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Design and Development of Fiber Reinforced Composite Propeller Shaft

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ABSTRACT

Composite material is a breakthrough in engineering especially in automotive application. Automotive parts which being produced by this material always performs better compare to conventional material. D.G. Lee et al. (2004) states that, drive shaft being produced by composite material offers up to 75% of weight reduction which will contribute to fuel efficiency, 160% increase in torque capability, and higher natural frequency which is about 9390 rpm for wider safety margin. The main constraint for using composite is the higher price of material especially the fiber. The main idea for this study is to replace the carbon fiber with much cheaper material, palm oil fiber. This new composite will later on being put into test using machine fault simulator at four different speeds and its dynamic characteristic will be recorded. The data obtained will be analyzed using skewness, kurtosis, peak to peak, crest factor and root mean square (RMS). From experimental results, we can see that lower RMS value is obtained for composite drive shaft compare to steel drive shaft with same diameter. Thus, it shows that the composite material is a suitable candidate to substitute the usage of steel as material for drive shaft for automotive application in term of vibration study.

KEYWORDS: Composite Materials, Dynamic Characteristics, Carbon Fiber, Vibration Study, Adhesion

1. INTRODUCTION

A. Propeller Shaft

A drive shaft as mention in Wikipedia (28 June 2011) is a mechanical component for transmitting torque and rotation, usually used to connect other components of a drive train that cannot be connected directly because of distance or the need to allow for relative movement between them.

Common material in manufacturing the drive shaft is steel. Steel was chosen because of low in cost and the ability to withstand the stress when subjected to torsion and shear stress. But, steel has low specific stiffness which causes the bending natural frequency to be low. As a result, drive shaft needs to be produced in two pieces when the length exceeds 1.5 m to avoid the whirling vibration at high speed, D.G. Lee et al. (2004). These will not only causing the increase in part complexity but also increased in weight which cause the drop of fuel efficiency.

Automotive industry has evolved and the focus now is the new material which can provide better performance with reasonable cost. The first composite drive shaft was developed by the spicer U-joint Division of Dana Corporation for the Ford Econoline models in 1985. Lee mention in his paper that general motor pickup truck which adopted the Spicer product enjoyed a demand three times that of projected sales in its first year (1988). High performance vehicle such as Mazda RX 8 used composite drive shaft to reduce the rotational mass (Wikipedia, 28 June 2011).

Most popular composite drive shaft in research and development nowadays is aluminium as matrix together with carbon and glass fiber as reinforcement. This composite if manufactured correctly with right stacking sequence and orientation will produced, as mention by Lee, mass reduction, increase in torque capacity, higher natural frequency and better fatigue properties.

B. Problem Statement

Most of the drive shaft produced nowadays used steel as material. According to F. Schmelz, et al (1992) when a length of a steel drive shaft is around 1.5m, it is usually manufactured in two pieces to increase the fundamental bending natural frequency. This will lead to part complexity and decrease the fuel efficiency due to increase in weight. Other than that, Schmelz also mentioned that due to low specific stiffness of steel (E/ρ), the natural bending frequencies will be lower than 5700 rpm (for one piece drive shaft). Specific stiffness of glass fiber is 1.5 times higher than the steel made it possible to manufacture the one piece drive shaft with higher natural bending frequency (more than 5700 rpm). As a result, drive shaft not only can rotate at higher speed without whirling vibration but most importantly reduce in weight which leads to fuel efficiency.

C. Objectives

1. Fabricate a hybrid composite material drive shaft for automotive application.
2. Test, analyze and compare the dynamic characteristic of composite drive shaft using spectrum analyzer.

D. Scope of Study

This study includes the study of vibration, composite materials, drive shafts and fiber. It also involve in manufacturing and testing the dynamic characteristic of the drive shaft.

2. METHODOLOGY

E. Research Methodology

For the completion of project, the work done will generally distributed into three phases which are:

1. Research and understanding of drive shaft and composite material.
2. Material preparation and fabrication of composite drive shaft.
3. Testing and analysis

1) Research and understanding of drive shaft and composite material

Early stage of project started with the research and analysis of composite material and drive shaft. Various journal and research paper related with this subject was read and analyzed. Weekly meeting with final year project (FYP) supervisor, Ir. Idris bin Ibrahim was conducted to gain new idea and ensure the project is on schedule. Engagement session with fiber expert, Mr Azuan b Maoinser, post graduate student, Miss Raja Fauziah and Mr. Tamiru was conducted to obtain opinion and latest information regarding fiber and vibration analysis.

