A Unique Instrumentation System Design for Measuring Forces on a Rotating Shaft

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Abstract

The design and construction of instrumentation systems require a broad background in many disciplines. The system design in this paper was further complicated by the subject of the measurement. Attempting to measure the bending forces on a rotating shaft is difficult in the extreme. We believe that the approach taken in the design of this Instrumentation and Measurement System is unique and has broader applications than those described by this paper. There is significant opportunity to further the performance of the Instrumentation and Measurement system as well as the post processing analysis tools.
Keywords: Corvair Aircraft Engine, crank shaft

1 Introduction

Instrumentation is a critical element for control systems and a design validation tool. In this latter role, instrumentation may also be utilized to perform measurements on systems that are utilized in applications for which they were not initially designed. It is these systems that present the greatest challenges to the design and use of instrumentation systems.

A prime example is automotive engines used in experimental recreational aviation. The use of automotive engines in aircraft is driven by purely financial considerations. An automotive engine converted for aircraft use is approximately one-third the cost of a certified aircraft engine. These conversions often exhibit systemic problems or failures whose cause is difficult to determine. In this situation instrumentation systems are the primary tools used to isolate and identify the root cause or causes of the system failures.

Crankshaft failure in these conversions presents the most difficulty. This paper describes the development and evaluation of an instrumentation and measurement system designed to identify the root cause of crankshaft failures. Crankshafts fail as a result of excessive force or fatigue due to repetitive bending moments. The problem presented to the instrumentation engineer is how to measure forces on a rotating body.

Instrumentation systems typically consist of three major components; sensors, signal conditioning components, and data recorders. The instrumentation design described here introduces a unique approach to measuring the physical forces on the shaft by applying the principals of Newtonian physics[7] - specifically Newtons three laws of motion. The usual method of measuring bending moments is direct measurement of the bending forces by measuring the bending moment of the metal itself.

The rest of this paper will demonstrate that bending forces can be determined with reasonable accuracy by taking advantage of these principals and designing custom sensors. In addition, once the data have been gathered, it is necessary to analyze them to isolate and identify the root cause of the failures. To implement this design and to perform the analysis requires the application of three major engineering disciplines: Electrical Engineering, Computer Science and Mechanical Engineering, along with the fundamental foundations provided by physics and mathematics.

This paper is structured as follows: Section 2 describes the overall requirements including information on the operation of reciprocating engines, a short discussion on the forces placed on an aircraft, the project plan as implemented including an overview of the system components, processes and tools used to design and build the instrumentation and measurement system. Sections 3 and 4 describes the actual hardware design and the software designs respectively, and Section 5 shows the results of the project including preliminary data analysis. Section 6 outlines the future work to be performed on the project.

2 Instrumentation and Measurement System Design

2.1 Problem Background

In experimental aviation, the builder can use any type of engine desired to power their aircraft. A certified aircraft engine can cost as much as the rest of the aircraft combined. To help lower the cost of flying, builders often use automotive engines in their experimental aircraft. However, installing these engines on aircraft can create problems because the engine is used in an application for which it was not intended.

This project was initiated by just such a problem. Since 1964, General Motors Corvair automotive engines have been converted for aircraft use due to their similarity to aircraft engines. Specifically, they are horizontally opposed six-cylinder engines that can produce 100 to 120 horsepower in a direct drive configuration. In the conversion process these engines are rebuilt using new or remanufactured parts to create essentially a new or zero time engine. The engine is modified to drive a propeller directly off the crankshaft. This can cause a problem in that the crankshaft bearings in the transmission must now withstand forces that they were not designed to take. When these conversions were first performed, the engine was put on low and slow aircraft that typically flew at airspeeds from 50 mph to 100 mph. Now these engines are in aircraft that are cruising at 150 mph with top speeds exceeding 180 mph.

It is these aircraft that have experienced broken crankshafts in 2005 and 2006. There has been a significant amount of speculation within the conversion community on the cause of the failures, and some engineering analysis has been done. However, the general consensus is that the problem must be caused by one of four specific forces that act on the crankshaft.

