Final Project Report

Team Thor

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EE 416 - Engineering Design

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Executive Summary

This document details the development, characteristics, validation procedures, and limitations pertaining to the beta prototype developed by WSU team Thor at the request of The Boeing Company. Additionally, the socioeconomic significance of this prototype and research will be discussed, and the current market conditions analyzed as they pertain to monetizing the fruit of this project.

The purpose of the prototype is to collect, analyze and interpret experimentally derived data about the loss of initially applied bolt preload force due to environmental or installation parameters. The intent is to develop an accurate mathematical model that can be leveraged to make useful predictions about the preload force on a joint over time. The system detailed below is designed to collect data regarding steel fasteners in aluminum structure responding to a transverse vibration force input. The system consists of three parts: a mechanical test bed, an electrical circuit for data collection and analysis, and a python-based user interface to present the data in a user-friendly manner.

The technical specifications for all three subsystems are discussed in detail in this document, as well as the procedures used to validate their performance. Due to time and budget constraints, the scope of the project had limitations, and engineering recommendations regarding these limitations are proposed, as well as the future work related to these proposals.

Bolt preload loss is a topic of concern for many industries, the most prominent of which are transportation and construction. Case studies such as a BMW vehicle recall and bridge failures are presented to illustrate the societal need for predictive bolt analysis for monitoring, design and even forensics. Finally, the current state of the market for reactive or blind fastener preload monitoring is evaluated. A subscription-based business model is proposed which can disrupt this market by monetizing ongoing research by employing a novel predictive monitoring method.

Introduction and Background

The Boeing Company, hereafter called the “client”, tasked Team Thor with research and experimental data collection regarding the loss of bolt preload. Preload is the clamping force that a threaded fastener exerts on the structure that it joins. The client was interested in experimental data that would associate the installation conditions of a fastener and various environmental effects such as vibration to the loss of preload.

Team Thor expanded upon this initial problem statement by not only performing research and acquiring test data but developing a software GUI. The purpose of the GUI is to add abstraction between the test data and the end user, presenting a research-based, experimentally derived mathematical model for preload loss in an intuitive manner.

It is important to differentiate between torque (T) applied to the nut of a fastener stack-up, and the preload force (F), which is the property being examined in this report. The two are related to one another in a direct manner, and their relationship is given below in equation 1.

$$T = kFd \quad (1)$$

$$k = \left(\frac{d_m}{2d}\right)\frac{\tan(\psi)\mu\sec(\alpha)}{1-\mu\tan(\psi)\sec(\alpha)}$$

d_m is mean thread diameter

ψ is thread helix angle

α is thread – to – thread angle

d is bolt diameter

Description of Culminating Design

The deliverable product is software based upon research and experimentation, and a viable electromechanical system for conducting these experiments. Consequently, the culminating design for the beta prototype has two elements: an experimental testing apparatus, and a GUI executable coded using the python language. The experimental testing configuration acquires data about bolted joint behavior and software converts data into a mathematical model and packages this model for ease-of-use.

The experimental testing configuration is designed to study bolt preload loss through a system of experimental and control parameters. Because the field of bolt preload modeling is continuously evolving as research progresses, the prototype product necessarily requires tooling to collect experimental data and an algorithm to convert raw sensor data into a usable form. The data collection method employs the three following subsystems:

- Mechanical test bed
- Data sensing and filtering
- MATLAB data analysis

Mechanical testing consisted of a modified Junkers test utilizing transverse vibration to induce preload loss and loosening. A 1750 RPM motor was fixed to a steel braided wire support to help react the forces appropriately into the specimen as shown on figure 1. The motor itself was mounted to a wooden base adjacent to the steel plate in which the bolt specimen is fastened to. The testing coupon is bridged between the in-plane motor plate and steel testing plate.

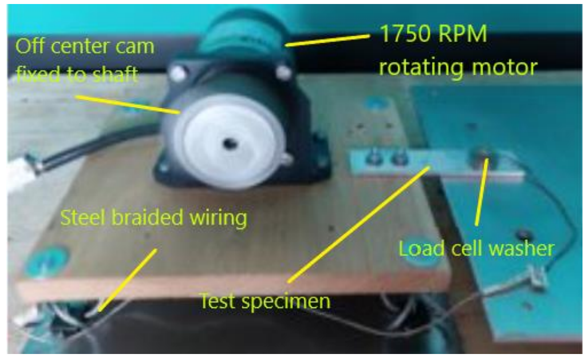

Fig. 1. Modified bolt testing setup for testing preload loss due to transverse vibration.

The test specimen is fastened twice to the motor plate to ensure loosening of the bolt occurs for the desired bolt first. The off-center cams rotate about the motor shaft to produce a force amplitude of roughly 500 Newtons. A load cell washer was used to determine the clamping force in place of an ultrasonic measuring device due to supply constraints.

Mechanical preload on a joint is sensed by an OMEGA™ brand LC901-1/4-5K load cell. This load cell is installed in a coaxial configuration with respect to the bolt being tested and is placed between the structure being joined and the nut. The load cell itself is surrounded by two specially designed load washers that ensure compression force is correctly applied onto the load cell for accurate measurement. Figure 2 below demonstrates a properly configured bolted joint for testing.