2) Material preparation and fabrication of composite drive shaft

Fabrication process started with material preparation. Aluminium cylinder was purchased at TSA industries Sdn. Bhd at Chandan Raya industrial area, Kledang. The aluminum has the diameter of 5/8" and length of 22". The reason of this size to ensure the drive shaft can fit into spectrum analyzer for analyzing purposes.

The fabrication process followed by the fiber preparation process. Empty fruit bunch was obtained from IOI palm oil plantation near Segamat, Johor. The empty fruit bunch is later on being shred using granulator at block 17, UTP. Fiber obtained from granulation process, being treated with hot water (approximately 90oC) for 1 hour. The reason for this process is to remove grease and impurities for better bonding of the fiber. After it cool down to room temperature, fiber is treated with NaOH solution for 24 hours. This is to improve the mechanical characteristic of fiber and to ensure better interfacial bonding of fiber. After it is treated with NaOH solution, it rinse with tap water. Sample being subjected to oven dry at 70oC for 24 hours.

In order to impregnate palm oil fiber with aluminum shaft, epoxy-hardener mixture was made. Epoxy hardener with ratio to 1:2 was chose and mix using mixer until the color of the mixture is equal. Fiber was added in the mixer to ensure the fiber is completely wetted.

A wrapper made of green net was prepared to fold the aluminum with fiber. The main purpose of using wrapper is to ensure palm oil fiber maintain its position around the aluminum shaft when the epoxy-hardener is still wet. The wrapper is taken off after 48 hours to help the composite drive shaft dry faster.

3) Testing and analysis

Composite drive shaft later on being tested using spectrum analyzer. It is subjected to a different speed. The dynamic characteristic of the composite drive shaft is recorded and compared with steel drive shaft having the same and smaller diameter.

a) Project Scheduling

The following Gantt chart is the list of activities for FYP 1 and FYP 2.

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Research on drive shaft		■	■	■	■									
Research on composite material		■	■	■	■									
Extended Proposal submission						■								
Proposal Defence								■						
Research continues							■	■	■	■	■	■	■	■
Fiber preparation							■	■	■	■	■	■	■	■
Interim Report submission													■	

Figure 1 Tabulation of work and dateline proposed in FYP1 semester.

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Lab booking	■	■												
Fabrication			■	■	■	■	■							
Progress Report submission								■						
Pre-EDX											■			
Dissertation writing									■	■	■			
Draft Report Submission												■		
Dissertation Submission (Soft bound)													■	
Technical Paper Submission													■	
Oral Presentation														■
Dissertation Submission														■

Figure 2 Tabulation of work and dateline proposed in FYP2 semester.

Fabrication process of drive shaft in this study is a little different from other paper. Most of research paper use filament winding process to reinforce the aluminum shaft, but, in this paper different approach was used. Much cheaper material with simple fabrication procedure was introduced.

