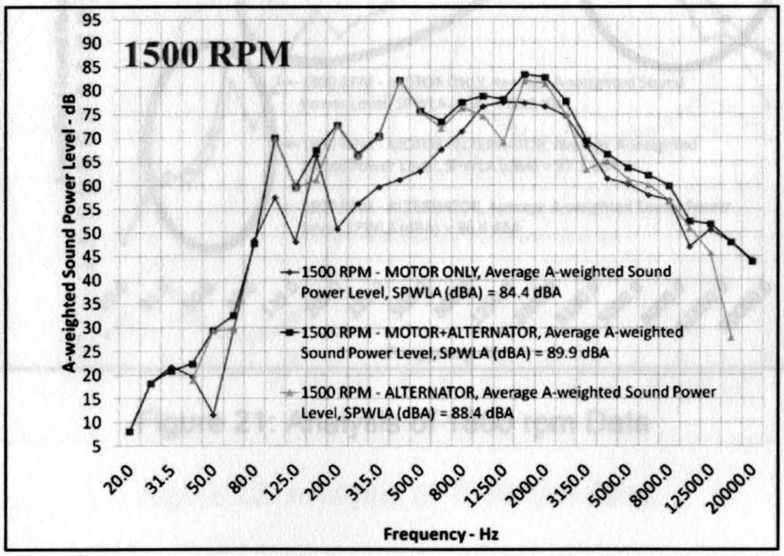


Figure 20: 1500 rpm Line Chart

Data Analysis

Using the same graph from before for 1800 rpm, one can see that the background levels (blue line) were measured to be about nine dBA away from the original test with the motor and alternator combined (red line). Overall, nine dBA is not horrible, but when further looking at the frequency domains, the data ended up being too closely related at higher and lower frequencies. Circled in red on the graph below are the problem areas within the data. Circled in green on the graph below is the area of the data that is deemed to be sufficient. In the case of the 1800 rpm test, this shows that the tool was generally a success in collecting data for this project.

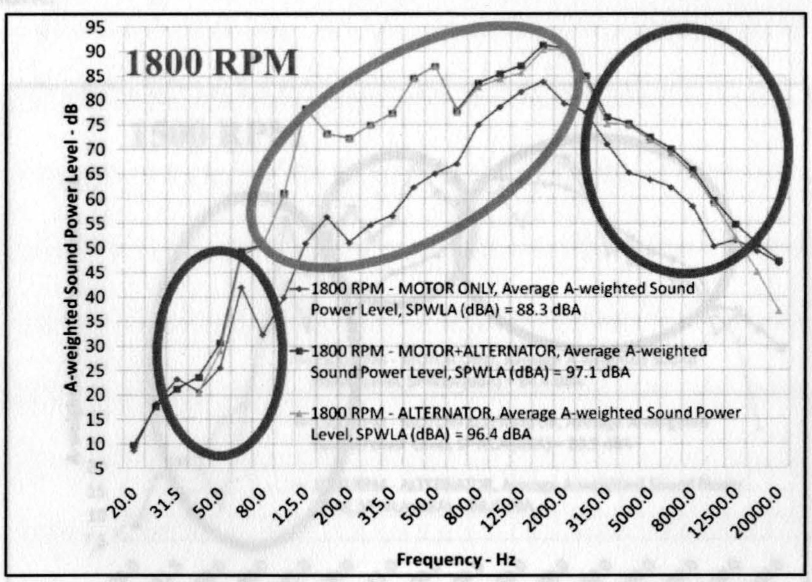


Figure 21: Analysis of 1800 rpm Data

Using the same graph from before for 1500 rpm, one can see that the background levels (blue line) were measured to be about five dBA away from the original test with the motor and alternator combined (red line). Overall, five dBA shows that there could be a problem with the test, and when further looking at the frequency domains, the data ended up being too closely related at a majority of the frequencies that were tested. Circled in red on the graph below are the problem areas within the data. Circled in green on the graph below is the area of the data that is deemed to be sufficient. In the case of the 1500 rpm test, this shows that the tool had issues with the output of 1500 rpm. This could be from a vibration resonance of the tool itself, possibly caused by misalignment.