2.2 Forces Acting on Aircraft Crankshaft

Four different propeller forces act on an aircraft engine and specifically the crankshaft. They include P-Factor, gyroscopic, torsional and maneuvering. P-Factor[1], caused by relative wind, has the effect of bending or side loading the crankshaft every 180 degrees with the maximum force when the descending blade is at its greatest angle of attack to the relative wind.

Gyroscopic forces oppose a change in direction. In maneuvering aircraft, the rotating propeller presents a gyroscopic force on the crankshaft that tends to oppose any change in direction of the aircraft. Although there is an additional force caused by the gyroscopic (precession) force, this force is small and is not considered to be a contributing factor in the crankshaft breakage.

Torsional force is the twisting force experienced by the crankshaft. There are two sources of torsional forces: the force that is imposed by the drag of the propeller in reaction to thrust (Newtons opposite and equal reaction) and the force caused by the power stroke of the engine.

The final type of force that acts on the propeller shaft are those imposed by maneuvering the aircraft. These loads can range from one to three g's in normal flight and up to ten g's momentary shock forces.

One or more of any of these forces may break the crankshaft. This had occurred three times in 2006, and the following picture shows that the area of breakage is directly behind the first bearing behind the propeller hub. Figure1(a) is a picture of a broken crankshaft. Figure1(b) shows the outline of the Corvair engine modified for aircraft use and the location of the propeller hub and the break. Figure 1(c) shows an actual picture of the engine that experienced two crankshaft failures.

Understanding the physical location of the failures and having a background in sensors and instrumentation, we can proceed to a discussion of the instrumentation system design.

2.3 Instrumentation Requirements

2.3.1 Environmental Considerations

Because there are four distinct sources that could cause the problem with the crankshaft breakage, and because designing one instrumentation system to measure them all would require resources we did not have, we elected to design a system that addressed just one of the possible sources. We chose to measure the bending forces caused by the rotation of the propeller. Reducing the focus of the instrumentation system to this one parameter narrowed the number of issues to be resolved.

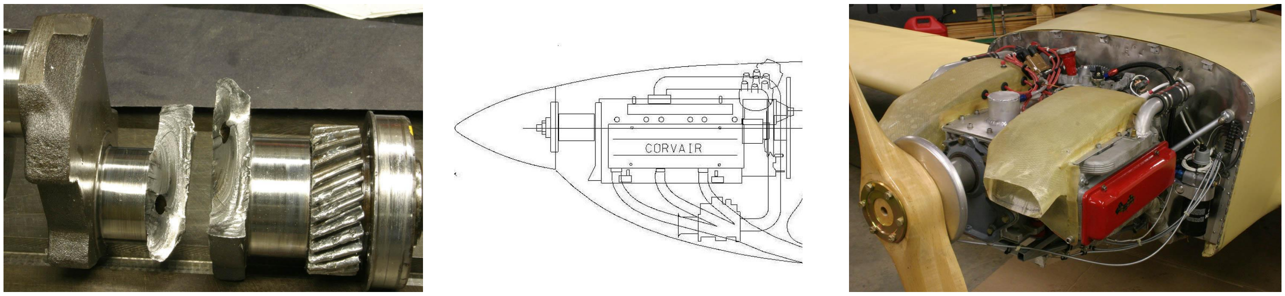
In addition to narrowing the number of parameters that would be recorded, we also needed to design a system that could be installed by non-technical people using regular hand tools. If the system was designed in this manner, it could be shipped around the country, collecting data from many different engines and providing extra depth to the data that we could analyze. Such data would facilitate statistical analysis to either identify the bending moment as the source of the problem or eliminate it.

The Corvair engine is a six-cylinder, four-stroke reciprocating engine with a two-blade aircraft propeller mounted directly on the crankshaft. From this information we can determine that we need to look at not only the magnitude of the bending force, but also the frequency of the force since any imbalance in the system will result in a force that will reverse itself at most every 180^o.

These force reversals have two principal sources, the propeller and the power stroke of the engine itself. The operating range of the engine is from 600 RPM to 3600 RPM, which translates into a propeller frequency range of 20 Hz to 120 Hz.

The power stroke frequency of the engine is computed on the fact that combustion occurs on every second rotation of the crankshaft. For a six-cylinder engine this means that there are three power impulses for every rotation of the crankshaft. This results in a frequency for the engine power pulses of 30 Hz and 180 Hz.

