Deterministic and probabilistic life assessment of a traditional car starter motor based on number of stop/start cycles

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Abstract
In this work, a deterministic and probabilistic life assessment for a traditional car starter motor, with the help of timely diagnosing of the starter faults and predicting its remaining useful life, based on number of stop/start cycles, and the corresponding brush and commutator wear, is realized. Furthermore, empirical equations accounting for deterministic and stochastic conditions, which can give the remaining useful life for both the commutator and brushes, are developed by utilizing curve fitting methods for fitting the experimental data, and Monte Carlo method for stochastic calculations. Use of the stochastic one, with the aim of real-time condition monitoring of the health of the starters in a car, can make sense to obtain the most robust and reliable cycles with the consideration of the uncertainties arising from human factors and accuracies of the measurement instruments. Moreover, the proposed empirical models produce life predictions in fair enough agreement with the experienced ones when compared; thus, the brush is concluded to be one of the most likely components to fail during the life of the starter. For the adaptation of the deterministic or stochastic models to other type internal combustion engines, the modification of the proposed models for both components in such a way that it could involve less efforts; for example, few similar experiments to be implemented on the different types of the engines or the directly consideration of the required torque to which the engine is exposed, might be several reasonable solutions that accordingly could save the development time and reduce costs.

Keywords: Life assessment, Starter motor, Automobile, Stop/start cycles, Stochastic analysis

1. Introduction

One of the most important components of a car starting system is the starter motor. The main function of the starter motor is to supply an adequate torque for the engine to reach a sustainable start-up revolution. Windover et al. (2015) expresses that starter motors are designed for nearly a life between 30000 and 60000 stop/start cycles (CSS), and their lives are mostly dependent on the total number of the CSS according to the information gathered from consulted technical experts. Ensuring long CSS during its lifetime without functional restriction is heavily an important issue, in particular for emergency situations and start-stop systems used in modern cars (Bayer and Schick, 2012; Murugesan et al., 2012). To enhance starter reliability under these conditions, it is required to concentrate on the main reasons for the faults of the motors when used in cars (Dziubinski, 2017). The common reasons for the starter failures can be summarized as brush and commutator wear, armature bearing fault, pinion gear wear and solenoid switch fault (Windover et al., 2015; Murugesan et al., 2014). With the aim of eliminating the pinion gear and armature bearing faults, a combination of starter/alternator has been developed in some currently start-stop systems (Windover et al., 2015). However, the traditional starter motors have been commonly used even in the newer start-stop and hybrid-system cars, as well as in today’s cars (Nagy et al., 2012). Beside their common use, starters are fairly suitable and profitable for remanufactured market (Saidani et al., 2017). From these aspects, there have been a lot of research efforts conducted towards diagnosis.
and timely maintenance of the starter faults. For example, Zaidi et al. (2011) presented a prognosis method for the gear faults by using the time-frequency features extracted from the motor current and hidden Markov models (HMMs) to predict the future state of the fault. Labbe et al. (2014) analyzed the armature magnetic reaction and accordingly, tested different prototypes built. Bayir and Bay (2004) proposed a fault diagnosis system for a serial wound starter motor by utilizing artificial neural network (ANN) trained based on the motor current signals. Murugesan et al. (2012) put forward a simulation model based on the experimental data for an electronic control unit (ECU) to control the battery voltage and current. Nagy et al. (2012) presents a non-linear dynamic model of the solenoid switch applying the Euler-Lagrange formalism. As for the brush and commutator wear, they are subject to wear during operation as other machine parts since the brushes are in friction with the commutator (Bayer and Schick, 2012; Honbo et al., 2005a; Sevim and Eryurek, 2006). To improve the performance and durability of the brush and commutator, few research studies have been conducted. For example, Honbo et al. (2005b) proposed an alternative solution of adding a phosphorous compound to the brush content for the necessity of developing nonleaded brushes because the lead dust may cause genetic disorders if incorporated. Similarly, Uecker (2003) implemented tests of different additives including Tin, Zinc and ZnCO,

and, found that the ZnCO yields the highest performance along with the durability of 62.000 $C_{SS}$ . Also, they claimed that the best material yields 48% longer than the standard grade with lead, and the commutator wear is reduced.

