

SIMULATION OF FAULT DETECTION SYSTEM OF AUTOMOTIVE COIL SPRING BY USING ACOUSTIC METHOD

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ABSTRACT – Due to rising client demand and accessibility to financing, local automotive manufacturer must become cost-competitive against well-known imported brand. As a result, manufacturer is facing more challengers in cost-effectiveness, manufacturing time, as well as quality of their production. Each product that reaches consumer are expected to be excellent in quality, and reliability. However, this could be a problem when quality check (QC) inspections are done using batch sampling method. This method only scans several samples due to complexity of structure and hard to detect fault occurred on the sample. Thus, this study is proposed to find a solution using acoustic method fault detection system to enable 100% automated inspection. This study focusses on automotive coil spring for its sample. Previous study has shown that each different sample conditions has its own distinctive vibration pattern when forced vibrated using same frequency of vibration. The study is done using coil spring model on Ansys simulation software platform that then verified against reference experimental data. Next, the model is used to simulate various fault conditions in order to recognize each different distinctive vibration pattern to reduce consumed cost and time to study the pattern trend. Results to this study shown that healthy and faulted coil spring's vibration pattern were distinctive clear and easily recognizable. Thus, it is concluded that it is possible to automate 100 % inspection within manufacturing line.

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INTRODUCTION

Coil springs are a crucial component of many suspension systems and are found on both the front and rear sides of the chassis. Their purpose is to absorb the impact energy the wheels receive when they come into contact with irregular terrain, thereby softening the oscillations transmitted to the car body. Springs usually work in the elastic regime, which implies that they revert to their former shape (FelipeBergha, 2021). Therefore, springs should be made of a resilient material to meet these criteria, and distinct material possibilities include martensitic steel grades. Figure 1 shows that the automotive coil spring can function as an impact absorber. Manouchehrynia et al states that there is a possibility that automotive coil spring could fail prematurely due to random vibrations loading that originated from various road conditions where rural roads increase a higher risk to failure (R.Manouchehrynia, S., 2022).

Fault detection and diagnosis (FDD) methods are used to monitor a system, determine when a defect has occurred, and determine the nature and location of the fault. Corrective procedures can fix a fault and prevent additional harm to the system if it is accurately detected and diagnosed (Justin flett, 2016). Fault detection and diagnosis systems have shown to be extremely useful in mechanical systems, and their use in automotive applications has grown in recent years.

Acoustic Emission (AE) is a non-destructive testing (NDT) technology used in structural engineering to detect damage. NDT is now widely employed, particularly in continuous real-time monitoring systems requiring minimal labour. It could also distinguish between the many forms of damage that can occur in RC beams. Despite these benefits, there are still challenges with employing the AE approach for monitoring applications, particularly when analysing recorded AE data due to the vast amount of data involved. Aside from that, the most challenging aspect of data processing is distinguishing between different AE sources and analysing AE signals to determine the essential harm mechanism. Clustering analysis is a technique that categorises a group of objects into a cluster. This study's three key objectives can be linked to the necessity for good data analysis in the clustering system.

Fault Detection Diagnosis (FDD)

In industry, fault detection and diagnosis (FDD) is critical for avoiding repeated shutdowns and maintenance, environmental and equipment damage, and catastrophic catastrophes (Nima Amini, 2021). The fundamental goal of fault detection diagnosis is to ascertain the defect's type, magnitude, and location, as well as the time it took to detect it, using the system's available metrics. Figure 1 depicts a general model-based fault diagnosis approach. Typically, fault diagnosis is accomplished in two stages. First, a signal known as residual is generated utilizing the system's available input-output

measurements. When the system is fault-free, the residual should be zero or close to zero, but the residual should be different from zero when a problem exists. Residual can be a scalar signal that contains information about a single fault or a vector that contains information about numerous failures. The residual generator might be anything from an analytical mathematical model to a black-box system model. The second stage is the decision-making process, which involves examining residuals for the presence of flaws. The decision-making method can be as simple as a threshold or as complex as many statistical approaches.

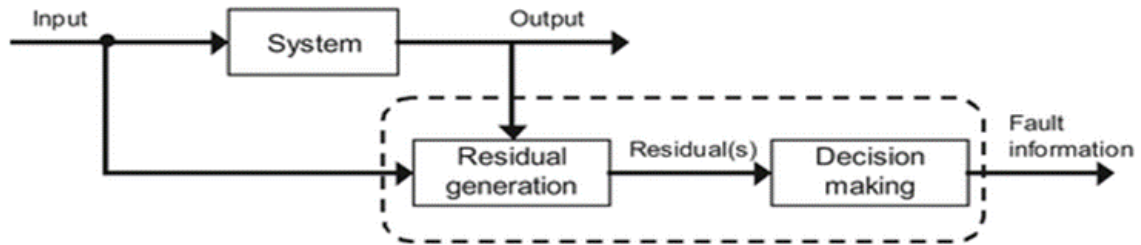


Figure 1. General scheme of model-based fault diagnosis.