The most common method of determining bending forces in a steel structure is the use of strain gauges. In our case a significant problem exists in how to mount strain gauges on a rotating shaft. In addition to that problem, the area of breakage is directly behind the first bearing following the propeller mount as shown in Figure 1. Placing strain gauges on the crank cheeks would be very difficult, requiring skills beyond the abilities that could be expected from an average engine builder. Another method is needed to determine what the forces actually were on the engines crankshaft.



(a) Broken Crankshaft (b)Modified Corvair Outline (c)Plane

Figure 1: Broken Crakshaft Example[3]

2.4 The Design

2.4.1 Bending Sensor

The first design problem to solve was the problem of measuring the bending moment on the crank. It is obvious from the difficulty of placement that the application of strain gauges was not an option. While there are methods of placing sensors inside of an operating engine, this typically is performed in a special facility, and the engine is so heavily modified that it could not be returned to service as an aircraft engine. So the question was how do we solve this problem?

Newton and his three laws of motion offer assistance [7]. It is the application of second law that aided us in designing this instrumentation system. Since the mass (m) of the reciprocating engine is known during operation and we can measure the acceleration (a) using accelerometers, the force (F) acting on the engine can be computed using the second law. Traditional accelerometers are subject to damage under high shock loads. For this application, a thermal accelerometer provides the high sensitivity while remaining immune to large shock loads. This provides the most robust method of measuring the accelerations. This device does present a problem in that its native frequency response is from 0 to 30Hz which is substantially below the 180 Hz specified. This required special signal conditioning to extend the range to at least 200 Hz to cover the entire range of interest.

The next required sensor determines engine RPM. We would like to compare the force frequencies over engine RPM. Knowing the engine RPM allows us to look for harmonics in the system. We selected the snap on inductive pickup from an automotive timing light to keep installation as simple as possible. This could be clamped around a coil lead, and the RPM could be determined by dividing the spark frequency by 3.

2.4.2 Signal Conditioning

Having now selected the sensors, we now turn to signal conditioning. To make the job as easy as possible and to reduce the amount of custom circuit boards that would have to be designed, we located a surplus sixteen channel signal conditioning board with a 12 bit analog-to-digital converter built by IO Tech. This board, a $DaqBoard100^{TM}$, provided nearly all of the signal conditioning required for the project. An advantage of this device was that it connected to the parallel port of a computer and could transfer data fast enough to supply 512 samples per channel per second. This easily exceeded the Nyquist Sampling Theorem [5] requirement that the data be sampled at twice the maximum frequency of interest. In our design we needed to be able to take samples at minimum rate of 2 * 180 Hz or 360 samples per second. The signal conditioning board came with software drivers that could be integrated with data logging software that allowed the data to be recorded directly to disk in real time.

There were two design issues that remained to be resolved for signal conditioning. This first was that the accelerometers had a 3db frequency of 30 Hz, which was well below our need for 180Hz. The frequency range of this device needed to be extended to meet the requirements of the project, so a custom board needed to be designed to perform this function. The second task was to design a circuit that would take the spark signal from the inductive pickup and convert it to a signal level that could be recorded by system.

The design for these signal conditioners is shown in Section 3, which describes, and documents the entire hardware system, interconnection diagram and printed circuit board layouts.

2.4.3 Data Recorder

The DaqBoard simplified the selection of a data recorder. Since the drivers for the acquisition board were software compatible with languages that ran on Windows 98, a laptop was procured on Ebay for less than $150 that came with the operating system and a hard drive of sufficient capacity to perform the role of recorder. The software that was developed for the data recorder is described in Section 4.

3 Hardware Design

Most of the signal conditioning is contained in the DAQ Board. However, the output from the accelerometers must be amplified and the frequency range needed to be extended. In addition to the signal conditioning required for the accelerometers, signal conditioning is required for the inductive pickup used for RPM measurement. Figure 2 is the block diagram of the instrumentation system designed for this application.