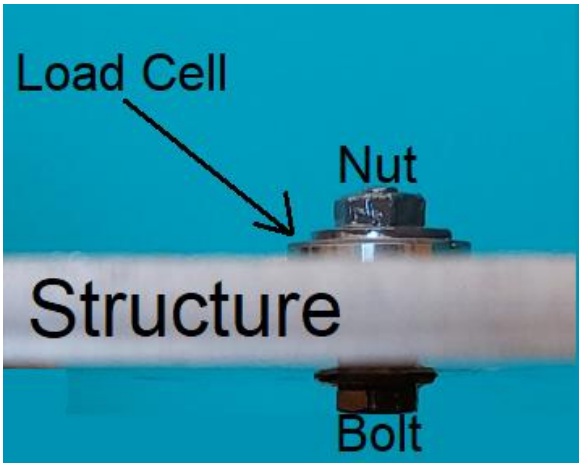

Fig. 2. A fay-sealed, bolted joint assembled for preload loss testing with a coaxial load cell.

The load cell will sense compressive force translated by the load washers and express this in the form of an analog DC voltage that varies from -0.800mV while unloaded to +8 mV when fully loaded at 5000 pounds of compressive force. This analog voltage data is interpreted into a 12-bit integer by the analog-to-digital (ADC) converter onboard an Arduino MKR zero board, which accepts analog voltages from 0 to 3.3VDC and expresses them with 4096 discrete levels, for a step size of 0.805 mV.

The valid voltage range of the ADC does not agree with the output of the load cell, which necessitates an analog circuit to condition the signal. The signal is first passed through an instrumentation amplifier with an effective gain of 1000 V/V. The negative voltage offset of the load cell when unloaded is corrected to a positive value by a regulated DC power supply placed in series with the amplified output. This adjusted signal is then passed through a passive RC filter with a cutoff frequency of 10 Hz that removes unwanted noise to stabilize the output voltage before being sent to the ADC pin on the Arduino microcontroller.

The signal conditioning circuit also allows for a customizable reference voltage other than the default 3.3VDC, which adjusts the step size or granularity of the ADC at the discretion of the test operator. This adjustment is accomplished by providing a different reference voltage from a regulated DC power supply to the analog reference pin of the Arduino. To eliminate noise in the reference voltage, two types of filtering are required. A 10nF capacitor is placed between the analog reference (AREF) pin and ground. A 1 uH inductor in series with a 100 Ω resistor is placed between the DC reference signal and the AREF pin. The signal conditioning circuit is shown below in figure 3.

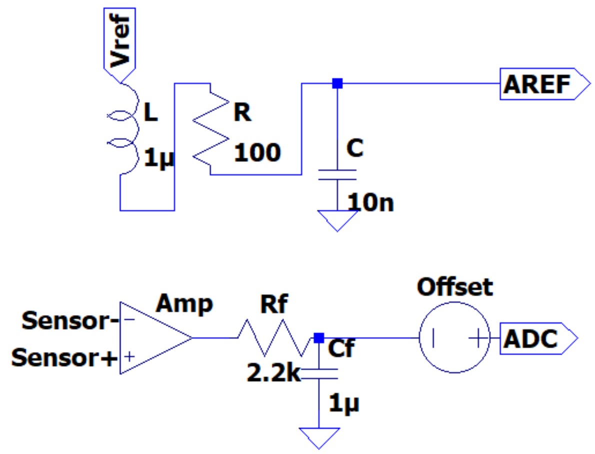

Fig. 3. Signal conditioning circuit diagram.

The Arduino sketch samples the analog voltage at a rate that can be configured by the test operator. Sampling period and interval parameters can be set by the test operator, and the analog voltage is averaged across the number of intervals specified and reported to a serial port at the provided period time. This serial data is exported to MATLAB as a vector of force with respect to the sampling period time. This sampling algorithm can be found in appendix B.

The MATLAB code first removes the sensor's voltage offset to establish a true zero for the discrete level of 0. The entire vector of data is then divided by the maximum value and multiplied by 100 to normalize preload force as a percentage of the initially applied amount. Finally, the set of data is processed by a least-squares algorithm to determine a mathematical expression that best describes the data set. Given that the response of the system being tested is governed by the force equation, the expression will have a general form of a second order differential equation as shown below in equation 2.

$$\mathrm{F(t)} = \mathrm{Ae^{Bt}} + \mathrm{Ce^{Dt}} \qquad (2)$$

A mathematical model for experiment parameters can be deduced by examining how the a, b, c and d coefficients of this differential equation solution is changed between iterations performed under different conditions, where parameters are modeled as modifiers for the coefficients of equation 2. This mathematical model is utilized by the Python executable program that serves as a GUI.

Our Python application was developed with presentation and data integrity in mind. The primary use case for the application would be querying the internal mathematical model to determine a time prediction for when a particular preload loss threshold is met.
To achieve these goals, the model view controller (MVC) architecture was used to develop the application. Some of the strengths of this design architecture include the separation of data from the user, providing a safety buffer between the two. This is crucial since tampering with the internal mathematical model would threaten the accuracy of predictions. MVC consists of three parts, the model, the view, and the controller. These are realized as individual classes within the software.