There are numbers of study on defect diagnosis in dynamic systems, from analytical methodologies to artificial intelligence and statistical approaches. Some approaches demand accurate system models (plants), quantitative, or qualitative models from a modelling standpoint. However, approaches that do not require any model knowledge depend solely on past system facts. In contrast, there have been several outstanding evaluations on fault diagnosis, which is worth noting that fault diagnosis method classification is frequently inconsistent (Justin Flett, 2016). This is mainly because researchers are frequently focused on a specific area of the vast discipline of fault identification, such as analytical models. This document presents a classification of defect diagnosis methods based on the contributions of many researchers. Figure 2 depicts the classification of fault diagnosis methods. Model-based, hardware-based, and history-based fault detection approaches are the three most common types.

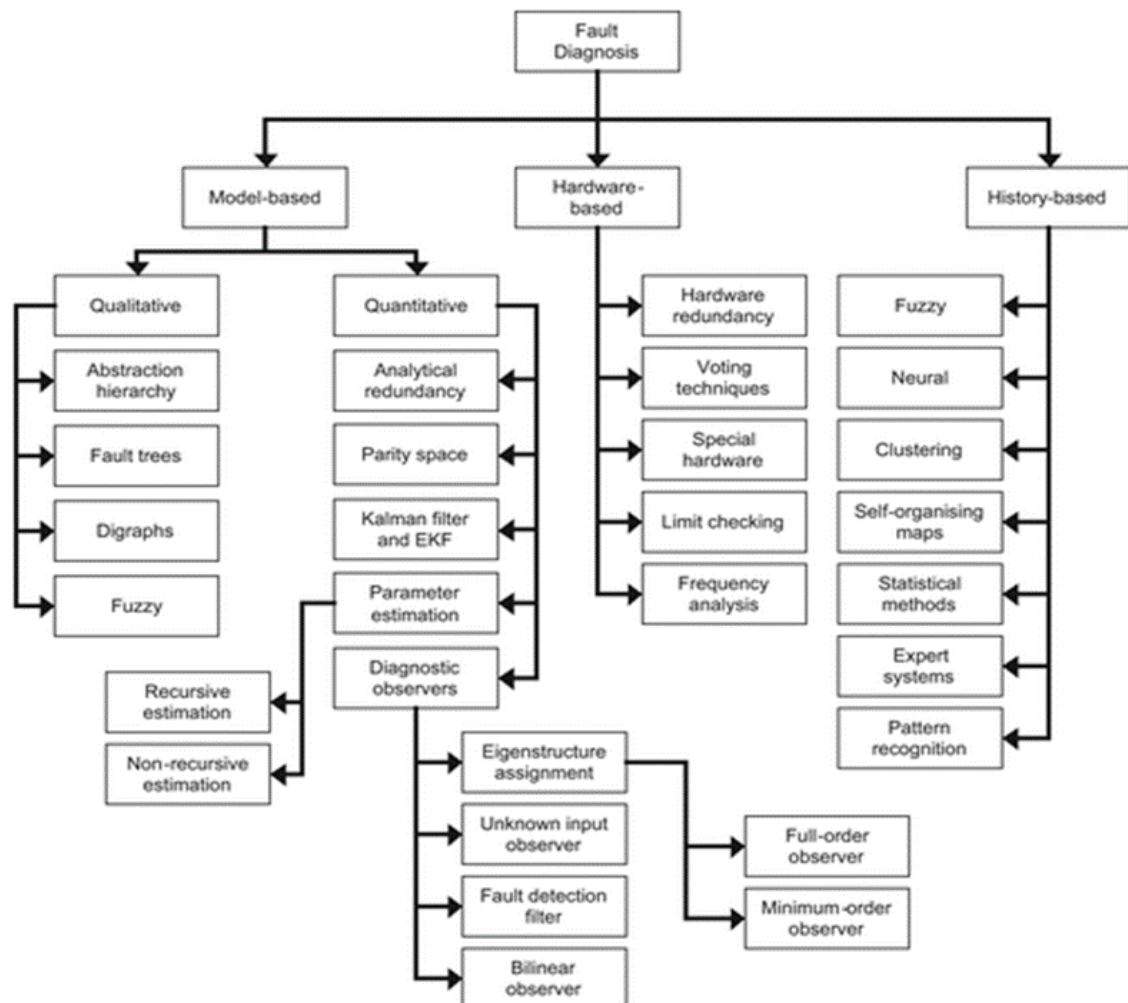


Figure 2. Classification of fault diagnosis methods.

Felipe Bergha states that coil spring is an essential part of a car suspensions system. Its main function is to absorb vibrations and bumps from the road and gives a comfortable ride. In time, they wear and tear even over normal use, elasticity of coil spring deteriorates over time. Thus, it is recommended to replace them for safety and comfort reason. However, in some rare cases, there are faults or defects occurred in the manufactured spring products. As the structure of the spring is complex, the usual way of fault detection for this product is random sampling for each batch of product. This is due to time required to check are significantly larger compared to manufacturing time for each spring. To prevent faulted product sold to consumer, it is very critical that manufacturer able to automate fault detection and include it into manufacturing line. This enables manufacturer to do 100% inspection on entire production. In this study, simulation of the several coil spring conditions were carried out and validated with real data to detect and recognize possible fault pattern. This will help increase possible fault pattern variety recognized within significantly reduced time and cost. Figure 3 shown indentation marks under protective paint which is commonly occurred and recognized as fault in spring manufacturing.