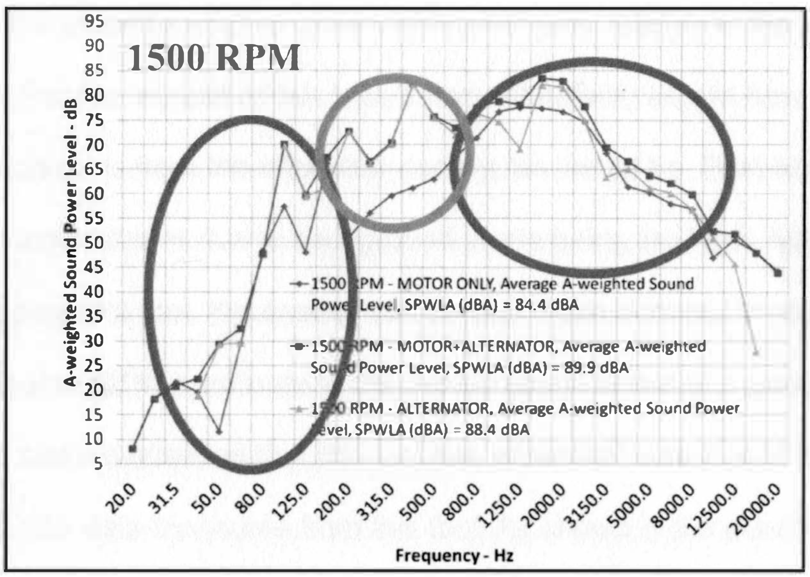


Figure 22: Analysis of 1500 rpm Data

Summary

Within this chapter, the data from the testing was shown, and then analyzed. After displaying the analyzed data, the reader should now be aware of some of the highlights of the tool, but also the problem areas that will need further testing to refine.

Chapter V

RESULTS, CONCLUSION, AND RECOMMENDATIONS

Introduction

This chapter will highlight the results and conclusion of this project. Future recommendations will also be given to make this tool more accurate and efficient as well.

Results

The development of this tool had provided sufficient results to be able to answer the project's original questions/hypotheses relative to the objective statement. Prior to the use of this tool, it was not entirely known how high the acoustic emissions from the alternator cooling fan would be. Past experiments have been inconclusive due to background levels being too high. But with the use of this project's tool, the answer can be that these acoustic emissions are in fact high enough to contribute to the overall sound levels of a generator set.

The second question that this tool has answered was that of the accuracy of the data measured from this tool. As shown in the previous chapter, there were some areas of the data that proved to be successful, and some areas that needed to be refined to improve the accuracy of the data.

But, the tool was an overall success, being able to output useable data to show that the tool did what it was intended to do.

In similar situations where alternators are spun without the use of an engine, the setup time was usually a problem. The alignment of the driving source compared to the test unit was a highly critical issue that had to be done by a special team, with special equipment. This tool showed that an alternate way of connecting two spinning components can be done quicker, and without the use of any special tools.

Final results show that the tool can be used, but the shaft that was used will need to be further analyzed as it was found to have a diminishing effect on the data due to vibration induced noise.

Conclusion

This project was meant to develop a tool that could be used for future testing of acoustic emissions of cooling fans within large alternators. Due to previous unsuccessful tests using tools of other nature, it was decided that a better tool needed to be developed.

Using 6S tools to plan and decide the best direction for this project has been an overall success. Using a KJ investigation, the project team was able to analyze the major requirements of the project. Using these key requirements, a critical parameter tree was be made to better illustrate these requirements. Through the use of concept generation and a Pugh matrix, a final decision on the direction of the project was decided upon to best meet the objective of the project. All of these 6S tools, and the entire project, were laid out on another 6S tool, the RACI diagram, in order to show the timeline that the project should follow, and to illustrate if the project was getting behind schedule.

With the concept for the tool chosen, the tool's construction commenced. Computer aided tools were used to optimize the design, and to construct it in a machine shop as well. Final assembly took place, and testing could be done to analyze how the tool performed.