b) Project Flow

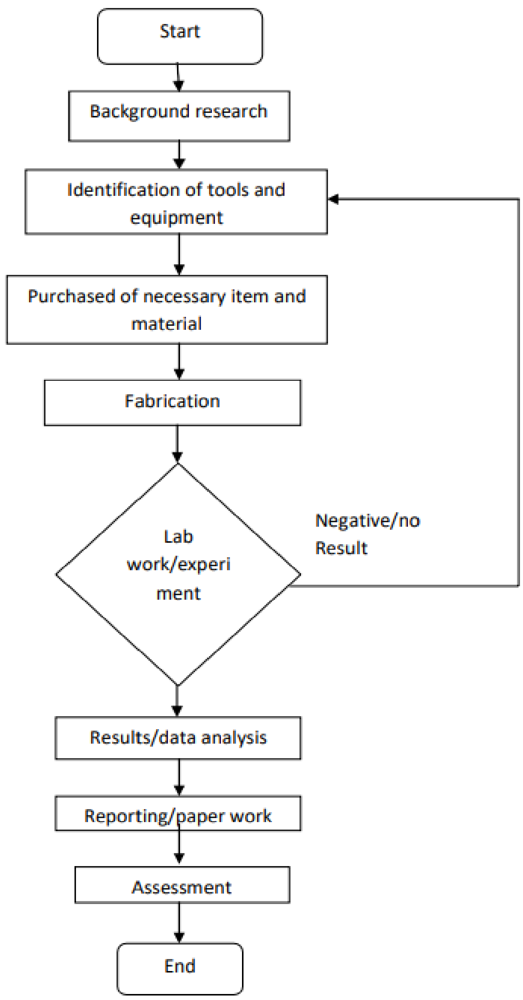

Figure 3 Project Flow

3. TOOLS AND MATERIALS

A.Machine Fault Simulator

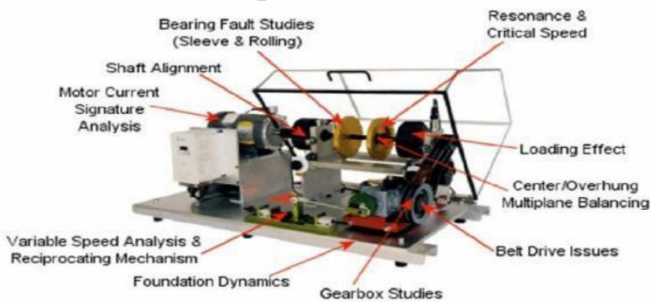

Figure 4 Machine Fault Simulator

To record and analyze the dynamic characteristic of drive shaft when subjected at different speeds. The maximum speed of machine fault simulator can be up to 3600 RPM. Can analyze the vibration of shaft with specific diameter of 3/8", 5/8" and 1". Equipped with software, VibraQuest pro that enabled the data to be converted into excel for further analysis.

B. Mixer

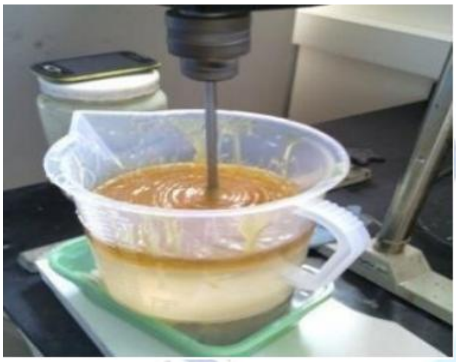

Figure 5 Mixer

To properly mix the epoxy and hardener for better bonding between natural fiber and aluminum shaft.

C. Granulator

Figure 6 Granulator

Granulator is a machine to grinding or shedding material into small pieces. In this study, granulator was used to shred the empty fruit bunches into small pieces ranging from 5mm to 20 mm. Empty fruit bunches need to be grind to ease the treatment process and most importantly to make it possible to wrap it around aluminum shaft.

D. Oven

Figure 7 Oven

Oven is a machine to remove moisture from any sorts of material. The temperature of this oven can be ranging up to 500oC and can operate for weeks or month, depends on the requirement and specifications. Oven is important to speed up the moisture removal process. It can also reach the dryness of material that cannot be achieved with normal 22 drying process. Removal of moisture content is important in order to have pure natural fiber and better mechanical characteristic.

4. MATERIALS

E. Empty Fruit Bunch

Figure 8 Empty Fruit Bunch

Empty fruit bunches is first granulated using granulator before treated with hot water to remove impurities. It is then treated with sodium hydroxide to improve the mechanical characteristic and separate it with one another.

F. Epoxy and hardener

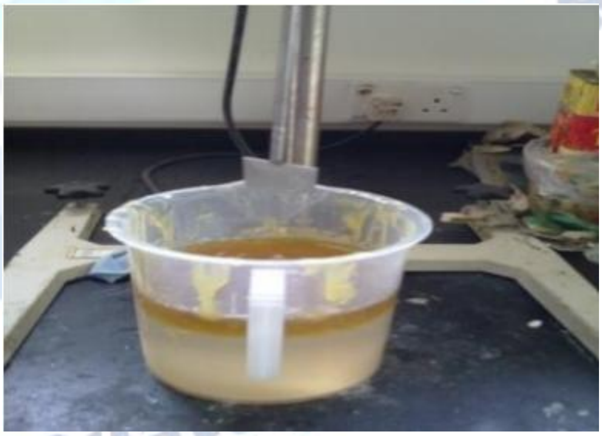

Figure 9 Epoxy and hardener

Epoxy and hardener with specific ratio was obtained and stirred using mixer. The mixture is stirred for approximately 30 minutes to ensure that it is well blend.