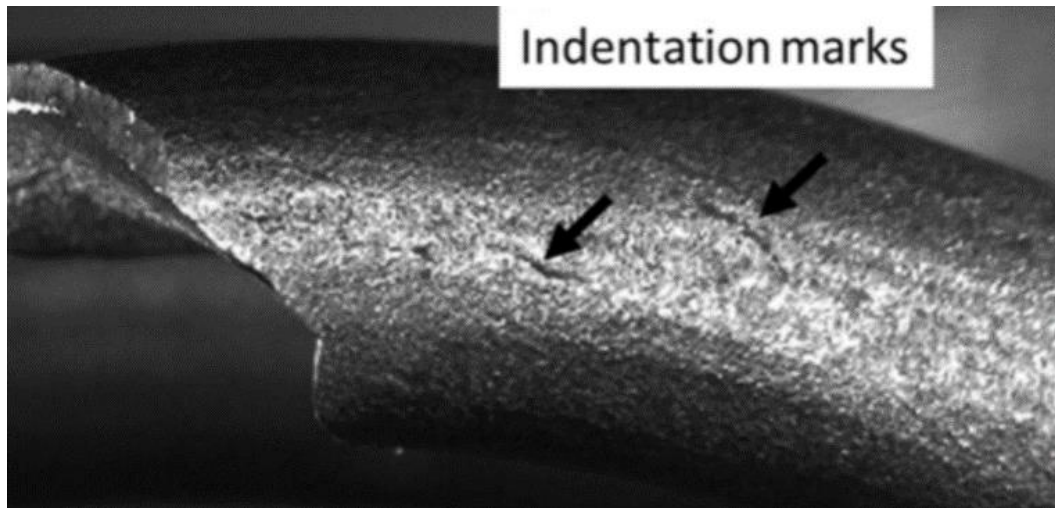


Figure 3. Indentation marks under protective paint.

Acoustic method

Acoustic testing method is non-destructive tests (NDT) which could be conducted on sample without destroying the sample. This is a very low cost and reliable testing method even on complex structures. There are sonic testing, vibration testing, and mechanical impedance testing rely on local effects to produce exciting vibrations in the specimen and then analyze vibration parameters such as resonance frequency and decay time. The most frequent acoustic approach is the current equivalent of a railway wheel tapper, which use a controlled power impact rather than a hammer and a transducer detector rather than an ear. Data analysis and recording can also be done electronically or digitally.

There are various more important uses of acoustic testing for products, the most notable of which is the cast iron casting test, where the resonance frequency of the casting has been demonstrated to be closely related. Complex components have their resonance frequencies, determined by their dimensions and stiffness. Once the frequency of a regularly applied force or a Fourier component of such is equal to or equal to the natural frequency of the structure in which it acts, the phenomenon of enhanced amplitude is known as resonance. When an oscillating force is delivered to a dynamic system at its resonant frequency, the system oscillates with more amplitude than while the same load is applied at a non-resonant frequency. The microstructure, hardness, and presence of flaws all influence stiffness. A modification in any of these dependencies will create a change in the resonance frequency, which can be used to find distinct components from the others. Cracks, voids, delamination, absence of bonding and hardness variations, and exterior dimensions and components with one portion of the manufacturing process missing or poorly completed in coatings, machine grooves and fins present can all be detected using resonance inspection. Furthermore, high-value component fingerprints can be captured, and later exams can compare freshly acquired fingerprints to already recorded fingerprints as a condition monitoring tool. This technique cannot detect or identify specific problems, but it can detect differences between components and reference components. Thus, it is a requirement to have a set of healthy, and various possible faulty pattern for detection and diagnose reference.

METHODOLOGY

Materials and design specifications

Material used for this study is SAE9254 type spring steel. It is made for automotive suspension and is commonly used because it has the properties of high resistance to stress and heat. In addition, heat treatment can increase the tensile strength of this material up to 2018 MPa. The size used for the coil spring for this shock absorber is mid-size, specifically for compact town cars. The chemical composition of SAE9254 is shown in Table 1.

Table 1. Chemical composition of SAE9254 Spring steel (wt%).

Element	wt%
C	0.58
Mn	0.63
P	0.009
S	0.008
Si	1.37
Cr	0.62

Spring detail specification has been set as shown in Table 2. Springs were compressed from their original length of 272 mm to 126.3 mm when fully bound at 8858 N. Then, at 246.9 mm, pull to complete rebound at 1260 N. The spring excitation cycle was repeated 100 times per set, with the frequency remaining constant at 1 Hz throughout the test. These experimental setups were simulated in this study. In order to maintain quality simulation, reference experiment was also conducted. Vertical-type push-pull-based fatigue testing equipment as shown in Figure 4 was utilized to drive spring subjects through compressions and tensions to simulate an automobile's vibration motion on the road. The shock absorber springs must be vibrated appropriately at various compressions and tensions. Simulated results then compared and validated with the experimental reference results (M. Faozi et al, 2022).

Table 2. Spring specification.