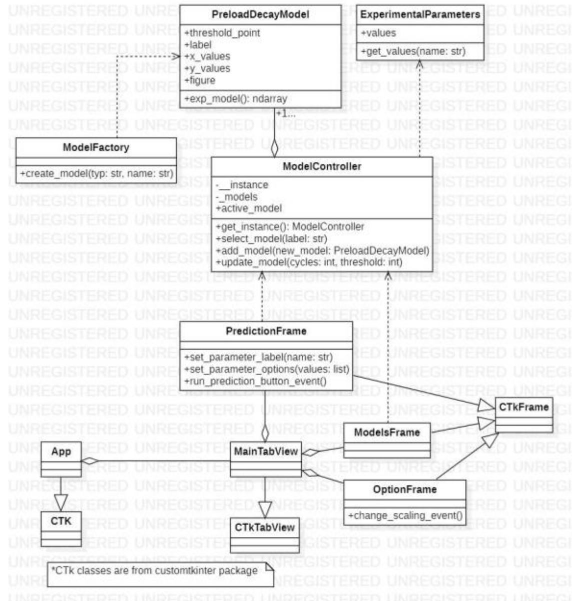

Fig. 4. UML diagram of the software architecture.

In particular, the models are the "PreloadDecayModel" objects which store the four coefficients used in a second order differential equation, as well as a list of threshold points. The views are the GUI of the application, created with the use of the customtkinter Python library. Finally, the controller class receives requests from the GUI classes, and safely performs manipulations on the objects. These updates are reflected in the GUI when the view receives the model data from the controller.
This architecture allows seamless prediction generation by allowing the user to select our determined parameters, update the model's threshold points, and display those points on an updated graph. Additionally, the architecture is very robust and expandable, enabling introduction of new parameters, models, or refactors with little effort. This was another important aspect of consideration for the software, knowing the scope of the project and how immense the scale of testing can be.

Project Management

Team Thor consists of 5 members. Each member was allocated tasks associated with the development or marketing of the product according to their respective professional disciplines. These tasks can be found at the end of the report presented in a GANTT chart.

- Eemaan Deol, Business Analyst
- Xavior Crowley, Communications Specialist
- Samuel Gibson, Software Engineer
- Collin Reynolds, Mechanical Engineer
- Eric Newman, Electrical Engineer

Eemaan worked on the financial strategies and goals for the business aspect of the project. She developed the financial statements, including the income statement, balance sheet, statement of cash flows, and the break-even analysis. Eemaan conducted some research on competition and contributed to the overall business plan development and accomplished project objectives. Furthermore, she helped to achieve financial, marketing, competition, and mission goals for the project. Lastly, she pitched parts of the business plan at the Business Plan Competition 2023 and Capstone Project Report Out Day.

Xavior's undertakings were largely in research and development of branding and strategic marketing to ensure a viable business proposition given the product. He designed and oversaw all branding and content creation including company logo, website, social channels, and advertising. He extensively analyzed market trends, opportunities, and threats to devise an effective marketing strategy that would support business goals and objectives. In addition, he maintained communication between the group to meet individual needs and deadlines. Finally, he wrote and managed a clear and comprehensive executive summary and business plan which was presented at the Business Plan Competition 2023.

Samuel's development tasks consisted of design and programming of GUI based python application, software documentation, and presentation of test data. He first developed an alpha prototype application where the goal was to display a placeholder representation of test data before moving onto the beta application, a more refined version of the alpha with additional features, style, and official test data. He provided software documentation of the application through in line comments in the source code, and a UML diagram.

Collin's responsibilities in product development concerned the development and mechanical research of the testing bed tooling. Developing an adequate tester based on the merits of previous research to correctly test and achieve loosening with available components. This consisted of CAD modeling, CNC machining and iteration based on experimentation.

Eric's responsibilities in product development concerned procurement and installation of the load cell sensors, as well as the signal conditioning and MATLAB analysis of raw data. He performed research regarding force measurement methods and decided based upon the relative merits of each. He designed the signal conditioning circuit used to obtain a useful stream of data from the load cell. Finally, he developed the Arduino code to average and sample the ADC, and the MATLAB code to convert the ADC data into a differential equation representation.

Summary of Business Analysis

According to market research, the preventative maintenance industry would greatly benefit from our development and creation of this predictive model. It is increasingly adopting big data and technologies, as well as projected to increase by a Compound Annual Growth Rate (CAGR) of 30% from $4 billion in 2021 to $15 billion by 2026 [1]. Our proposed company, Thor Solutions, would offer predictive bolt monitoring software and consultation to meet the demands of the businesses most vulnerable to preload loss factors. By targeting fields such as aerospace, automotive, construction, and energy, we would best deliver a proactive approach to bolt monitoring not currently in the market.

The main competition for this company would be direct and internal traditional monitoring methods. However, these are reactive processes that can necessitate higher costs of labor and equipment, are unable to meet all the customer’s needs, and can be time-consuming. In contrast, with our company leveraging predictive modeling software, it benefits from minimal labor or additional equipment, can expand to a variety of other bolts and parameters, and immediately generates data for use, thus making it viable in the preventative maintenance market.