G. Sodium Hydroxide (NaOH)

Figure 10 Sodium Hydroxide (NaOH)

Sodium hydroxide in the crystal form like in figure 10 will be transformed into aqueous form to treat the natural fiber for better mechanical characteristic.

H. Aluminum rod

Figure 11 Aluminum rod

Aluminum rod was chosen as the shaft due to light weight. The diameter of aluminum shaft is 5/8" and it is 22" long. This drive shaft will later being reinforce by natural fiber to transform it to composite material with better mechanical characteristic.

5. RESULTS AND DISCUSSION

A. Vibration Study

One of the keys component in this research is the vibration study. A fabricated drive shaft with the aluminum diameter of 5/8" was tested using machine fault simulator. The function of machine fault simulator is to record the vibration characteristic of the material. Drive shaft was subjected at 4 different speeds (500 rpm, 1000 rpm, 1500 rpm and 2000 rpm). Result of vibration characteristic then compared with steel drive shaft with same diameter, 5/8", and smaller diameter, 3/8". A few methods was used to compare and analysis the results, namely, RMS (root mean square), peak to peak, Kurtosis, skewness and crest factor.

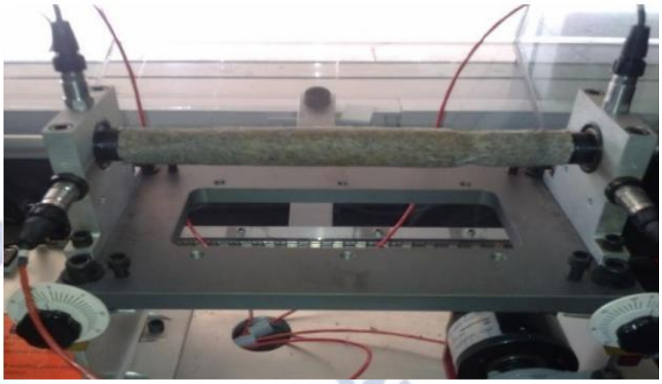

Figure 12 Composite drive shaft fitted at machine fault simulator.

The results obtained from the experiment is in form of time wave form. The graph obtained is amplitude versus time. In order for the result to be analyzed, it is exported in excel form (from graphical to numerical data). After being analyzed using 5 methods mention above, it is then plotted using graph. The data analyzed is the one obtained from the accelerometer closest to the source of rotation, motor. Reason for it is because, it yield the most vibration across the drive shaft. Data obtained from different accelerometer across the drive shaft also being analyzed.

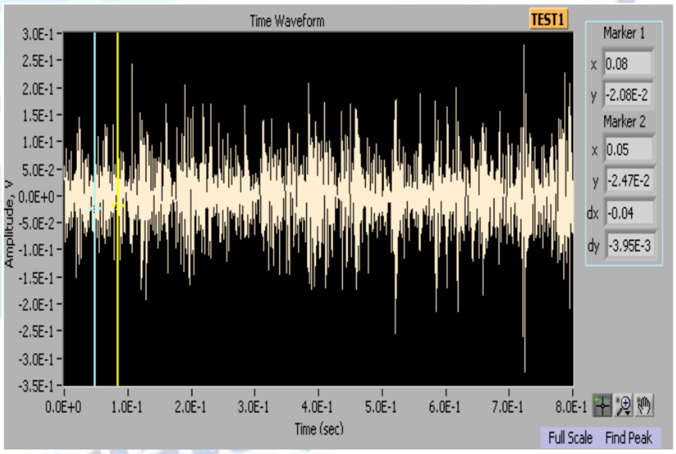

Figure 13 Example of raw data obtained using VibraQuest Pro.