Wire diameter (mm)	14.3	±0.06
Mean coil spring (mm)	101.7	±2
Effective no. of coil (turns)	6.3	±0.05
Spring rate (N/mm)	63	NIL
Free height (mm)	275	NIL
Average Hardness (HV)	585~615	NIL

**Figure 4.** Low-Frequency Spring Fatigue Testing Machine.

Simulations design

The design for the coil spring is sketched entirely using Catia V5 software. This software selection is based on the easiness to export to Ansys software to conduct simulation. There are four designs that were conducted. The first design is a healthy coil spring without fault and the other three designs with fault structure. The designs of this coil spring were entirely according to the specifications as in the Table 2. Design of coil spring without failure shows on Figure 5.

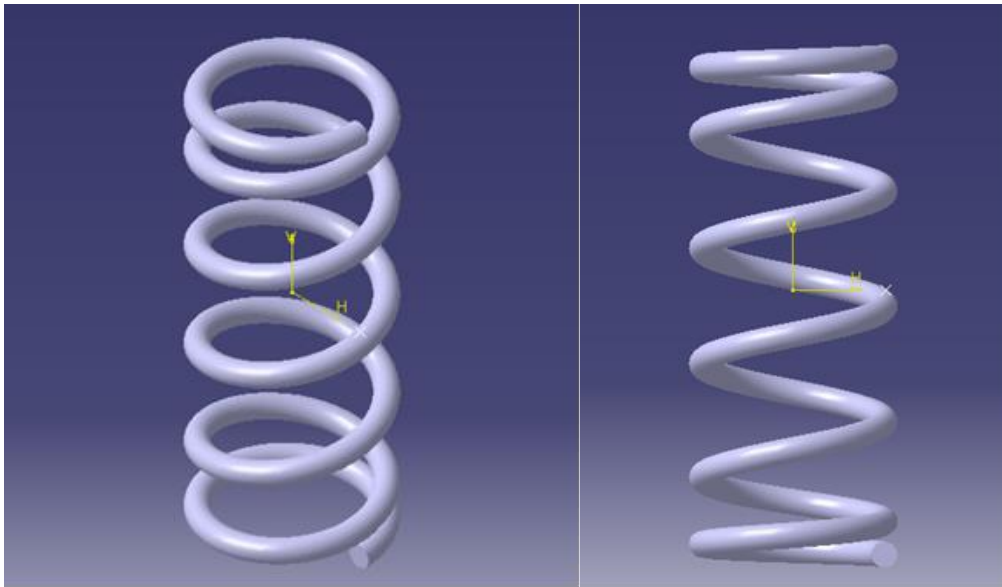


Figure 5. First design of healthy automotive coil spring

The faulted design is shown in the figure below. Figure 6 shown a fault on the coil spring. Figure 7 shown two faults on the coil spring while Figure 8 shown three faults on the coil spring body. All these designs were simulated to obtain acoustic results using harmonic response profile. Using Ansys Mechanical APDL and mechanical workbench to conduct harmonic response analysis on coil spring, we can determine steady-state sinusoidal response to sinusoidal changing loads that act at specific frequency. Phase offset can be use with different load types. Workbench project schematic also contains Modal analysis to characterize the structure. This analysis didn't use modal superposition.

To adapt to robust design, base accelerations should be set to cover a wide frequency range. By fixing a base in Ansys and applying acceleration load to the entire model with the ACEL command can be used to simulate the test. The resulting movement at a place on the FEA model is relative to a fixed, non-moving based and different entirely in comparison. To replicate acceleration movement at a base, acceleration input at a specific geometry were set into the Ansys's Harmonic analysis. Frequency response simulated on coil spring on this study were velocity and acceleration.

