Prediction of the Fatigue Life of the AISI 1513 Carbon Steel Lower Arm Based on Strain-Life Approach

HUSAINI¹-a, TEUKU Edisah Putra¹-b*, MUHAMMAD Reza Rizky¹-c

¹Department of Mechanical Engineering, Universitas Syiah Kuala, Darussalam 23111, Banda Aceh, Indonesia
a husainiftm@unsyiah.ac.id, b edi@unsyiah.ac.id, c mrezarizky@mhs.unsyiah.ac.id

Abstract. The purpose of this study is to predict the fatigue life of a lower arm as a vehicle is driven on a straight and turn roads. The measurement of strain signals was carried out by attaching a strain gauge to the left lower arm and driving it with an acceleration of 30 km/h. According to the results, the lowest fatigue life was obtained just as the vehicle turned clockwise, which was 2.6E+6 cycles to failure. This value was lower by 123 % and 1,862 % than it was driven straight and counter-clockwise. Similarity, when the vehicle turned to the right, the lower arm on the left side received a higher strain, contributing to a shorter fatigue life.

1. Introduction
The stability and control of the vehicle entirely depends on the friction between the tire and road surface [1]. This dynamic interaction results in vibrations detrimental to vehicle components. Vibration contributes to the mechanical damage of a component due to the dynamic load. Therefore, the suspension system dampens the vibrations in the wheel due to uneven road surfaces, therefore, it is not felt directly by the driver or passengers [2-7].

Several components have varieties components in a suspension system, such as the lower arm, which functions to connect the suspension system to the main frame of the vehicle and as a wheel drive controller, both back and forth. There are several studies that predict the fatigue life of a lower arm [8, 9], however, these studies utilized strain signals measured on a straight road. Since a lower arm functions to stabilize the vehicle when turning, therefore, the main purpose of this study is to determine its fatigue life when driven on straight and bent roads based on the strain-life approach.

2. Materials and Method
In order to determine the material, a chemical composition test was performed. The tested specimen was injected with argon gas electrodes. Furthermore, the lower arm was designed using computer aided design (CAD) and was analyzed using finite element analysis (FEA). FEA is a numerical method for solving technical problems through finite element modeling, in the form of meshes with boundary conditions and certain physical quantities. It can also be used to analyze non-structures, by modeling several types of materials and variations in the size of elements at the location of the structure. In the simulation process, it is necessary to review certain things that impacts hugely on the results, such as meshing, force, and support.

The mesh process was carried out to divide parts of geometry into small parts or elements. In this research, the mesh used was a tetrahedron [10] with a size of 5 mm. Its size will greatly affect the level of accuracy of the simulation results because the smaller its size, the more thorough results obtained. It produced high-quality meshing used for the solid boundary representation model imported from the
CAD system, with 32,812 nodes and 16,887 elements. In this research, the load given was the weight of the vehicle, passenger(s) and goods which was 1,045 kg, and 420 kg culminating to 1,465 kg or 14,366.74 N. The total force was divided by four which depicts the number of wheels that hold the vehicle. Therefore, the maximum load received by the lower arm was 3,591.68 N with a displacement support and force in the bushing and ball joint sections, as shown in figure 1.

Figure 1. Load and boundary conditions.

Equivalent stress is often referred to as von Mises stress [11] which is usually obtained from hoop, longitudinal and radial directions. These are represented by $\sigma_1$, $\sigma_2$, $\sigma_3$. The equivalent stress $\sigma_e$ is mathematically represented as follows:

$$\sigma_e = \frac{1}{\sqrt{2}} \left[ (\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy} + \tau_{yx} + \tau_{zx}) \right]^{1/2}$$

where $\sigma_x$, $\sigma_y$, $\sigma_z$ are the normal stresses in the direction of the $x$, $y$ and $z$-axes, while $\tau_{xy}$, $\tau_{yx}$, $\tau_{zx}$ are the shear stresses.

Strain signals were measured by attaching a strain gauge at the lower arm, with the installation location chosen based on the stress distribution. The frequency for measuring the strain signals was 500 Hz [12]. After mounting the measuring equipments, the vehicle was then ran on a straight, clockwise and counter-clockwise roads, at the speed of 30 km/h.

Generally, fatigue signals are characterized by statistics, therefore, there are a number of statistical parameters used for monitoring patterns and classification of random signals. The parameters usually used in observing the behavior of strain signals include mean, standard deviation (SD), root-mean square (r.m.s.), and kurtosis. For a signal $F_j$ with the number of data $n$, the mean value $\bar{x}$ is estimated by:

$$\bar{x} = \frac{1}{n} \sum_{j=1}^{n} F_j$$

SD is used to determine how data are distributed in a sample and the number of average variability in a data set. SD can be stated as follows:

$$SD = \sqrt{\frac{1}{n} \sum_{j=1}^{n} (F_j - \bar{x})^2}$$

r.m.s. is used to estimate the total amount of energy contained in a discrete data $F_j$. This is expressed by:

$$r.m.s. = \sqrt{\frac{1}{n} \sum_{j=1}^{n} F_j^2}$$
Kurtosis is a statistical parameter that is sensitive to spikes in the data with a discrete equation as follows:

\[ K = \frac{1}{n(\text{SD})^4} \sum_{j=1}^{n} (F_j - \bar{X})^4 \]  

(5)

In general, it is estimated that 50 - 90 % of structure failures are caused by fatigue, thereby, making it a serious problem [13-15]. An accurate fatigue life assessment can be performed by the strain-life approach while considering the plastic form in the local area. Its analysis is used to estimate the risk of damage caused by repetitive loads and determine the life of a structure or component. By predicting the fatigue life, the risk of total damage can be minimized and the structure used to predetermine design targets. This approach is generally used for flexible materials.