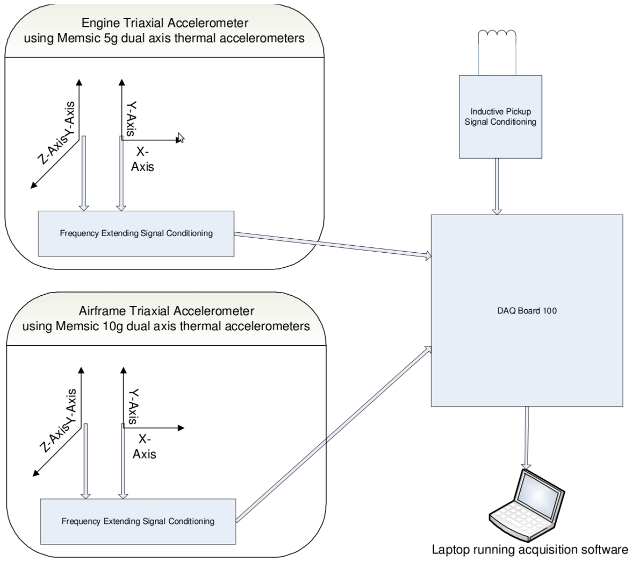


Figure 2: System Block Diagram

The dual axes thermal accelerometers are mounted on a PC card along with its signal conditioning and two cards are mounted in an enclosure to create a triaxial accelerometer with the vertical or y axis duplicated. Two of these sensor chassis were developed to provide the capability to measure data from both the engine and the airframe. This will allow for transfer functions to be performed in the future, potentially collecting data in flight.

3.1 Accelerometer Signal Conditioning

After reviewing several off the shelf accelerometers, we did not find any that would meet the environmental requirements and measurement dynamics required for mounting on a running aircraft engine. This was due to momentary shock loads of 100g that may last 0.1 to 0.2 seconds and a maximum dynamic range of +/- 6g and an expected maximum magnitude of +/- 1.5g from 20 Hz to 180 Hz. Therefore, we selected thermal accelerometers These accelerometers directly support measurements from 0 to 30Hz without any signal conditioning. This frequency response is far less than that needed for our application, requiring additional signal conditioning that will provide a flat frequency response up to 200 Hz with at lest 3 dB of attenuation at 250 Hz.

Memsic Corporation, the manufacturer of the thermal accelerometer, provided a reference design for this device to extend the range well beyond 160 Hz. This application note and reference design is contained in an appendix of [2]. Using that reference design and careful layout, we have extended the range to 200 Hz and validated the performance using a calibrated test stand.

Two of these sensor assemblies are connected to DAQ Board 100. The output of the calibration of these sensors is contained [2].

3.2 RPM Inductive Pickup

The RPM Inductive pickup was an actual inductive pick up for a timing light. It was wired into a simple comparator circuit to provide a square wave signal that would represent the running frequency of the engine by recording the firing pulses to the distributor.

This circuit is a simple comparator that fires an output when the trigger from the input changes the + terminal of the operational amplifier. The negative terminal is held at the reference value as determined by R3 and R2. The input is coupled through C1 and the input is clamped by the diodes D1 and D2 to clip the signal should it exceed the input voltage (5volts) or ground. It is possible to have a signal whose potential is less than ground due to the nature of reactive devices. The output of this circuit is connected to the DAQ Board 100 as described in the following Section.

3.3 Final Signal Conditioning and Digitizing

The DAQ Board 100 has general amplifiers that provides gains of 1,2,5,10,and 20 under software control. The output of these gain stages are connected to a 16 channel MUX that acts as a switch to the 12 bit Flash Analog to Digital Converter. Eight of the sixteen channels are assigned to the two triaxial accelerometer g outputs, six to monitoring signals and one assigned to a tachometer input. This unit is connected to a laptop computer to record the digital data and to allow quick review of the acquisition data.

This hardware records data at the rate necessary to determine the forces acting on the engine. A program was developed that controls the recording of the data. The rate at which the recorder gathers data is defined as the sample rate. As described in Section 2 a six-cylinder engine has three power strokes per revolution. The operational RPM range of the engine is 600 to 3600, which results in a power stroke frequency of 30 Hz to 180 Hz. With a two-blade propeller the displacement forces over the same RPM range results in a frequency of 20 Hz to 120 Hz. Based on the Nyquist rate [5] for discrete sampling theorem we need to sample at least 2 times the frequency of interest. For this application, the sample frequency selected was 512 Hz, which is more that 2.5 times the maximum frequency of interest.