The company's pricing structure would be a subscription-tier service that accommodates a range of customers and business sizes starting from $1,000 to $10,000 a month. The market strategy would focus on reaching maintenance managers, safety managers, and engineers, to provide services ensuring safety and increasing productivity while reducing overhead costs. We would initially concentrate on opportunities in the Seattle area with plans to expand throughout Washington and beyond to grow the company. In phases, the company would build brand awareness, secure initial customers by direct and online sales, increase brand visibility through digital or physical advertising and industry publications, and refine the software to address problems and future demands. In addition, we would aim to retain customers by routinely communicating via meetings, email, and in-app messaging.

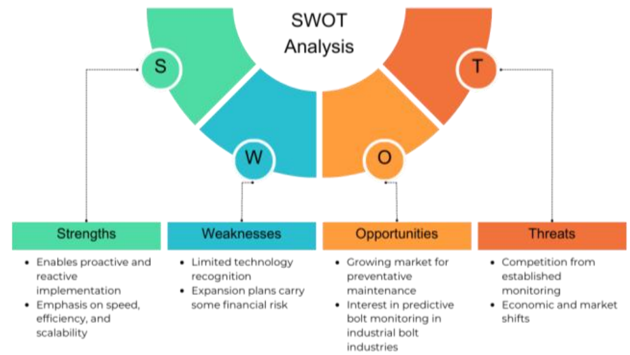

Fig. 5. Strengths, weaknesses, opportunities, and threats (SWOT) analysis conducted for the product.

Broader Impacts and Contemporary Issues

The client, as an aerospace company, stands to benefit from this product for many reasons. Aircraft deal with many issues such as vibration, humidity, and sharp changes in temperature that can all impact the preload behavior of a bolt. Additionally, they are interested in minimizing the weight of an aircraft, as it reduces fuel economy and payload weight. Installing bolt monitoring sensors on an aircraft is cumbersome and opposes best design practices. The most elegant solution is predictive bolt modeling, which can proactively determine bolt preload issues without the installation of additional equipment. Predictive preload data would also be of great use to airline customers who purchase planes, as they could anticipate when a bolt is about to require preventative maintenance. These bolt corrective actions could be accomplished during regularly scheduled FAA inspections, minimizing downtime, and thus increasing profit.

The utility is not limited to the aerospace industry. Any vehicle sector, such as maritime or automotive, has similar interests concerning product reliability and weight reduction; hence, they would reap benefits from this technology for the same reasons. Mathematical modeling of bolt preload could also be used by design engineers for vehicles or buildings to determine optimal fastening solutions for new systems or comparisons between similar fasteners made by different manufacturers. A good example is the BMW recall of N55 inline six-cylinder motors using the VANOS variable valve timing module, which impacted over half a million vehicles. This bolt could come loose or even break in service, causing engine damage if not treated [2]. Predictive modeling would have allowed for a more optimal fastener choice and could have prevented this situation entirely.

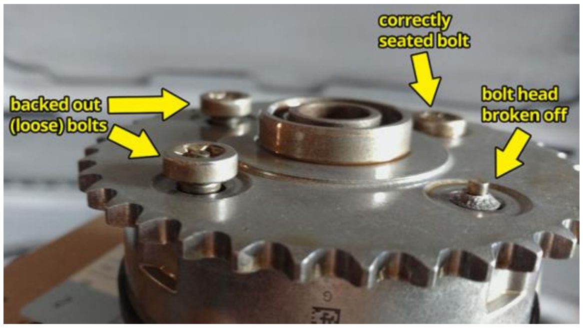

Fig. 6. Loosening or broken bolts common to a BMW VANOS variable valve timing module.

Mathematical models are bi-directional. The same equation that can predict failure can be used in a forensic manner to analyze the failure cause of a bolted joint. If the size, material, time of failure and expected environmental stressors can be determined, then the torque value at the time of installation can be calculated. This would be of particular interest to government agencies such as the Department of Transportation. A good example of this use case would be the failure of the Tacoma Narrows Bridge in 1940, where leveraging this forensic capability could accelerate the investigation process.

Analysis, Modeling, and Simulation

A successful preload decay profile was performed on a .250" AN4 bolt installed with an initial torque of 40 inch pounds. This baseline test was performed at 70 degrees Fahrenheit at a 52% relative humidity using 23.6 Hz , 500 N vibration. This set of conditions acts as the control which the experimental parameters are compared to. The 2nd order differential equation coefficients from this data set were 0.8541, -0.007126, 93.78 and -1.385×10^{-6} for A, B, C and D respectively according to equation 1. The data plot is shown below in figure 7. This equation is the base of the mathematical model, the behavioral impact of variation of environmental or installation parameters will be expressed in terms of modifications to these values. These modifiers will also be in the form as the original equation and act as a multiple, hence the A and C components of parameters will be multiplicative, which the exponential terms B and D will be additive. Equation 3 below clarifies this analysis, where A1 and B1 are initial baseline values, and A2 and B2 are the values of the modifying parameter.