According to the literature review, it is observed that most of the research conducted have been concentrated on the diagnosis of faults of the starters using the fluctuations in the motor or battery current. However, the task of diagnosis and prognosis of the faults of the brush and commutator is still a new research area and significantly associated with the remanufactured market; therefore, this task needs to be improved in such a way that an experimentally confirmed mathematical model could be developed accounting for the task not only deterministically but also stochastically because almost all of engineered systems include uncertainties. To that end, in this work, an experimentally confirmed mathematical model of deterministic and probabilistic life assessment in terms of the brush and commutator wear for a traditional car starter motor, based on number of stop/start cycles is presented.

The reminder of this paper is organized as follows: in Section 2, the experiment equipments, the measurement procedure and the life prediction process of the starter motor are explained. In Section 3, the results of the experiment are analyzed and the obtained deterministic and probabilistic empirical equations are presented. In Section 4, conclusions are drawn concerning the main contributions and limitations of the proposed model.

2. Material and Method

2.1 Experiment equipment

A traditional gasoline internal combustion engine (1.6 L, 4-cyclinder) and new traditional starter motor were used in this experiment. The starter motor and its base components, and its mounting on the gasoline engine are shown in Fig. 1. For the measurements of the surface roughness ($S_a$) of the commutator conductors ($S_{com} a$), a 3-D optical profilometer with 20x lens objective, having an accuracy of 0.15 nm (Fig. 2a and 2b), and a personal computer including interface software to store the measured $S_{com} a$ data were used. To measure the heights of four brushes ($H_{brush}$), a micrometer having an accuracy of 0.001 mm was used (Fig. 2c). Also, a digital caliper with the accuracy of 0.01 mm was used to measure the diameter of the commutator ($d_{com}$) (Fig. 2d).

2.2 Measurement procedure

First of all, before starting the stop/start cycles ($C_{SS}$) for this experiment, the $S_{com} a$ values (of four conductors marked with numbers 1, 2, 3, 4, as can be seen in Fig. 2a), the $H_{brush}$ values and the $d_{com}$ value were measured. After that, the assembled starter motor was mounted on the engine, and first, 100 $C_{SS}$ were carried out at a constant rate, one cycle per two seconds. Again, the $S_{com} a$ and $H_{brush}$ values were measured. From these two measured data at the result of 100 $C_{SS}$, because it was observed that there was a slight increase in wear of the commutator and brushes, 400 $C_{SS}$ were carried out for the next four trials. Totally, 1700 $C_{SS}$ or five trials (100, 4 x 400 cycles) were conducted for five days (one trial per a day). The $d_{com}$ values were measured only at 0 and 1700 cycles because of the slight decrease in the diameter, and finally the $S_{com} a$ and $d_{com}$ for the worn-out commutator, and the $H_{brush}$ for the worn-out brush were measured so that it could be possible to accurately predict the life of the starter motor. All these measurements were

carried out at room temperature (20-25 °C).

Fig. 1. The starter motor (a), its base components (b), and its mounting on the gasoline engine (c).

Fig. 2 Four commutator conductors marked by numbers (a), the optical profilometer with three objectives (b), the micrometer (c), and the digital caliper (d).
2.3 Data analysis and life prediction of the starter motor under uncertainty

The main aim in this step is to make life prediction of a traditional starter motor based on the experimental data under deterministic and stochastic cases. To that end, first, all of the experimental data consisting of inputs (\(C_{SS}\)) and the wear parameters (the mean value of \(Sa_{com}\) values of four commutator conductor surfaces (\(Sa_{com}\)), the diameter of the commutator (\(d_{com}\)), and the mean value of four brush heights (\(H_{brush}\)) belonging to the new starter motor and the worn-out one were measured. The life of the worn-out commutator, based on the data consisting of the two \(d_{com}\) values measured and the corresponding values of \(C_{SS}\), was determined by the linear extrapolation method. Second, based on all of the experimental data obtained, two empirical equations were derived giving relationships between \(C_{SS}\) and \(Sa_{com}\), and between \(C_{SS}\) and \(H_{brush}\) by utilizing the curve fitting approaches. Third, the lives of the commutator and brushes were deterministically predicted within the maximum and minimum ranges of the wear parameters, \(Sa_{com}\) and \(H_{brush}\).