During testing, it was found that the tool had vibration induced noise at a majority of the rpm range that the test unit was spun at. Upon further investigation, it was found that the driveshaft being used was aligned incorrectly for the style of shaft that was used. The driveshaft that was built for this tool is a double-cardan shaft. When aligning a double cardan shaft, the angle at the double cardan joint takes up all the angle of the shaft, while the single joint at the test unit uses an optimal angle of zero degrees. This is illustrated below, with red lines showing how the alignment should look:

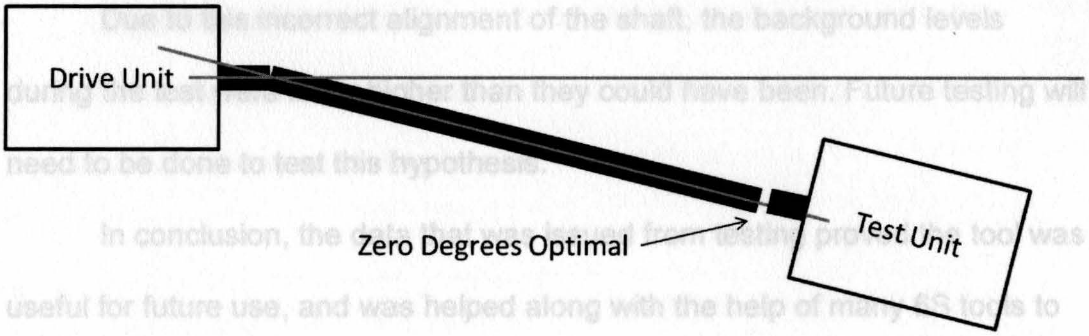


Figure 23: Double-Cardan Driveshaft Alignment

During the initial testing of the tool, it was noticed that the alignment was likely the cause of vibration induced noise. The shaft was not aligned as a double cardan shaft should be, but as a single cardan shaft should be aligned. The single cardan shaft needs to be aligned with both the drive unit and test unit being parallel, and the shaft having two joints with two similar angles. This is illustrated below, with red lines showing how the alignment should look:

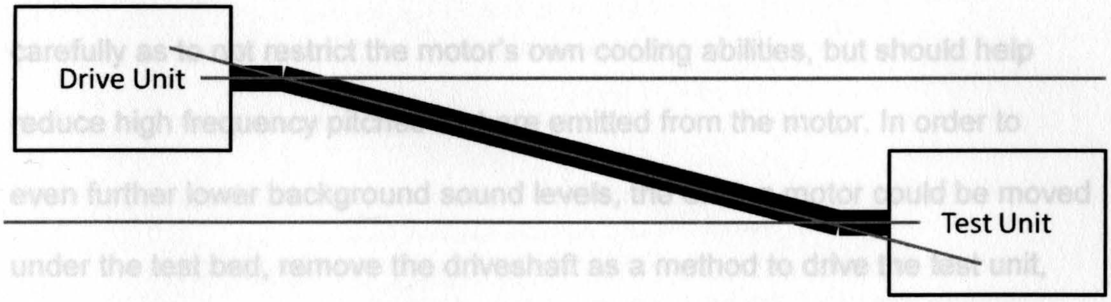


Figure 24: Single-Cardan Driveshaft Alignment

Due to this incorrect alignment of the shaft, the background levels during the test were likely higher than they could have been. Future testing will need to be done to test this hypothesis.

In conclusion, the data that was issued from testing proved the tool was useful for future use, and was helped along with the help of many 6S tools to achieve that success.

Recommendations

To follow-up the success of this project, more testing will need to be done to evaluate the method of alignment with the driveshaft that was used. With reduced vibration induced noise, the background levels will likely be reduced, which will give way to more accurate data of the alternator cooling fan noise. Along with the reduction in background sound levels, additional acoustic dampening could be added to the drive motor. This must be done carefully as to not restrict the motor's own cooling abilities, but should help reduce high frequency pitches that are emitted from the motor. In order to even further lower background sound levels, the driving motor could be moved under the test bed, remove the driveshaft as a method to drive the test unit, and use a drive system similar to a belt/pulley system. This style of drive would likely further remove any problems with alignment, and therefore reduce more vibration induced acoustic emissions.