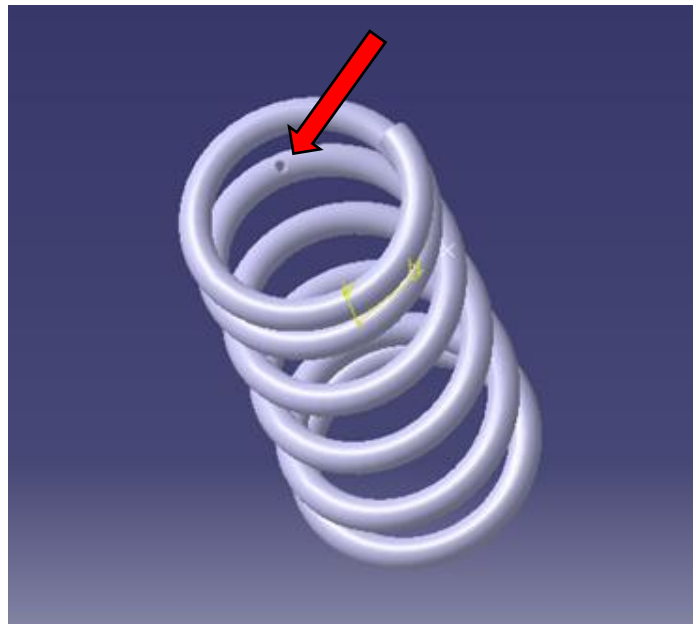


Figure 6. Second design with one fault (crack) automotive coil spring

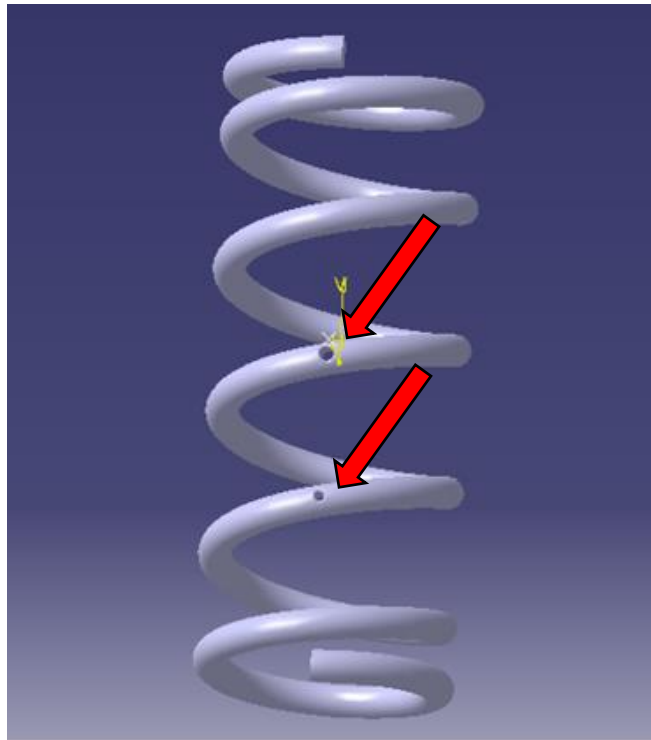


Figure 7. Third design with two faults (crack) automotive coil spring

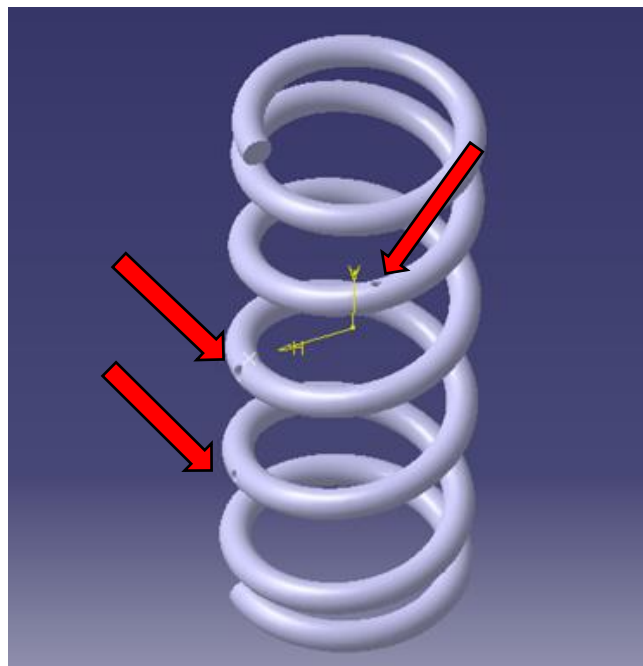


Figure 8. Fourth design with three faults (crack) automotive coil spring

Geometry statistic of the design for nodes counts were 7350, while element counts were 1386. Meshing size were set as program-controlled default with minimum edge length set at 22.46 mm. Fixed support geometry for the coil spring was specified at the three faces on the bottom while force focal point was two faces on the top of the coil spring. Force was set at 8858 N as in reference experiment. Excitation of the simulation was set to sinus harmonic response.

RESULTS AND DISCUSSION

Results were simulated in Ansys 2021 software student version. To gain basic understanding of the simulated coil spring model, analysis on total deformation, equivalent stress and harmonic response were conducted. Harmonic response analysis is a technique for simulating how a structure will respond to dynamic loads that is sinusoidally excited.

Result for total deformation was in a range of 0 mm to a maximum of 111.72 mm as shown in Figure 9(a). Total deformation indicates that the coil spring model was well within elastic region with its maximum total deformation is about half to its free height. On the other, for equivalent stress shown in Figure 9(b), minimum range was 2.995×10^{-5} MPa up to a maximum of 1743.3 MPa. The maximum reachable simulated equivalent stress is still under tensile strength. Also note that inner side that shown in red color of the coil spring are critical region where von-Mises stress distribution was the highest compared to another region. This is also distinctive coil spring character that can be recognized.