The Coffin-Manson model [16, 17] can be used to obtain the relationship between stress amplitude and a number of cycles. This model is stated by:

\[ \varepsilon = \frac{\sigma_f}{E} \left(2N_f\right)^{b} + \varepsilon_f \left(2N_f\right)^{c} \]  

(6)

where \( \varepsilon \) is the strain amplitude, \( \sigma_f \) is the fatigue strength coefficient, \( E \) is the material modulus of elasticity, \( N_f \) is the number of cycles to failure for a particular stress range and mean, \( b \) is the fatigue strength exponent, \( \varepsilon_f \) is the fatigue ductility coefficient and \( c \) is the fatigue ductility exponent.

According to the Morrow model [18], the mean stress can be enhanced by adjusting the elastic strain-life. The model is defined by:

\[ \varepsilon = \frac{\sigma_f - \sigma_{\text{mean}}}{E} \left(2N_f\right)^{b} + \varepsilon_f \left(2N_f\right)^{c} \]  

(7)

where \( \sigma_{\text{mean}} \) is the normal mean stress. The SWT parameter [19] was proposed by K.N. Smith, P. Watson and T.H. Topper and mathematically expressed by:

\[ \sigma_{\text{max}} \varepsilon = \frac{\sigma_f^2}{E} \left(2N_f\right)^{2b} + \sigma_f \varepsilon_f \left(2N_f\right)^{b+c} \]  

(8)

where \( \sigma_{\text{max}} \) is the maximum stress.

Fatigue damage for each loading cycle \( D_i \) is represented by:

\[ D_i = \frac{1}{N_f} \]  

(9)

The Palmgren-Miner rule [20, 21] was used to determine the cumulative fatigue damage, which is:

\[ D = \sum \left( \frac{n_i}{N_f} \right) \]  

(10)

3. Results and Discussion

The results of the chemical composition test show that the material consists of 0.08 % carbon (C), 1.31 % manganese (Mn), 0.002 % silicon (Si) and of 0.005 % phosphor (P). From the compositions of manganese and carbon, it was concluded that this material belongs to the medium alloy steel type. According to ASTM A29/A29M-05 [22], the material used to fabricate the lower arm was the AISI 1513 carbon steel. Figure 2 illustrates the stress distribution of the lower arm, with a maximum value of 358.82 MPa, which occurred on the upper side near the bushings. This value was smaller than the yield
strength of the AISI 1513 carbon steel, at 450 MPa [23]. This result was similar to study by Kim et al. [9].

Figure 2. Stress distributions of the lower arm.

The measured strain signals are shown in figure 3, with the mean values of -12 µε, -9 µε, and -0.5 µε for the straight, clockwise, and counter-clockwise roads, which shows that the lower arm accepted a compressive load. The road with the highest strain amplitude range was the clockwise, which was 8 µε to -33 µε with the strain gauge affixed at the left lower arm. Therefore, when the vehicle was turning to the right (clockwise), the component received a higher stress. However, on the counter-clockwise road, the stress received by the component was lower, at 8 µε to -13 µε, with the straight road providing a strain amplitude range between 2 µε to -28 µε. The clockwise road provided the highest strain amplitude ranges, at 3 µε and an r.m.s. value of 10 µε. While the straight and counter-clockwise roads gave an SD of 2 µε, with an r.m.s. value of 12 µε. All the strain signals gave the kurtosis value above 3, which means that they were non-stationary [24, 25].

According to the Coffin-Manson model, the fatigue damage for the straight, clockwise, and counter-clockwise roads were 5.6E-6 damage per block, 1.9E-5 damage per block, and 9.8E-7 damage per block, respectively. The Morrow model gave the fatigue damage of 3.1E-6 damage per block, 1.3E-5 damage per block, and 9.3E-7 damage per block. The SWT model gave the lowest fatigue damage, as 3.8E-11 damage per block, 8.6E-7 damage per block, and 6.8E-7 damage per block. The clockwise road gave the highest value, followed by the straight and counter-clockwise. These values were proportional to the SD, where the clockwise road also gave the highest SD. The high fatigue damage of a component lowers its fatigue life. Therefore, the clockwise road with the highest fatigue damage value gave the lowest fatigue life, of 2.6E+6 cycles to failure. The straight road gave the fatigue life of 5.8E+6 cycles to failure and the counter-clockwise road gave 5.1E+7 cycles to failure.
4. Conclusion
This work aims to predict the fatigue life of a lower arm just as a vehicle was driven on a straight and turn roads. The results show that when the vehicle turned in a direction, the lower arm located on the opposite received a higher strain, thereby, giving a lower fatigue life of 1,862 %. In this case, when the vehicle turned to the right, the lower arm on the left side received a higher strain, contributing to a shorter fatigue life. This corresponds to the primary function of the component that is to stabilize a turning vehicle. With this function, a lower arm works more active just as the vehicle turns, and tend to be passive provided the vehicle runs on a straight road.

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