B. RMS (Root mean square)

In mathematics, root mean square (abbreviated RMS or rms), also known as the quadratic mean, is a statistical measure of the magnitude of a varying quantity. It is specially useful when varieties are positive and negative. It can be calculated for a series of discretevalue or for a continuously varying function. The name comes from the fact that it is the square root of the mean of the summation of square values. Formula for rms is stated below.

$$X_{rms} = \left(\left(\frac{1}{N}\right)\sum x_1^2\right)^{\frac{1}{2}}$$

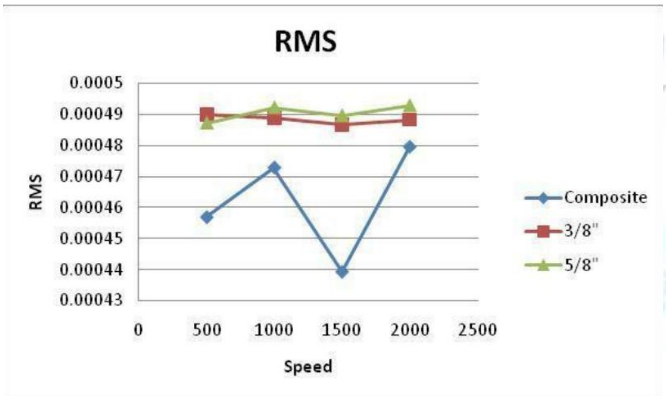

Figure 14 RMS versus speed

As we can see from the graph above, the magnitude of amplitude at accelerometer located nearest to the source of rotation is smaller at all speed compare with steel drive shaft with same and smaller diameter, 3/8" and 5/8". This clearly shows that composite drive shaft yield least vibration compare to conventional drive shaft.

C. Peak to Peak

Peak to peak analysis was used as an indication of the amount of lateral movement of the machine. It is also used to see whether unbalance in mass occurred in the system. Theadvantage of this technique is that it only require information about one input and one output. Consequently, it represents the most widely applicable and least demanding of data in all mathematical methods for estimating capacity and capacity utilization (Kirkley and Squires 1999). Peak to peak analysis has been applied in many situation like fisheries by Ballard and Roberts (1977), Ballard and Blomo (1978), and Hsu (2003). Further information of the technique, including the mathematical specification of the approach, also provided in Kirley and Squires (1999). The formula for peak to peak analysis is given below

Formula: max X – min X

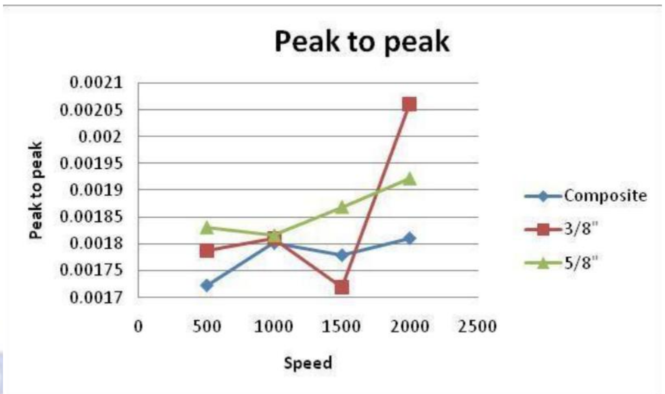

Figure 15 Peak to peak versus speed.

As we can see from figure 15, the amplitude for composite is lowest at almost all speed except at 1500 rpm. The significant difference can be seen at the 2000 RPM where composite has the amplitude difference at 0.00181, instead 5/8" and 3/8" drive shaft have the value of 0.00206 and 0.00192 respectively. This is 13.81 and 6.08 percent more compare to composite drive shaft.

D. Skewness

Skewness is a measure of asymmetry of normal distribution statistical method. For a very good condition of machine, the skewness is zero and any symmetric data should have skewness near zero. Negative values for the skewness indicate data that are skewed left and positive values for the skewness indicate data that are skewed right.