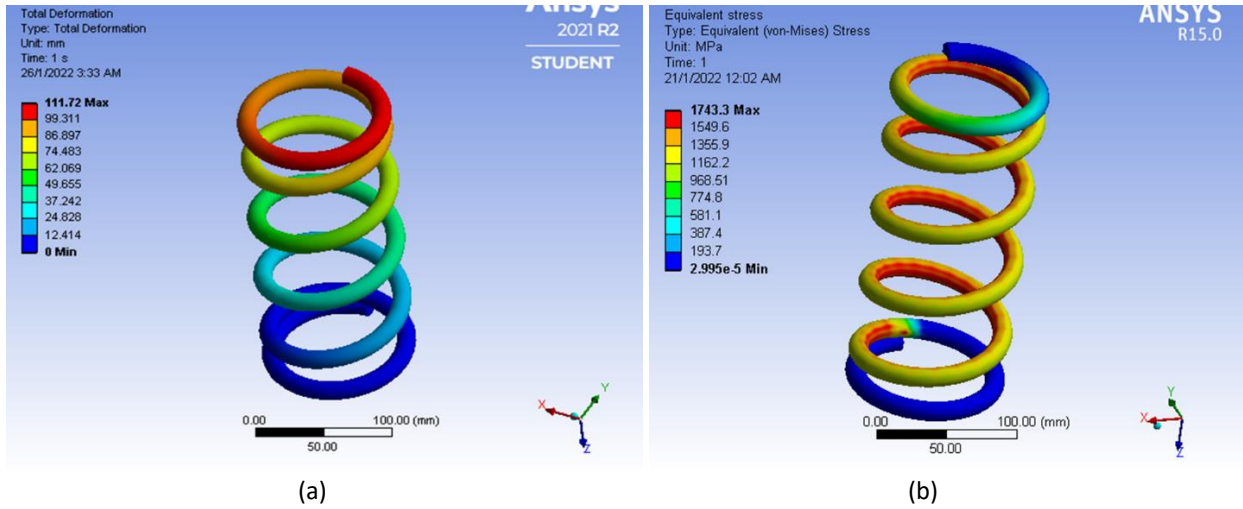


Figure 9. (a) Total deformation, (b) Equivalent stress

Figure 10 shown phase angle-frequency graph for this simulated excitation. This figure shown a similar pattern for all four designs with only slight differences. Its minimum vertical axis was at -90° and maximum at 90° . The sinusoidal cycle starts from 0 to 1 Hz frequency and maintained within the range. When compared the simulated velocity test result to reference result, similar graph pattern can be seen. Thus, validating and verifying that the simulated result is correct.

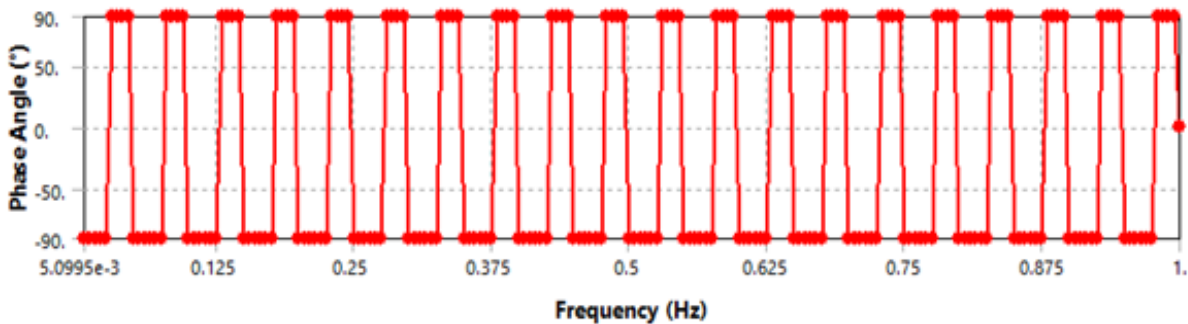
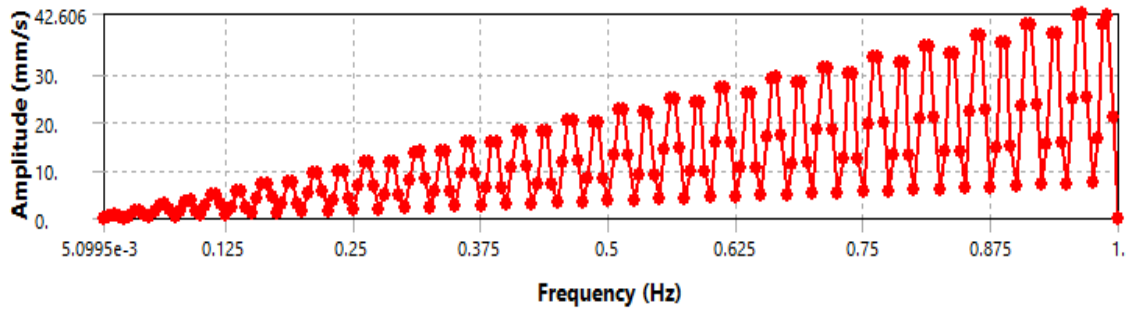


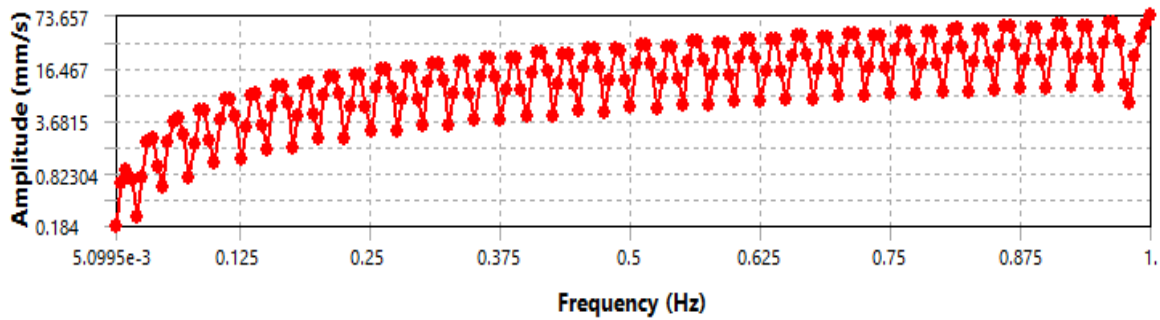
Figure 10. Velocity phase angle-frequency graph of simulation result.