Beyond the fixes mentioned above, the tool developed within this project was a success, and should be used for further testing of acoustic emissions of alternator cooling fans.

REFERENCES

[1] "Parallelepiped." *Merriam-Webster*, n.d. Web, June 21, 2014, http://www.merriam-webster.com/dictionary/parallelepiped.

[2] F. A. Everest and K. C. Pohlmann. *Master Handbook of Acoustics*. New York: McGraw-Hill, 2009.

[3] A. L. S. Chan, "Single value representation of sound spectrum," *Single Value Representation of Sound Spectrum*, 2008. Web, June 21, 2014, http://personal.cityu.edu.hk/~bsapplec/single.htm.

[4] "Sound power," *Wikipedia*. Wikimedia Foundation, June 18, 2014. Web, June 21, 2014, http://en.wikipedia.org/wiki/Sound_power.

[5] "Sound pressure," *The Engineering Toolbox*, n.d. Web, June 21, 2014, http://www.engineeringtoolbox.com/sound-pressure-d_711.html.

[6] F. Mello, "Cummins power generation unveils acoustical testing center at Fridley headquarters--English blog," *English Blog Cummins Power Generation Unveils Acoustical Testing Center at Fridley Headquarters Comments*. Cummins Power Generation, October 25, 2011. Web, June 12, 2014, http://www.cumminspowerblog.com/en/2011/10/25/cummins-power-generation-unveils-acoustical-testing-center-at-fridley-headquarters/.

[7] ISO, "ISO 3744:2010 Acoustics--Determination of sound power levels and sound energy levels of noise sources using sound pressure--Engineering methods for an essentially free field over a reflecting plane," *ISO*, 2010. Web, March 2014, http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnucsnu=52055.

[8] ISO, "ISO 12001: 1996 Acoustics--Noise emitted by machinery and equipment--Rules for the drafting and presentation of a noise test code," *ISO*, 1996. Web, March 2014, http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnucsnu=21256.

REFERENCES

[1] "Parallelepiped." *Merriam-Webster*, n.d. Web, June 21, 2014, http://www.merriam-webster.com/dictionary/parallelepiped.

[2] F. A. Everest and K. C. Pohlmann. *Master Handbook of Acoustics*. New York: McGraw-Hill, 2009.

[3] A. L. S. Chan, "Single value representation of sound spectrum," *Single Value Representation of Sound Spectrum,* 2008. Web, June 21, 2014, http://personal.cityu.edu.hk/~bsapplec/single.htm.

[4] "Sound power," *Wikipedia*. Wikimedia Foundation, June 18, 2014. Web, June 21, 2014, http://en.wikipedia.org/wiki/Sound_power.

[5] "Sound pressure," *The Engineering Toolbox*, n.d. Web, June 21, 2014, http://www.engineeringtoolbox.com/sound-pressure-d_711.html.

[6] F. Mello, "Cummins power generation unveils acoustical testing center at Fridley headquarters–English blog," *English Blog Cummins Power Generation Unveils Acoustical Testing Center at Fridley Headquarters Comments. Cummins Power Generation*, October 25, 2011. Web, June 12, 2014, http://www.cumminspowerblog.com/en/2011/10/25/cummins-power-generation-unveils-acoustical-testing-center-at-fridley-headquarters/.

[7] ISO, "ISO 3744:2010 Acoustics–Determination of sound power levels and sound energy levels of noise sources using sound pressure–Engineering methods for an essentially free field over a reflecting plane," *ISO*, 2010. Web, March 2014, http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnucsnu=52055.

[8] ISO, "ISO 12001: 1996 Acoustics–Noise emitted by machinery and equipment–Rules for the drafting and presentation of a noise test code," *ISO*, 1996. Web, March 2014, http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnucsnu=21256.

[9] L. C. Morse and D. L. Babcock, *Managing Engineering and Technology: An Introduction to Management for Engineers*. Upper Saddle River: Prentice Hall, 2010.