$$A_1 e^{B_1 t} \times A_2 e^{B_2 t} = A_1 A_2 e^{(B_1 + B_2)t} \quad (3)$$

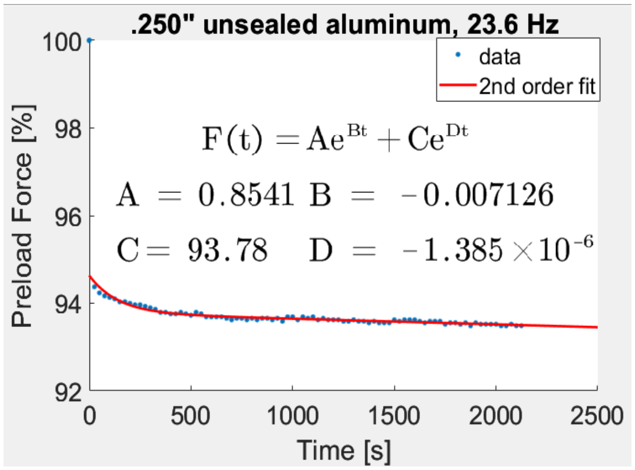

Fig. 7. Preload loss curve for quarter inch bolt, unsealed aluminum structure.

The first parameter of consideration was the application of BMS5-45, class A-2 polysulfide sealant. All other conditions were otherwise identical to the control situation in the above paragraph. The application of this sealant had a large dampening effect on the vibration response of the preload decay model, as shown by the yellow curve of figure 8. The A, B, C and D coefficient modifier values according to equation 3 for properly applied sealant are 0.4658, 0.0510, 1.0612 and -9.1570E-7 respectively, where E indicates multiplication of 10 to the power of the following integer.

The next variation tested was improperly applied sealant. BMS5-45 CL A-2 sealant has an “application life” of 2 hours. This means that sealant application and torque should be performed within 2 hours of mixing the two components of the sealant together. At the request of the client, this application time limit was intentionally violated by assembling the sealed joint 3 hours after mixing. The joint was otherwise assembled identically to the previous sealant test. The resultant vibration response showed quicker preload loss than the unsealed control test, which suggests that improper application of faying sealant compromises the integrity of the joint and is cause for rejection or rework. The A, B, C and D modifiers are 116.4186, 0.0071, -0.0062 and -0.0004 respectively.

The effect of increasing vibration frequency from 23.6 Hz to 29.3 Hz while maintaining the same amplitude of vibration accelerated the preload decay considerably. It should be noted that this non-linear factor is significantly more complicated to model than sealant, so these results should not be considered indicative of vibration variation in general. The A, B, C and D modifiers for this test were 4.9728, -0.0032, 0.9540 and -0.0001 respectively.

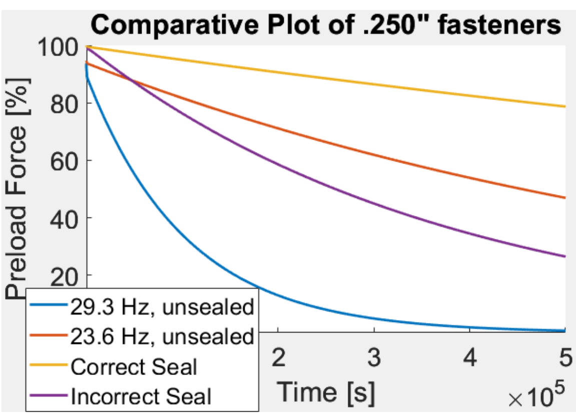

Fig. 8. Comparative plot for sealant application and vibration frequency.

Beta Prototype Development and Validation

The client did not issue a list of deliverable requirements for this project, so the validation procedure is somewhat ad hoc. Additionally, the field of bolted joint vibration analysis is not a matter of settled science - research in the topic is ongoing. The data obtained by the test bed and sensing system was used to form 2nd order differential equation solutions and plot them. The results of our test system were therefore compared to similar tests performed in peer-reviewed academic articles.

Figure 9 below contains experimentally derived data sets from Ying Li *et al* from the Beijing University of Technology [3]. A comparison of the top and bottom data plots shows that increasing the frequency of transverse vibration from 6 to 8 Hz caused the rate of preload decay to increase (both curves are red in the figure). In a similar manner, when we experimentally increased vibration frequency from 23.6 Hz to 29.3 Hz, this also increased the rate of preload decay as indicated above in figure 8.

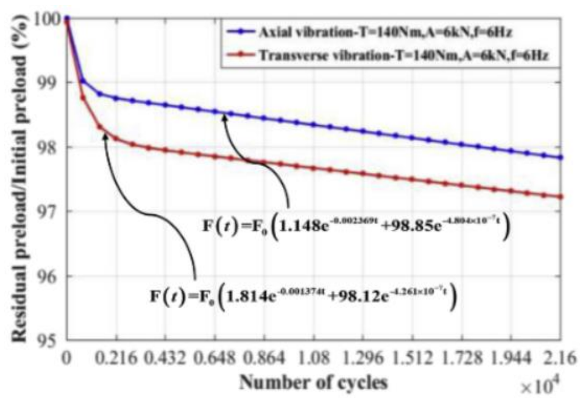

Fig. 9a. Comparative data sets from peer-reviewed research article, 6 Hz vibration.