As regard to the stochastic case, the \(Sa_{com}\) and \(H_{brush}\) were assumed to be random variables with Gaussian distributions to obtain the most reliable and robust useful life of the starter motor under uncertainty. In the stochastic case, the limit values of \(Sa_{com}\) and \(H_{brush}\), which were measured from the worn-out commutator and brushes, were accepted as the mean values for the random \(Sa_{com}\) and \(H_{brush}\) variables. A standard deviation for each of these variables (\(\sigma_{std}\)) can be simply calculated by

\[
\sigma_{std} = \sqrt{(\sigma_{mea})^2 + (\sigma_{sys})^2 + \cdots}
\]

where, \(\sigma_{mea}\) refers to the standard uncertainty related to the measurement uncertainty stemming from human factors, \(\sigma_{sys}\) represents the standard uncertainty related to the systematic uncertainty stemming from the accuracy of an instrument. Similarly, various types of the standard uncertainty can be added to Eq. (1) if necessary. Herein, two standard uncertainties were taken into consideration in the implementation of the stochastic process. After determining the standard deviations of two wear parameters (\(Sa_{com}\) and \(H_{brush}\)), the stochastic characteristics of the corresponding \(C_{SS}\) were obtained from these two empirical equations by using the MCS method. As a result, the minimum \(C_{SS}\) of the distributions obtained for the commutator and brushes were accepted to be the most reliable and robust cycles, which refer to the most reliable and robust useful lives of the starter motor in terms of the lives of commutator and brush.

3. Results and analysis

The experimental data consisting of the \(C_{SS}\) and the corresponding \(Sa_{com}\), \(H_{brush}\) and \(d_{com}\) values are shown in Table 1. According to the table, it can be said that as the cycle increases, both the brush height and surface roughness of the commutator decrease. Moreover, especially the differences in \(H_{brush}\) since 500 \(C_{SS}\) explicitly increase compared to that in the first 100 \(C_{SS}\).

Table 1 The experimental data consisting of the \(C_{SS}\), \(Sa_{com}\), \(H_{brush}\) and \(d_{com}\).

<table>
<thead>
<tr>
<th>(C_{SS})</th>
<th>(H_{brush}), mm</th>
<th>(Sa_{com}), µm</th>
<th>(d_{com}), mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>17.883</td>
<td>0.978</td>
<td>37.02</td>
</tr>
<tr>
<td>100</td>
<td>17.822</td>
<td>0.956</td>
<td>-</td>
</tr>
<tr>
<td>500</td>
<td>17.785</td>
<td>0.910</td>
<td>-</td>
</tr>
<tr>
<td>900</td>
<td>17.627</td>
<td>0.851</td>
<td>-</td>
</tr>
<tr>
<td>1300</td>
<td>17.584</td>
<td>0.803</td>
<td>-</td>
</tr>
<tr>
<td>1700</td>
<td>17.447</td>
<td>0.751</td>
<td>37</td>
</tr>
</tbody>
</table>

As a reference to the computational model or the empirical equation to predict the life of the starter motor, the \(Sa_{com}\) and \(d_{com}\) values of a worn-out commutator, and the \(H_{brush}\) value of a worn-out brush were measured to be 0.697708 µm, 35.6 mm and 11.5 mm, respectively. From the experimental data, a linear fitting the \(H_{brush}\) values to \(C_{SS}\) (Fig. 3a) was applied. On the other hand, based on the data consisting of the two \(d_{com}\) values and the corresponding \(C_{SS}\), the life of the worn-out commutator with a diameter of 35.6 mm was determined to be 126520 cycles. Moreover, the corresponding cycle for the \(Sa_{com}\) of 0.697708 µm were found to be 126520 cycles. After adding the found \(Sa_{com}\) of 0.697708 µm
and the corresponding 126520 cycles to the experimental data, an exponential fitting the \( \overline{\text{Sa}}_{\text{com}} \) values to \( C_{SS} \) (Fig. 3b) was applied.