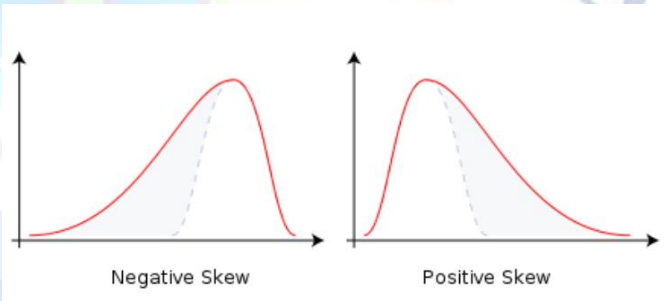

Figure 16 Graphical explanation of skewness.

Negative skew is the one where the tail is longer, which mean the mass of the distribution is concentrated on the right of the figure. It has relatively few low values. The distribution is said to be left skewed or skewed to the left.

Positive skew in the other hand, has longer right tail. In other word the mass of distribution is concentrated on the left of the figure. It has relatively few high values. The distribution is said to be right skewed or skewed to the right.

On the other hand, if the distribution is symmetric, which often is not the case due to many factors, the mean= median and the skewness will be zero. In this case, graph value 28 which closer to zero will be consider have better distribution. Formula for skewness is given below:

$$g = E\frac{(s-\mu)^3}{\sigma^3}$$

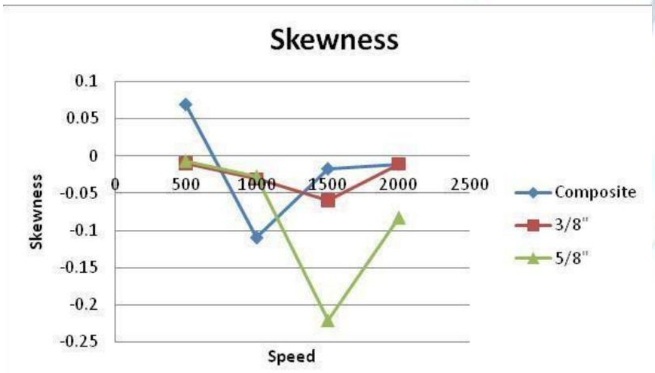

Figure 17 Skewness versus speed.

From the graph above, we can say that drive shaft with diameter 3/8″ has better normal distribution followed by composite and 5/8″ drive shaft. From above graph, we can say that, at low speed, all 3 drive shaft has positive value. This means that, it has few high values (peak) at low speed. As speed increased, the value of skewness dropped and become negative which shows that increased in number of high value frequency. At the maximum speed, composite drive shaft and 3/8″ shaft has positive value compare to 5/8″ which has negative value.

E. Kurtosis

Kurtosis is any measure of the "peakness" of the normal distribution. In a similar way to the concept of skewness, kurtosis is a descriptor of the shape of a probability distribution. It can be used to measure how the signal is distorted due to faults or machine deterioration.

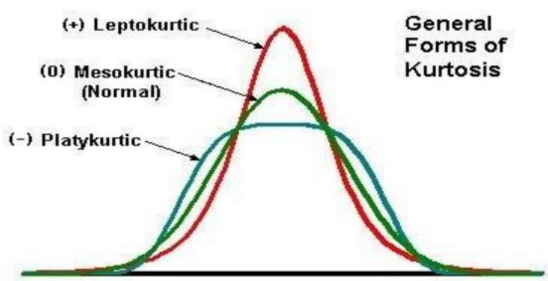

Figure 18 Kurtosis

Mesokurtic distribution is a terminology used when the distribution is normal. It can be achieved when the value of Kurtosis is zero. Positive excess kurtosis is called "leptokurtic" or mean slender. In term of shape, a leptokurtic distribution has a more acute peak around the mean and fatter tail. On the other hand, negative kurtosis is called platykurtic, which means broad. In term of shape, a platykurtic distribution has a lower, wider peak around the mean and has thinner tails. The formula for kurtosis is given below.