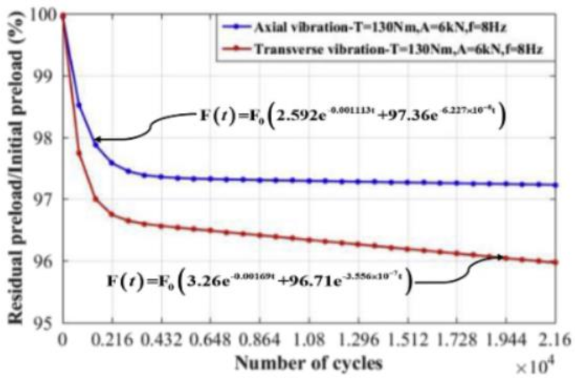

Fig. 9b. Comparative data sets from the same article at 8 Hz.

The general differential equation solution form of all four of our data-fitted curves also agrees with the referenced article. According to the reference data, all A coefficients are much smaller in magnitude than the C coefficients, and both are positive numbers. The exponential coefficients B are larger in magnitude than D, and both are negative numbers. The curve fit equations describing our data set also have these same properties regarding the magnitudes and signs of the four coefficients determined through curve fitting. Consequently, the shape of these plots is also very similar.

Unfortunately, no peer-reviewed vibration analysis has been found for joints containing polysulfide sealants such as BMS5-45 as was used in this project. As such, no comparison can be performed for validation purposes. It is noteworthy that the correctly applied sealant did exhibit better preload retention than the improperly applied sealant did according to the yellow and purple plot lines of figure 8, which agreed with our expectations.

To ensure the integrity of the data collected, temperature and humidity were held constant at 70 degrees Fahrenheit and 52% respectively. The quarter inch fasteners were uniformly torqued to 40 inch-pounds using the same torque wrench, with the torque being applied to the nut instead of the bolt head. For both sealed installations, BMS5-45 sealant was applied to all surfaces required by BAC5000 for a day sealed joint, except for the load cell itself to prevent any interference with measurement. A depiction of appropriate fay sealant application is shown below in figure 10, where both the red and blue lines indicate areas where a bead of faying sealant was used.

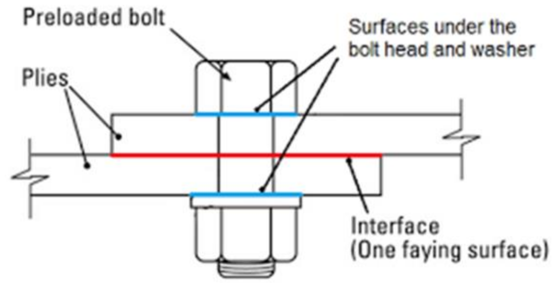

Fig. 10. A bolted joint between two structural members utilizing a faying surface seal.

To ensure the software could implement actual test data, we added a model instance to the software derived from the results of our unsealed, aluminum plate test. This was successful, as the four coefficients did not break the code or require additional refactoring, there was seamless integration. The software's graph was able to display the same curve as MATLAB, and manipulations and predictions were able to be determined with this baseline.

Limitations and Recommendations

The primary limitation placed on this project was related to the budget. With only $3000 available to spend, the range of affordable sensors and mechanical testing tools was very restricted. Therefore, testing was conducted with a relatively weak 50 W DC motor. Similarly, the load cell sensor used to measure joint preload was not optimal, as better options were unavailable due to either a lack of supply or prohibitively high cost.

The 50 W DC motor had a rotation speed of only 0-30 Hz, and the amplitude of the induced vibration was limited to around 500 Newtons by the low power. This low vibration amplitude was insufficient to overcome the static friction force of correctly installed fasteners with diameters greater than 0.250". The construction of a larger and more robust test setup is suggested that could apply up to 6 kN of force to break torque on large fasteners [3]. According to NASA, the F-15B flying test bed encountered vibrations from 0 - 1325 Hz over the entire profile of a flight [4]. The client stated that this project can be extended to military airframes such as the F-15; thus, the most robust test system should include this capability.

The load cell sensor unfortunately caused some mechanical noise when vibration was applied to the test system. The structural member adjacent to the load cell makes uneven contact with the load washer on a microscopic level, causing a noisy mechanical connection. While this noise was only around 3 or 4 discrete voltage levels of variance over the 4096 level, 12-bit range, it was very noticeable for the test of properly applied sealant where the change in preload between the initial value and smallest value measured were quite small.

Our suggestion is to utilize an ultrasonic measurement solution that can directly determine the elongation of the bolt due to the force exerted by the threaded nut. This form of measurement, when properly calibrated, would minimize mechanical noise. Further, use of an ultrasonic probe would allow seal joints to be assembled in full compliance with the BAC5000 specification. In the seal tests we performed, the load cell was not sealed as it would interfere with measurement. BAC5000 fay seals are supposed to include all interfaces of the hardware stack less the nut and bolt. As the ultrasonic probe is externally mounted to the bolt under test, it does not need to be sealed, thus allowing a test seal joint to meet all engineering requirements.

Two vibration frequencies were assessed in this project - 23.6 and 29.3 Hz. Though the relationship from our test data does align with peer-reviewed publications, it is not safe to extrapolate these data sets to other frequency points. Vibration is a non-linear force input; thus, the response can't be expressed in the form of a linear additive or multiplicative scalar. This greatly complicates a mathematical model between vibration variations and bolt preload behavior. Extensive finite element analysis should be accompanied by deep-learning bolstered study of many data sets with varying frequencies.