The software programs that gathered the data and performed post analysis are described next.

4 Software Design

There are five sequential software operations required to extract the magnitude forces from the system. These steps are: (1) to record time history data, (2) to filter the recorded data, (3) to convert data from time domain to frequency domain, (4) to correlate data from all three axes and (5) to convert results into force magnitudes Each of these operations has unique requirements and introduces its own errors. This paper will describe each of the operations, identifying the design of the software and the results obtained.

4.1 Record Time History Data

The hardware described in Section 4 is able to record data at the rate necessary for the task of determining the forces acting on the engine as described in the previous section. A program was developed that controls the recording of the data. The program records the data across all sixteen channels and stores the information in binary form in a removable flash drive. This allows the data to be mailed back to the author for analysis while the system is shipped to other builders desiring to measure their engine installations.

4.2 Filtering Recorded Data

Since the rate of change occurs at a much slower rate than the sample rate it is necessary to provide initial filtering to remove any high frequency information and retain the trend information that falls within the frequency of interest. The acquisition program on the recorder computer provides a software filter using a boxcar format that is in addition to the hardware filters. A noncausal averaging system is used and is more commonly referred to as a SINC filter and is represented as follows:

$$y(n) = \frac{1}{2M+1} \sum_{k=-M}^{M} x(n-k)$$

or the more common form for 3 elements [5, page 47]

$$y(n) = \frac{x(n) + x(n-2) + x(n-2)}{3} \sum_{k=-M}^{M} x(n-k)$$

A combination of hardware and software filters provides the best filtering techniques while minimizing the ultimate phase shift. This system was used to record data from several engines to create a data base of time history data and allows the development of the post processing programs. Figure 3 is a sample plot of 1 second of time history data from a representative engine.

These data samples were taken from an engine that was accelerated from idle which is approximately 600 RPM to maximum RPM which is around 3,000 RPM. This data was collected utilizing the filters described above and the individual data points were moved into a data base.

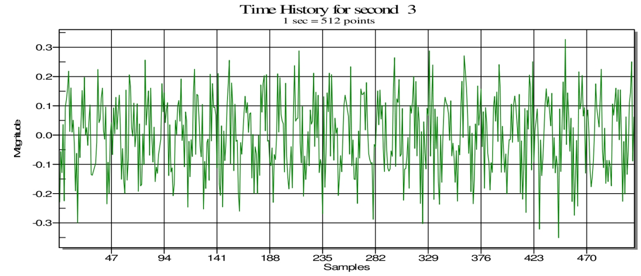


Figure 3: Time History Data Plot

The data base selected is Microsofts SQL Server to allow the development of stored procedures and to allow the use of Microsoft Visual Basic to provide a rapid method of developing user interfaces. Visual basic is designed to directly interface with the SQL Server and contain native data base utilities that simplify the ability to scan, iterate and extract data from very large tables. An average data collection run lasts from two to four minutes at 512 samples per second which results in an average data set of 61,000 to 122,000 records, so the ability to rapidly and natively access the records is important to the ability to process the data into its final form for analysis.

4.3 Convert Time Domain Data to Frequency Domain

The primary method of converting time history discrete data into the frequency domain is to use Fourier transforms. The method selected for this application is based on the description and examples contained in Fourier Series Representation of Discrete-Time Periodic Signals. This utilizes the basic concept of linear combinations of harmonically related complex exponentials.

Converting these formulas to program code and processing the time history data for one second (512 samples), the resultant data set is two data arrays of 256 elements. They are the real part and the imaginary parts of the complex result of the operation. Each element of the array represents a discrete frequency based on the sample rate. Since our sample rate is 512 samples per second and the Nyquist rule applies, the resultant element value is 1 Hz and a total dynamic range of 256 Hz.

Taking this data and combining it according to the Fourier process for magnitude gives us the resultant magnitude plots for the signal shown in Figure 3 in Figure 4

4.4 Correlating Data from All Three Axes

The figure showing the Fourier transform above was selected for its clarity to highlight the basic principals utilized in this analysis. It should be noted that the majority of the transforms do not allow for such clear identification of peak values. Figure 5 is a more typical plot of the transform output.