$$Kurtosis = E\frac{(s-\mu)}{\sigma^2}$$

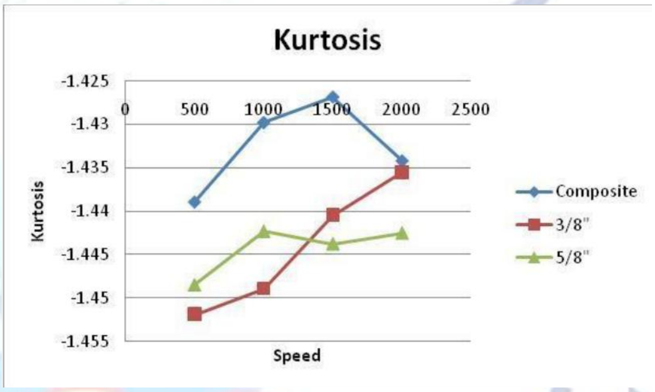

Figure 19 Kurtosis versus speed

From the graph above, we can see that all value obtained is negative for all shaft, including composite and steel. This mean, all the shaft follow the platykurtic distribution. But composite drive shaft has the value closer to zero at all 4 different speed compare to 3/8″ and 5/8″ steel drive shaft.

F. Crest factor

Crest factor or also known as peak-to-peak average ratio (PAR) is a measurement of a waveform, calculated from the peak amplitude of the waveform divided by the RMS value of the waveform. It is therefore a dimensionless quantity. The main function of this measurement is to get an idea of the quality of the signal. It is also to give an idea of how much impacting occurred in waveform. Signal with more peaks will have higher crest factor. The formula for crest factor is given below:

$$Crest\ Factor = \frac{max(|X|)}{X_{rms}}$$

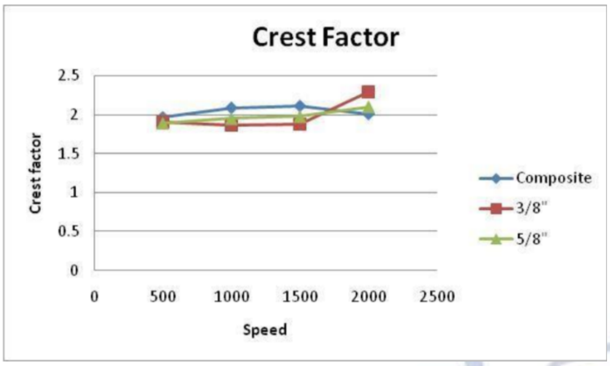

Figure 20 Crest factor versus speed

As we can from graph above, the crest factor is almost flat at all speed for all type of drive shaft. The value of crest factor for all drive shaft also is about the same. This shows that all the value obtained for all type of drive shaft is good.

G. Vibration study along the drive shaft.

For above analysis, the value obtained is from the accelerometer located nearest to the source of rotation, motor. For this segment, the study for vibration value at both ends will be conducted. RMS has been chosen as a method to analyze the time wave form of drive shaft. RMS is found to be more accurate in order to find the quadratic mean of time waveform that has both negative and positive value.

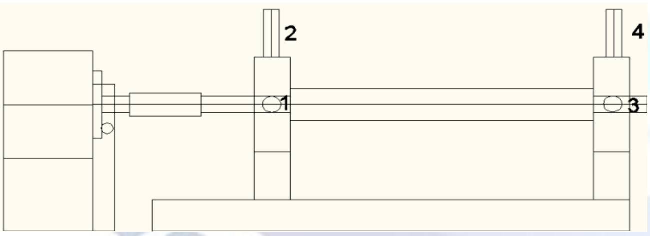

Figure 21 Location of accelerometer at machine fault stimulator.

As we can see from figure 21, there are 4 accelerometers at machine fault stimulator. Two accelerometers at each end with one of it read the horizontal acceleration and the other one read vertical acceleration.

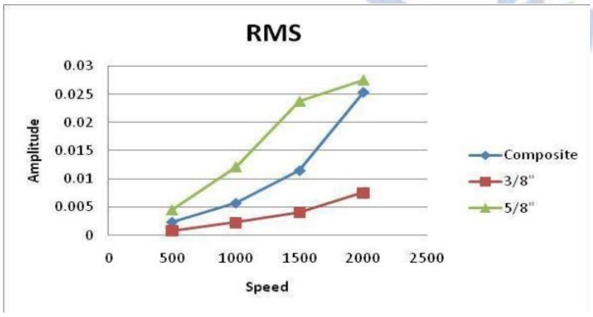

Figure 22 RMS value versus speed at accelerometer 1.