[10] R. S. Russell and B. W. Taylor, *Operations Management: Creating Value along the Supply Chain*. Hoboken, NJ: John Wiley & Sons, 2009.

[11] M. S. Phadke, *Quality Engineering Using Robust Design*. Englewood Cliffs, NJ: Prentice Hall, 1989.

[12] *ISO 3744:2010 Acoustics–Determination of sound power levels of noise sources using sound pressure–Engineering method in an essentially free field over a reflecting plane*. Geneva: International Organization for Standardization, 2010.

[13] "LMS testing solutions," *LMS SCADAS Data Acquisition Systems: Siemens PLM Software*. Siemens Product Lifecycle Management Software, Inc., n.d. Web, June 19, 2014, http://www.plm.automation.siemens.com/en_us/products/lms/testing/scadas/.

APPENDICES

APPENDIX A

Sample KJ Questionnaire

SAMPLE KJ QUESTIONNAIRE

Vote on the importance of all of the following:

1. Tool should have a quiet power source.
    a. Quietly cooled electric motor.
    b. Power source outside of 1-meter acoustic measurements.
    c. Limited setup/knowledge needed to test.
2. Should have vibration isolation.
    a. Test unit should be vibration isolated from floor.
    b. Test unit should be vibration isolated from driving mechanism.
    c. Able to do vibration testing within same test tool.
3. There should be an easy to use tool for testing various sized alternators.
    a. Have a skid able to withstand heavy alternator weights.
    b. Have ability to mount various sized alternators (height/width/length).
    c. Easy to move in and out of test cell with fork-truck.
    d. Power source mounted to tool.
4. There is no need for full load testing.
    a. No testing done currently at full load.
    b. Nearly impossible to test larger alternators with low background acoustic levels.

APPENDIX B

PBIT Savings / Other Benefits

PBIT SAVINGS / OTHER BENEFITS

	PBIT Savings	Avoidance Savings	Potential Growth
2013	**$ 0**	**$ 0**	**$ 0**
2014	**$ 0**	$20,000	**$ 0**
2015	**$ 0**	**$ 0**	**$ 0**
2016	**$ 0**	**$ 0**	**$ 0**

Other Potential Benefits:

1. Better knowledge of our product's performance.
2. Acoustic emissions optimization.

Figure 25: PBIT Savings

Collaboration with another group within the company had brought about avoidance savings for 2014 because the other group would not have to replicate this project to develop another tool of their own, as both teams had similar goals (vibration/acoustics).

APPENDIX C

Test Plan

TEST PLAN

Table 3: Test Plan

Test Number	Speed	Drive Source	Test Unit	Fan Guard
1	150	Yes	Yes	Yes
2	300	Yes	Yes	Yes
3	450	Yes	Yes	Yes
4	600	Yes	Yes	Yes
5	750	Yes	Yes	Yes
6	900	Yes	Yes	Yes
7	1050	Yes	Yes	Yes
8	1200	Yes	Yes	Yes
9	1350	Yes	Yes	Yes
10	1500	Yes	Yes	Yes
11	1650	Yes	Yes	Yes
12	1800	Yes	Yes	Yes
13	1950	Yes	Yes	Yes
14	150	Yes	Yes	No
15	300	Yes	Yes	No
16	450	Yes	Yes	No
17	600	Yes	Yes	No
18	750	Yes	Yes	No
19	900	Yes	Yes	No
20	1050	Yes	Yes	No
21	1200	Yes	Yes	No
22	1350	Yes	Yes	No
23	1500	Yes	Yes	No
24	1650	Yes	Yes	No
25	1800	Yes	Yes	No
26	1950	Yes	Yes	No
27	150	Yes	No	Yes
28	300	Yes	No	Yes
29	450	Yes	No	Yes
30	600	Yes	No	Yes
31	750	Yes	No	Yes
32	900	Yes	No	Yes
33	1050	Yes	No	Yes
34	1200	Yes	No	Yes
35	1350	Yes	No	Yes
36	1500	Yes	No	Yes
37	1650	Yes	No	Yes
38	1800	Yes	No	Yes
39	1950	Yes	No	Yes