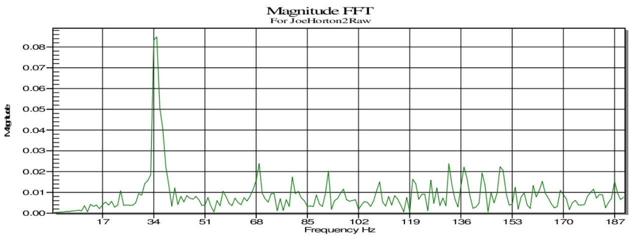


Figure 4: Magnitude Plot

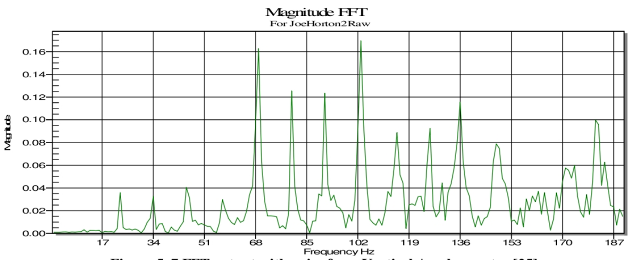


Figure 5. 7 FFT output with noise from Vertical Accelerometer [25]

Figure 5: FFT output with noise

This plot shows the difficulty in determining which peaks are the result of input forces and which peaks are sensor noises or harmonics. To eliminate those peaks that are not the principle frequencies (propeller and power strokes), it is necessary to perform a correlation of the three axes measurements.

It can be observed that peaks near 68Hz and 102Hz appear to correlate exactly between the vertical and longitudinal axes. If we were to look at the lateral axis we would see the same correlation. These frequencies correlate to our 2:3 ratios for engine and propeller forces.

By correlating the peak values it is possible to determine the RPM as well as identifying damaging harmonics. Random impulses are not of concern in our analysis, however harmonic inputs are. It is the harmonic impulses that create bending moments in the shaft and are carried at the input to the first bearing as well as between the first and second bearings.

The differences in the acceleration magnitudes are due to the mounting of the engine on the airframe. When performing the correlation it is necessary to normalize magnitude of the data. This is accomplished by selecting the absolute peak for each axis, determining the axis that has the largest peak, and then multiplying the other two axes by a factor that will result in each axiss peak value to be equal to the others.

The next step is to add the axes frequency bins together to develop a correlated peak value for that period and then select the top two values. These top two values should be the propeller and the engine power pulses. This process resulted in the plot shown in Figure 6.

There are three dominate peaks shown in this plot at 69 Hz, 91 Hz and 103Hz. The peaks at 69 Hz and 103 Hz should be the propeller and engine power stroke inputs to the system. An interesting peak is occurring at

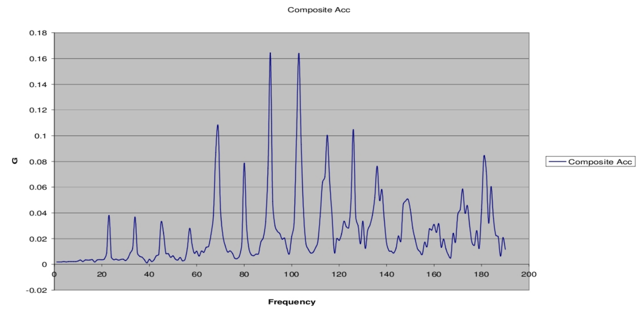


Figure 6: Composite Magnitude Acceleration FFT

91 Hz that does not seem to correlate to any expected mechanical frequency. If this peak is duplicated in further processing, it will indicate an unexpected input that will require further study.

4.5 Convert Results into Force Magnitudes

The final stage is to create a Time History of Magnitudes (Figure 7). This shows an overview of the magnitude of forces over the duration of the test. This gives a three dimensional approximation of the forces since the mass of the engine system remains constant in our formula for force F=ma.