Figure 11 shown the simulated velocity results for all four designs. Amplitude-frequency graph for first design which is the healthy one is shown in Figure 11(a). Figure 11(b) shown graph for second design, (c) shown graph for third design and (d) shown graph for fourth designs. From the figure, we can observe it is increasing in amplitude up to maximum of 42.606 mm/s along the frequency axis. Through (a) to (d), it shown a trend of increment as fault/defect increase in numbers where (b)'s maximum amplitude is 73.657 mm/s, (c)'s maximum amplitude is 64.94 mm/s and (d)'s maximum amplitude is 66.91 mm/s. Second's design amplitude increase significantly compared to (a) and (c) might be due to unbalance force

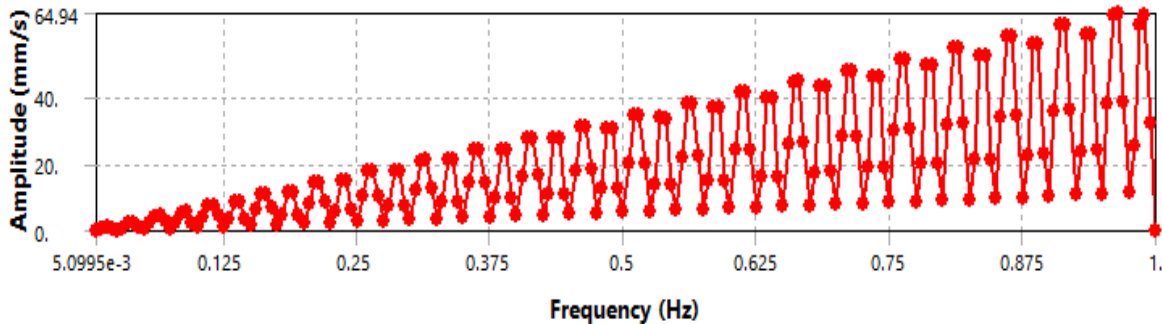
causing extra load to work on the coil spring. The unbalance force showing sigmoidal increment pattern where it is different compared to the other design.



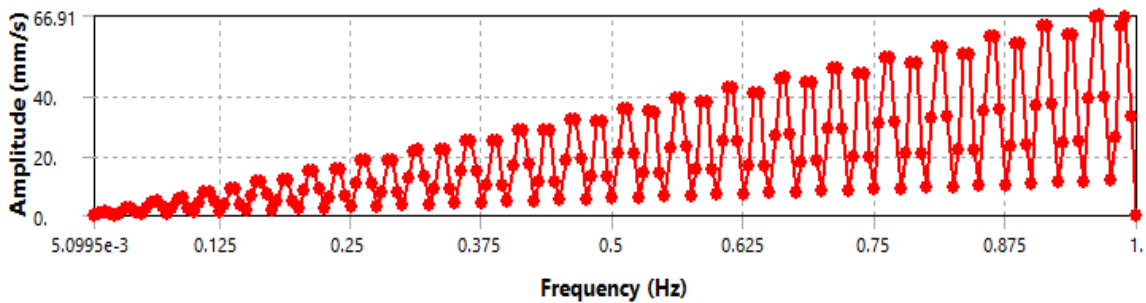
(a) Amplitude-Frequency for first design



(b) Amplitude-Frequency for second design



(c) Amplitude-Frequency for third design

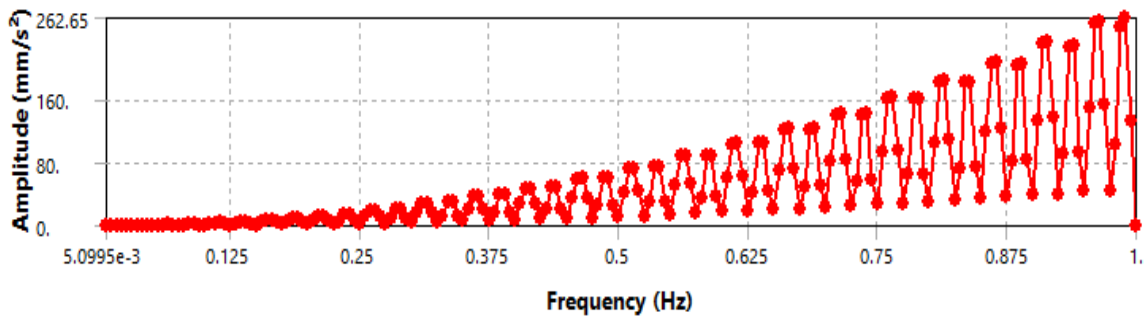


(d) Amplitude-Frequency for fourth design

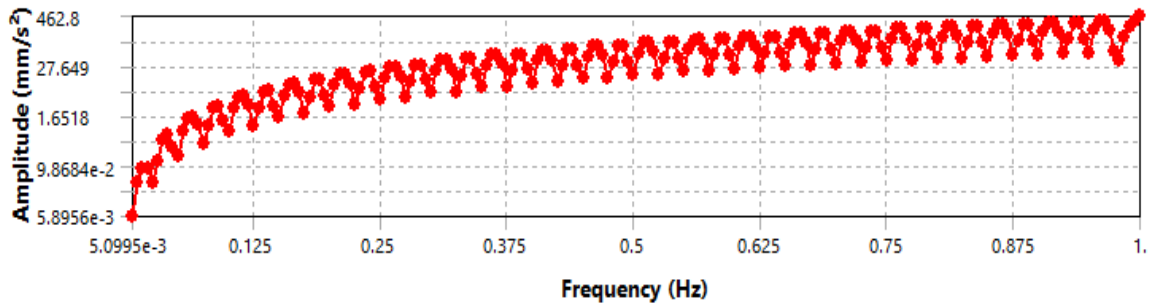
Figure 11. Velocity amplitude-frequency graph of simulation result