![Fig. 3 The linear fitting the \( H_{\text{brush}} \) values to \( C_{SS} \) (a) and the exponential fitting the \( \overline{\text{Sa}}_{\text{com}} \) values to \( C_{SS} \) (b).](image)

At the result of the fitting process, two empirical equations are derived, one of which, with an accuracy of \( R^2 = 0.97 \), gives the predicted cycle for a given or measured \( H_{\text{brush}} \) (\( C^d_{SS_{\text{brush}}} \)) (Eq. (2)), and the other, with an accuracy of \( R^2 = 0.99 \), gives the predicted cycle for a given or measured \( \overline{\text{Sa}}_{\text{com}} \) (\( C^d_{SS_{\text{com}}} \)) (Eq. (3)).

\[
C^d_{SS_{\text{brush}}} = -3899 H_{\text{brush}} + 6.973e+04
\]

\[
C^d_{SS_{\text{com}}} = 8.797e-11 e^{(-24.14 \overline{\text{Sa}}_{\text{com}})} + 786 e^{(-1.235 \overline{\text{Sa}}_{\text{com}})}
\]

where \( \overline{\text{Sa}}_{\text{com}} \) is normalized by a mean of 0.8495 and standard deviation of 0.1051.

From the Eq. (2), the cycle number of the worn-out brush with the height of 11.5 mm were predicted to be 24892 cycles for the deterministic case. On the other hand, from the Eq. (3), the cycle number of the commutator with \( \overline{\text{Sa}}_{\text{com}} \) of 0.697708 \( \mu \text{m} \) could be found to be 126520 cycles as well.

For the stochastic case, the observed standard uncertainty based on our measurement experience (\( \sigma_{\text{mea}} \)), the systematic uncertainty taken from the accuracy information of the measurement instruments (\( \sigma_{\text{sys}} \)), the calculated standard deviations (\( \sigma_{\text{std}} \)), the allowable limit values, and the assigned distributions for \( \overline{\text{Sa}}_{\text{com}} \) and \( H_{\text{brush}} \) are presented in the Table 2. In the process of the stochastic life assessment, the Gaussian distributions having mean values (the limit values), and standard deviations (\( \sigma_{\text{std}} \)), which are indicated as \( N \) (mean, standard deviation) in Table 2, are used for the wear parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>( \sigma_{\text{mea}} )</th>
<th>( \sigma_{\text{sys}} )</th>
<th>( \sigma_{\text{std}} )</th>
<th>Limit values</th>
<th>Distribution definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \overline{\text{Sa}}_{\text{com}} ) (( \mu \text{m} ))</td>
<td>0.00015</td>
<td>0.00015</td>
<td>0.000212</td>
<td>0.697708</td>
<td>( N ) (0.697708, 0.000212)</td>
</tr>
<tr>
<td>( H_{\text{brush}} ) (mm)</td>
<td>0.01</td>
<td>0.001</td>
<td>0.01005</td>
<td>11.5</td>
<td>( N ) (11.5, 0.01005)</td>
</tr>
</tbody>
</table>

With the implementation of the stochastic process by using the MCS method with 1000000 realizations, the lives of the commutator and brush under stochastic conditions were calculated based on Eq. (2) and (3). Table 3 shows the life and statistical results of the life assessment process under the deterministic and stochastic cases. Herein, the coefficients of variation and skewness belonging to \( C^d_{SS_{\text{com}}} \) and \( C^d_{SS_{\text{brush}}} \) distributions are given for a more detailed statistical future research towards the reliability-based robust design and life optimization of the starter motor. In the stochastic case, less cycle numbers were obtained for both two components because the minimum cycle numbers of the output distributions
were taken into consideration as the most robust and reliable results. According to the results of life assessment, the uncertainty case have a significant effect on the commutator life compared to that of the brush life.

The obtained distributions of $C_{SS\text{com}}^d$ and $C_{SS\text{brush}}^d$ under uncertainty are indicated in Fig. 4. As seen in the figure, the distributions are similar to the statistical characteristics of Gaussian distribution since it is symmetrically-distributed (the skewness values of them are close to 0, as can be seen in Table 3).

Table 3 The deterministic and stochastic lives of the commutator and brush, and their statistical characteristics found.

<table>
<thead>
<tr>
<th>Components</th>
<th>Life under deterministic case (cycles)</th>
<th>Life under stochastic case (cycles)</th>
<th>Coefficient of variation</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commutator</td>
<td>126520</td>
<td>100460</td>
<td>0.0470</td>
<td>0.1444</td>
</tr>
<tr>
<td>Brushes</td>
<td>24892</td>
<td>24710</td>
<td>0.0016</td>
<td>-0.00005</td>
</tr>
</tbody>
</table>

Fig. 4 Distributions of $C_{SS}$ found for commutator (a) and brush (b) under uncertainty.