Conclusions and Future Work

A larger and more robust test fixture needs to be created that can measure a wider range of fasteners. Using this more robust solution, fasteners of larger sizes need to be tested, as well as using different structural materials than aluminum. Though requiring considerably more expense, it may be a good idea to place this test fixture within an environmentally controlled chamber, so that the impact of varying relative humidity and temperature can also be determined.

All vibration tests performed in this project were done using transverse or shear-oriented vibration. To develop a better understanding of how vibration will affect bolt installation, axial or tension-oriented vibration also needs to be assessed. Bolts also will passively lose preload without any vibration due to a gradual settling of the joint materials that were disturbed by the application of torque. A week to month long duration test should be performed on several different size fasteners to figure out how to model this passive loosening effect as well.

Future software work involves further iterative refinement, and integration of untested parameter results. Considering the architecture of the software, this should all be feasible, since refactors would require minimal work to introduce new features, models, controllers, or views as needed. Additionally, the way that parameters are stored in the application can be significantly improved, since they are currently stored as global constants. Encapsulating a parameter as its own object that knows exactly how to modify a second order differential equation would be preferable and reduce coupling.

This project produced a beta prototype that can effectively obtain experimental data and characterize it mathematically, as well as translating the mathematical model though a GUI. The research and experiments contained in this report and the beta prototype provide the client with a functional and effective test bed design that can be scaled up to have greater utility. The client, as well as other industries, can leverage this data collection and analysis process to increase the reliability and safety of their products, leading to greater revenue and customer satisfaction.

Acknowledgement

Team Thor first gives thanks to The Boeing Company for presenting us with this opportunity to learn and participate in exploring a frontier region of mechanical engineering. We appreciate the guidance and encouragement provided by our mentors Nihar Desai and Rajesh Koli that helped us develop a viable vibration test methodology that Boeing will benefit from in the future.

Team Thor would like to thank Dr. Xiaopeng Bi for his insights in developing a mechanical system to effectively translate vibration into a test joint. We additionally thank Dr. Jacob Murray for his invaluable guidance with navigating the hurdles presented during development of the beta prototype and advice offered during design review sessions. Finally, we thank Dr. Beattie for his professionalism and passion for business that allowed our team to find success in the WSU business plan competition.

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Appendices

A. Group Photograph

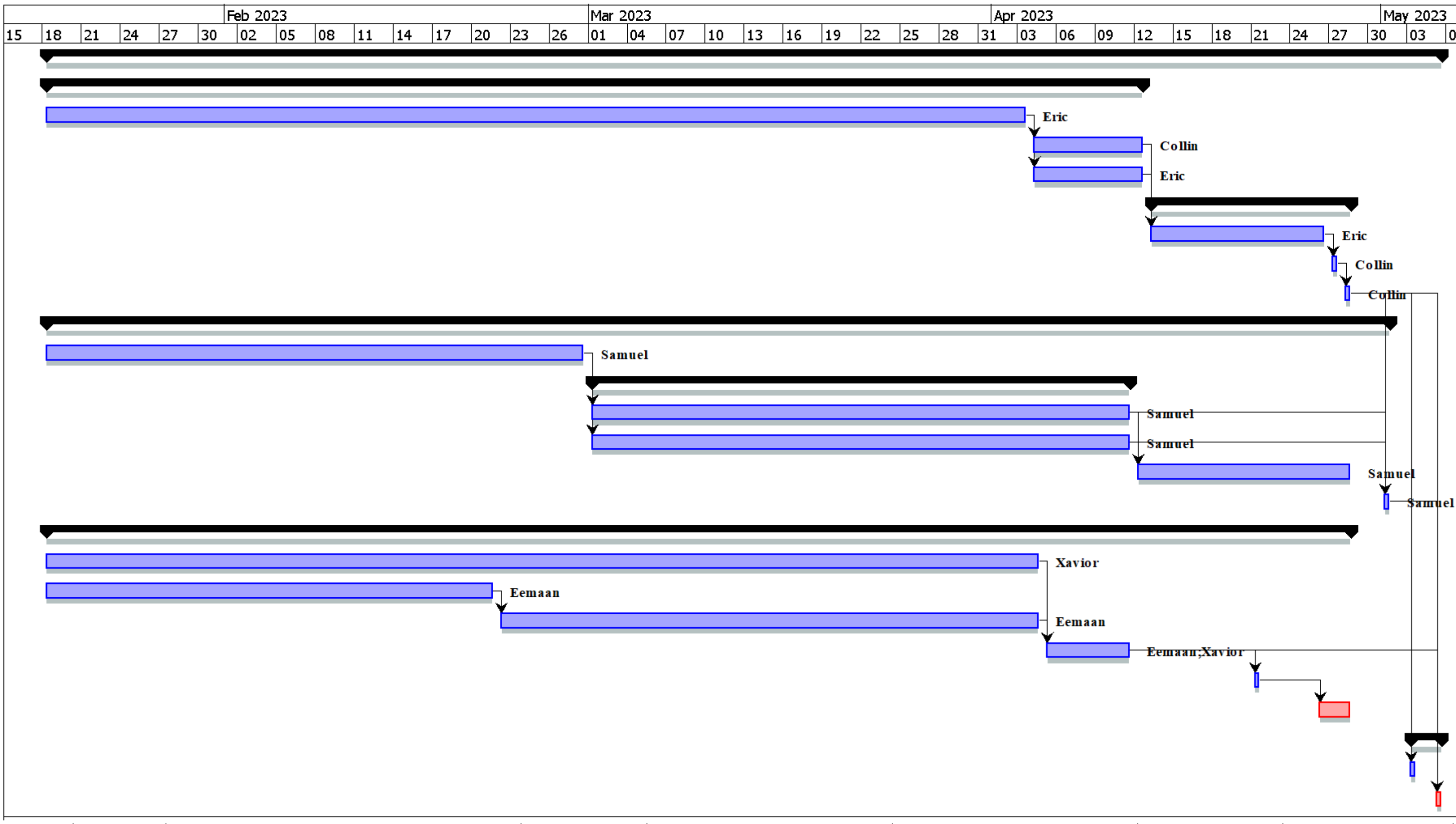
From left to right: Eric Newman, Collin Reynolds, Xavier Crowley, Samuel Gibson, Eemaan Deol