Figure 12 shown simulated acceleration amplitude-frequency results for all four designs. Figure 12(a) shown amplitude-frequency graph for healthy first design, (b) is second design with one fault, (c) is third design with two faults and (d) is fourth design with three faults. The maximum amplitude for (a) is 262.65 mm/s², (b) is 462.8 mm/s², (c) is 400.32 mm/s², (d) is 412.46 mm/s². Trend seen in velocity also seen in the graph for acceleration where maximum amplitude increasing as fault numbers in coil spring increase with exception of eccentric increment shown by second

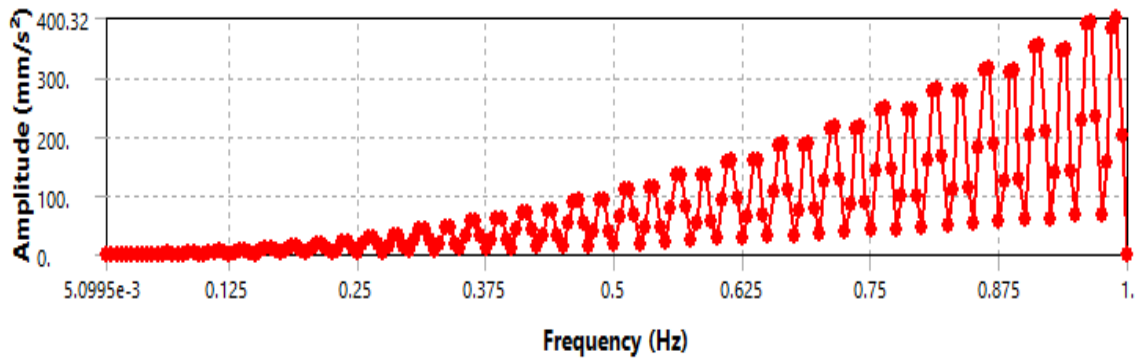
design. It also showing sigmoidal increasing pattern. The increasing trend seen here also can be seen in reference experiment results confirming the results shown are validated.



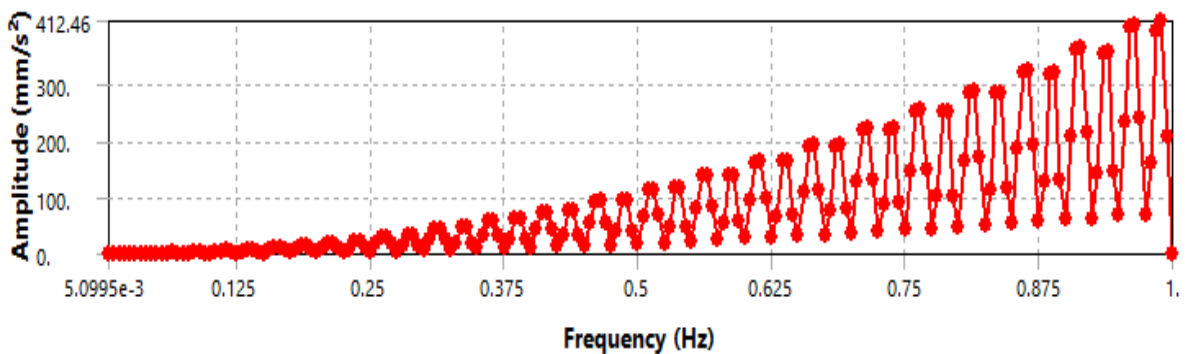
(a) Amplitude-Frequency for first design



(b) Amplitude-Frequency for second design



(c) Amplitude-Frequency for third design



(d) Amplitude-Frequency for fourth design

Figure 12. Acceleration amplitude-frequency graph of simulation result

CONCLUSION

Fault detection proses on automotive coil spring were simulated and verified. Method used for this study is non-destructive test, acoustic method type fault detection and diagnosis to monitor the system, determine when a defect occurred, and determine the nature and location of the fault. Simulation were referred to reference experimental result which was studied previously by the author.

From the graph pattern shown above, we can conclude a rising pattern will result from increasing the level of defect design. As can be observed in the acceleration test on the fourth design, where the flaw yielding the maximum amplitude at 412.46 mm/s² while in the first design which is a healthy sample without defects only shows 262.65 mm/s² at the highest peak. On graphs using different designs with the same parameters, changes in pattern level can be noted. Using the results obtained in this study, we can recognize the differences between healthy to faulty coil spring using automated checking system installed into manufacturing line that match manufacturing rate.

However, line density, noise peak that was observed in reference experiment could not be replicate in the simulation. More complex parameter have to be consider into the simulation in order to obtain more accurate approximation.

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