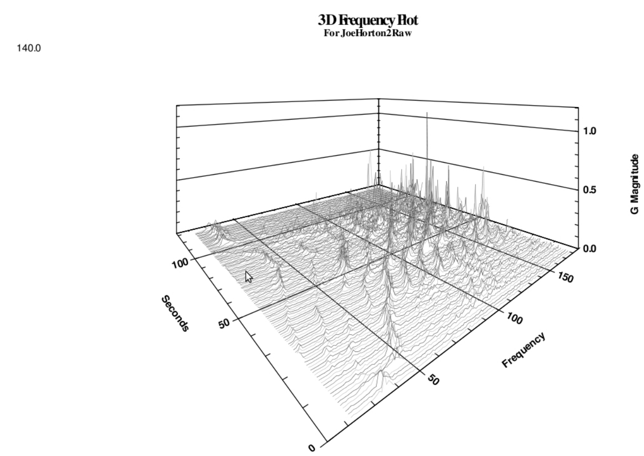


Figure 7: Time History of Acceleration Magnitudes

The software developed for this application allows this plot to be rotated 360^o along the x axis and $+/-90^o$ along the y axis. This allows closer examination of either a specific time or a specific frequency. As the engine RPM increase, several harmonic vibrations occur about 20 seconds into the test. This can be seen by the quantity of peaks appearing on the graph as one moves along the Seconds axis in an increasing direction.

While the peak magnitudes of the "g" forces appear to increase with frequency, the overall effective power of the forces at those frequencies is reduced due to the minimal time that the system is exposed to the peak value.

From the data it is obvious that the higher the frequency, the less the delta distance is required to meet the 1g of acceleration. This means that the relative energy required to move the engine that amount is considerably less. This is based on the formula $W = Fd$.

Further analysis need to be performed to determine if the variance in frequency is due to the durometer of the rubber mount. A further calibration may be necessary to determine the actual force required to move the engine in the mount and apply that factor to this analysis.

4.6 Error Analysis

A comprehensive error analysis has not been performed but the following error sources have been identified and an attempt at quantification of the potential error has been performed. The following paragraphs describe the error sources and their contribution to the overall error figure for the system.

Sensor Errors The sensors used for this project are Memsic Corporation thermal accelerometers with a $+/-5g$ range absolute. Absolute accelerometers actually measure the force of gravity and can be calibrated by noting the output values perpendicular to the ground then rotating the unit 180^o and noting the new value. The difference between the two measurements is divided by $2g$ to get a $volts/g$ value. If a precision angle measurement tool is used to measure different angles of the accelerometer in relation to the force of gravity, the linearity of the accelerometer can be determined. For example if the accelerometer is placed perpendicular to the gravity force line the accelerometer should indicate $0g$. The error sources for this device are shown in [4]. The largest error here is the transverse sensitivity at 2%. This means that an acceleration that appears on the transverse axis to the primary axis may have up to a 2% coupling error. This relates to a 4% error of the current magnitude.

Digitizing Error The next layer of error that can occur are those errors inherent digitizing the analog output from the sensor. This error is $+/-\frac{1}{2}$ the least significant bit of the A/D converter. The range of the A/D converter is 12 bits which resolves to 4096, providing a resolution of 4094 counts. The input range is 0 to 5 volts, so the binary resolution is 0.00122 volts per bit. The dynamic range of the sensor is 0 to 3 volts so the overall resolution of the digitizing system is approximately $3.5mg$.

This value is loaded into a floating point variable for storage so no additional computational errors are anticipated. The data is stored into sequential data base records for further processing. The errors to this point are additive and are magnitude errors and the total possible error is $3.5mg + 8mg \approx 11.5mg$ [6, Ch 5].

FFT Conversion Errors The final error of the system is that determined by the resolution of each frequency bin of the FFT process. The input to the FFT is 512 samples per second and the output is 256 real and 256 imaginary elements. When these elements are combined, the result is 256 magnitude bins representing 1 Hz per bin. This is based on the fact that the input of 512 samples represents 1 second of data. The result of this process identifies that maximum granularity of the frequency output is 1 Hz and can only be considered the power within a 1 Hz band width. For example if a sinusoidal frequency of 50.25Hz is processed, the entire magnitude will be cumulated in the 50Hz bin. If the frequency is 50.55, the magnitude will be reflected in the 51Hz bin [6, Ch 6].