B. Arduino Sampling Code

```
void setup() {
  // put your setup code here, to run once:
  Serial.begin(9600);
  analogReadResolution(12);
  //analogReference(EXTERNAL);
  pinMode(A1, INPUT);
}

void loop() {
  // put your main code here, to run
repeatedly:
  const int PERIOD = 500; // milliseconds
  const int INTERVALS = 250;
  const int WAIT = round(PERIOD /
INTERVALS);

  unsigned int avg = 0;
  for (int i = 1; i <= INTERVALS; i++) {
    avg += analogRead(A1);
    delay(WAIT);
  }
  avg = avg / INTERVALS;
  Serial.print(avg);
  Serial.print(", ");
}
```



	WBS	Name	Duration	Start	Finish	Predecessors	Resource Names
1		**Bolt Preload Project**	**78 days**	**1/18/23 8:00 AM**	**5/5/23 5:00 PM**		
2	**1**	**Testing Preparation**	**61 days**	**1/18/23 8:00 AM**	**4/12/23 5:00 PM**		
3	1.1	Acquire materials and sensor	54 days	1/18/23 8:00 AM	4/3/23 5:00 PM		Eric
4	1.2	Construct mechanical test bed	7 days	4/4/23 8:00 AM	4/12/23 5:00 PM	3	Collin
5	1.3	Configure sensor circuit	7 days	4/4/23 8:00 AM	4/12/23 5:00 PM	3	Eric
6	**2**	**Testing**	**12 days**	**4/13/23 8:00 AM**	**4/28/23 5:00 PM**		
7	2.1	0.250" Fastener Testing	10 days	4/13/23 8:00 AM	4/26/23 5:00 PM	4;5	Eric
8	2.2	Experiment Data Analysis	1 day	4/27/23 8:00 AM	4/27/23 5:00 PM	7	Collin
9	2.3	Create Mathematical model	1 day	4/28/23 8:00 AM	4/28/23 5:00 PM	8	Collin
10	**3**	**Create executable application**	**74 days**	**1/18/23 8:00 AM**	**5/1/23 5:00 PM**		
11	3.1	Create program structure	30 days	1/18/23 8:00 AM	2/28/23 5:00 PM		Samuel
12	**3.2**	**Develop GUI**	**30 days**	**3/1/23 8:00 AM**	**4/11/23 5:00 PM**		
13	3.2.1	Create visual interface	30 days	3/1/23 8:00 AM	4/11/23 5:00 PM	11	Samuel
14	3.2.2	Make placeholder math model	30 days	3/1/23 8:00 AM	4/11/23 5:00 PM	11	Samuel
15	3.3	Commenting and Documentation	13 days	4/12/23 8:00 AM	4/28/23 5:00 PM	13;14	Samuel
16	3.4	Integrate Mathematical Model	1 day	5/1/23 8:00 AM	5/1/23 5:00 PM	9;13;14	Samuel
17	**4**	**Business Model**	**73 days**	**1/18/23 8:00 AM**	**4/28/23 5:00 PM**		
18	4.1	Branding and Marketing	55 days	1/18/23 8:00 AM	4/4/23 5:00 PM		Xavior
19	4.2	Develop Subscription Model	25 days	1/18/23 8:00 AM	2/21/23 5:00 PM		Eemaan
20	4.3	Financial Plan	30 days	2/22/23 8:00 AM	4/4/23 5:00 PM	19	Eemaan
21	4.4	Executive Summary	5 days	4/5/23 8:00 AM	4/11/23 5:00 PM	18;20	Eemaan;Xavior
22	4.5	BPC Presentation Online	1 day	4/21/23 7:00 AM	4/21/23 5:00 PM	21	
23	4.6	Pullman BPC Conference	3 days	4/26/23 8:00 AM	4/28/23 5:00 PM	22	
24	**5**	**Presentations**	**3 days**	**5/3/23 8:00 AM**	**5/5/23 5:00 PM**		
25	5.1	Boeing Presentation	1 day	5/3/23 8:00 AM	5/3/23 5:00 PM	9;16;21	
26	5.2	Final Presentation	1 day	5/5/23 8:00 AM	5/5/23 5:00 PM	9;16;21	