To find the reliable and robust cycles for the commutator and brushes at a specified running time, different curve fitting methods were applied to the simulated data consisting of the cycles for the deterministic case and their corresponding cycles for the stochastic case; therefore, the best fitting method was chosen to be the method of power curve fitting for both the commutator and brush data. These data and its power fitted curves are shown in Fig. 5, respectively, both of which give a good $R^2$ value of 0.99.

Fig. 5 The power curve fitting for the commutator cycles data (a) and brushes cycles data (b).
From the curve fitting process, the derived empirical equations giving the corresponding stochastic cycle against the deterministic cycle for the commutator and brushes are given below respectively:

\[ C_{SS,\text{com}}^{\text{st}} = 1.125 \times C_{SS,\text{com}}^{\text{de}} \times 0.9698 \]  
\[ C_{SS,\text{brush}}^{\text{st}} = 0.8423 \times C_{SS,\text{brush}}^{\text{de}} \times 1.016 \]  

(4)  
(5)

The stochastic cycles obtained from these empirical equations are accepted as the most promising life assessment results because they are found under real-time conditions including the uncertainties arising from human factors and accuracies of the measurement instruments.

As regards to the availability of the starter motors for cars with the start/stop technology for stochastic conditions, if it is assumed to be at least 15 \( C_{SS} \) per day as an average cycle, the commutator and brushes are estimated to last for 18 and 5 years, respectively. From those results, it can be observed that the brushes need to be improved such that it can perform its function at least for 10 years under the conditions, which include the uncertainties and are subject to a large number of \( C_{SS} \).

Because the predicted stochastic life of brushes (24710 \( C_{SS} \)) by the proposed model are close to the experienced minimum life of a starter motor in practice (30000 \( C_{SS} \)), it can be observed that the proposed model could produce life predictions in fair enough agreement with the experienced ones. Moreover, it can be possible to conclude that the brush is one of the most likely components to fail during the life of the starter. As for the predicted stochastic life of the commutator component, it can be said that the predicted stochastic life of the commutator (100460 \( C_{SS} \)) is explicitly longer than the experienced maximum life in practice (60000 \( C_{SS} \)). From that point, the commutator component can be considered to be one of the least likely components to fail during the life of the starter.

4. Conclusions

In this work, the life assessment of a traditional starter motor under deterministic and stochastic conditions were intended in consideration of wear of the commutator and brush components belonging to the motor. Because a starter motor life was known to be mostly dependent on the number of stop/start cycles, the life assessment was addressed in terms of the total number of the cycles in this investigation. At the result of the experiment, it is clearly seen that the stochastic life of both the starter components are less than the deterministic life of those because the minimum value of \( C_{SS} \) of the distributions obtained for the commutator and brushes are accepted to be the most reliable and robust cycles under uncertainty. In addition to that, considering uncertainties in this system made a significant effect on the commutator life compared to that of the brush life. Furthermore, two empirical equations for both deterministic and stochastic conditions, which give the remaining useful life for both the commutator and brushes, were developed. Use of the stochastic one, with the aim of real-time condition monitoring of health of the starters in a car, can make sense because it can predict the most robust and reliable cycles based on real-time conditions consisting of the uncertainties arising from human factors and accuracies of the measurement instruments. Finally, the proposed model could produce life predictions in fair enough agreement with the experienced ones when compared; thus, it can be possible to conclude that the brush is one of the most likely components to fail during the life of the starter.

For the adaptation of the deterministic or stochastic models to other type internal combustion engines, the modification of the proposed models for both components in such a way that it could involve less efforts; for example, few similar experiments to be implemented on the different types of the engines or the directly consideration of the required torque to which the engine is exposed, might be several reasonable solutions that accordingly could save the development time and reduce costs. As for the availability of the starter motors for cars with the start/stop technology, the commutator and brushes were estimated to last for 18 and 5 years for stochastic conditions, respectively. Accordingly, the brushes could need to be improved such that it can perform its function at least for 10 years under the conditions, which include the uncertainties and are subject to a large number of \( C_{SS} \). For the future works, the lives of the starter components can be investigated at different temperatures, such as cold climates. In addition to that, a mathematical model that is able to integrate the tasks of diagnosis and prognosis of all of other common starter faults can be developed.
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References