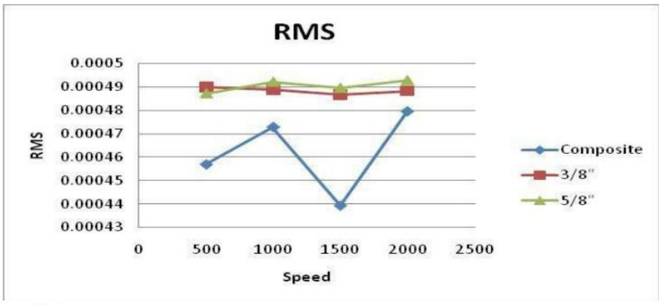

Figure 23 RMS versus speed at accelerometer 2.

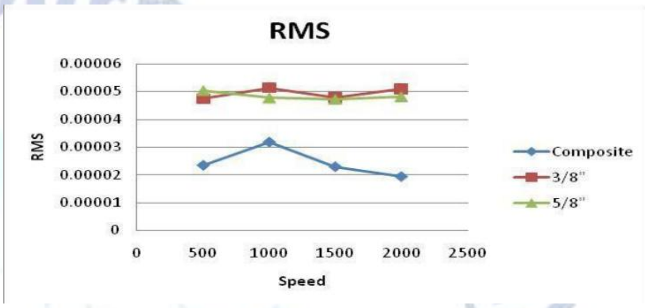

Figure 24 RMS versus speed at accelerometer 3.

From all 3 graphs above, we can concluded that, higher vibration occur at nearest source of rotation in horizontal direction. Both accelerometers at point 1 and 4 that reads the acceleration in horizontal direction has much lower value compare to accelerometer that reads the horizontal value. The acceleration for point 3 in other hand cannot be obtained due to system faulty.

From the graph above, we can also concluded that composite drive shaft has lower vibration compare to steel drive shaft except at point 1 where the RMS value for composite drive shaft is lower compare to steel shaft that have same diameter, 5/8", but higher compare to drive shaft with smaller diameter, 3/8".

H. Mass reduction.

One of the key points of fabricating composite drive shaft other than having higher natural bending frequency is significant mass reduction. For composite drive shaft, the mass of drive shaft is contributed by the mass of aluminum and fiber. Total mass of composite drive shaft is 0.525 kg. For conventional drive shaft made of steel with same diameter is weighing.

Item	Weight (kg)
Composite drive shaft	0.525
Steel drive shaft 5/8"	0.857
Steel drive shaft 3/8"	0.3086

Table 1 Mass of drive shaft.

Percentage of mass reduction of composite drive shaft with same diameter:

$$\frac{composite\ (kg) - steel\ (kg)}{steel(kg)} \times 100\%$$

$$\frac{0.525\ kg - 0.857\ kg}{0.857kg} \times 100\% = 38.74\%$$

As mentioned in literature review, weight has major effect on vibration and fuel efficiency. Heavier the material will caused bigger impact in vibration and reduced in fuel efficiency. By reducing almost half its original weight, the composite drive shaft will vibrate less and has higher fuel efficiency.

6. CONCLUSION

A.Conclusion

Composite material is a solution for a better drive shaft. It has significant weight reduction, higher natural bending frequency and less part complexity. Exploring potential EFB as natural fiber to substitute the usage of carbon/glass fiber is a worth and highly potential study as the resource is abundant and much cheaper compare to glass/carbon fiber.

From the graph obtained from the experiment conducted using machine fault simulator, we can conclude that composite drive shaft, with lighter weight yield smaller vibration effect along the drive shaft compare to steel drive shaft having same diameter. At some speed and some point, composite drive shaft also yield smaller vibration effect compare to steel drive shaft with smaller diameter and lighter mass. This shows that composite drive shaft is a suitable substituted for better drive shaft with smaller vibration effect.

B. Recommendation.

1. Fiber length has much effect on the mechanical properties. Longer fiber length has better mechanical properties. In this study, granulator was used and the end product of fiber is relatively short. For better mechanical properties, modified version of granulator or special chopping machine can be used to obtain longer fiber length.
2. Fiber is strong at its direction. In order to produce a stronger reinforcement and better load distribution, the fiber should be arrange in desired angle and direction instead of random distribution.

Proper adhesive or adhesion method can be introduced in order to solve the "small gap" or "fiber pull out" problem.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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