5 Conclusion

During the course of this project we analyzed the problem and narrowed the focus to allow a cost effective measurement system to be developed. The system was built and the software for both the data acquisition and the post processing was developed by the author.

Generally, the system performed as expected collecting data from five different engines. The software performed without any problems and the acquired data were representative of the input observed on the two test engines that were measured prior to the system being sent to other builders to collect data.

Two major issues were discovered with the system that needs to be addressed. The first issue is that the forces measured and shown in this paper do not approach the theoretical loads expected. Using Mr. Bensons analysis contained in Attachment 2, we should have expected to see forces in the range of 281 lbs or greater. This did not happen in any of the data collected so far. Additionally, there is evidence of harmonic vibrations at certain RPM ranges; however, none of these approaches a level of force that could be considered damaging to the engine or crankshaft.

The first author, based on his personal experience with his own engine, made the assumption that the engine could be considered as a free body exposed to the forces and that the mounting methods could be ignored. This needs to be tested with more rigor.

The second issue is the design for measuring RPM. The RPM input failed to provide adequate data on engine RPM and RPM had to be estimated from the forces. This was not always possible, especially in data sets that have multiple peaks that show the same 2:3 relationship of propeller forces to engine power strokes. A root cause analysis needs to be performed on the RPM sensor circuit and a robust method needs to be devised before continuing with the data collection effort.

6 Future Work

We would like to make three modifications to the system, probably in two phases. This first phase would be to fix or replace the RPM input circuit with a circuit that is more reliable, and to develop a method of measuring the force required to move the engine in its mounts. With these modifications, it will be possible to gain additional accuracy in the force measurements.

In the second phase We would replace the signal conditioning box and laptop with a smaller, DC powered device that would allow the measurement system to measure forces in flight. This will require the recording device to be able to handle large serial flash drives as a typical flight is a minimum of 15 to 20 minutes from engine start to shutdown with most lasting up to 3 hours. A flight of three hours requires a flash drive of at least 256 Mbytes

The nearest removable flash drive that is larger than this figure is 256 Mbyte. The basic requirements for the recorder would be the same as those contained in Section 2 with the following additional requirements: small size, the ability to record directly to a flash drive, be 12V DC powered, use removable flash, and be able to withstand maneuvering forces. This system would be the next generation acquisition system that would provide information on the actual forces experienced in flight.

Acknowledgments

Outside of school, many individuals from the Corvair Aircraft Engine community contributed to the information contained in this work, but three were essential contributors to the basic design as well as testing the system. The first is Mark Langford from Huntsville, AL. Mark has survived three in-flight crank shaft failures. He has collected and documented most of the engineering research on the subject. The second is Dan Benson of PRS Engineering. Dan and some of his staff performed the solid modeling and the metallurgy research referenced in the document. The third is Mr. William Wynne, my Corvair mentor and foremost proponent of the Corvair Aircraft Engine Conversion. In essence, William wrote and is still writing the book on this conversion.

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References

[1] Quinapoxet Model Flying Club. Asymmetric thrust explained. http://www.qmfc.org/school/asym.htm. Last Accessed 10/9/2009.

[2] John R. Kearney. A unique instrumentation system design for measuring forces on a rotating shaft. Master's thesis, University of Nevada, Reno, May 2008.

[3] Mark Langford. Corvair kr2s engine. http://home.hiwaay.net/ langford/corvair. Last Accessed 10/9/2009.

[4] Memsic. Memsic sensor data sheet for +/- 5g accelerometer (mxr6150gm). http://www.memsic.com /data/products/MXR6150M/mxr6150gm.pdf. Last Accessed 10/9/2009.

[5] Alan V. Oppenheim, Alan S. Willsky, and S. Hamid Nawab. *Signals and Systems*. Prentice Hall, second edition, 1997.

[6] B.A.R.B. Randdall and B. Tech. *Application of BK Equipment to Frequency Analysis*. Bruel and Kjaer, 1977.

[7] Raymond A. Serway and John W. Jewett. *Physics for Scientists and Engineers with Modern Physics*. Brooks Cole, 7th edition, 2007.