336 *Journal of Mechanical Science and Technology, Vol. 19, No. 1, ⟨Special Edition⟩ pp. 336~342, 2005*

The Noise Reduction of a DC Motor Using Multi-body Dynamics

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The DC motor of a vehicle may cause noise and vibration due to high-speed revolution, which can make a driver feel uncomfortable. There have been various studies attempting to solve these problems, mostly focusing on the causes of noise and vibration and a means of preventing them. The CAE methodology is more efficient than a real test for the purpose of looking for various design parameters to reduce the noise and vibration of the DC motor. In this study, a design process for reducing brush noise is presented with the use of a computer model, which is made by using a multi-body dynamics program (DADS). The design parameters to reduce the brush noise and vibration were proposed using a computer model. They were used to reduce the noise and vibration of the DC motor and verified by the test results of the fan DC motor in the vehicle. This method may be applicable to various DC motors.

Key Words : DC Motor, Hertz Contact, Brush Noise, Multi-body Dynamics, Durability Test

1. Introduction

The DC motor of a fan motor (hereinafter called the DC motor) is widely used as a control motor because of its excellent features : it has a simple structure, it is easy to operate, its revolution is easy to control, and it has an affordable price. However, the DC motor revolves at a high speed, so it may cause noise/vibration during operation of the system. In particular, the DC motor used in the actuators of automobiles and home appliances can give discomfort to users due to noise/vibration, hence the design process is required to solve the problem.

A survey of previous studies shows that the main cause of noise/vibration in DC motors is the dynamic interaction between the brush and the commutator. Due to the structure of a DC motor, there is contact between the brush and the commutator, which causes friction. This friction is the main cause of noise/vibration in DC motors, which is generally known as brush noise. In addition, noise/vibration can also be caused by nonparallel armature and the interaction between the armature shaft and bearing. (Kang, 2005 ; Kim and Ahn, 2000)

In this research, a multibody dynamic model of the DC motor was proposed and an analysis was performed to understand the dynamic property of the DC motor, which is used for a fan in vehicles now in development. Analysis results primarily observed reaction forces between parts that constitute the motor. This was because the noise

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and the vibration that is ultimately caused by the motor are closely related to the reaction forces between parts. It is generally known that the noise of the brush is closely related to the reaction force between the brush and the commutator. The dynamic analysis analyzed the effects of design variables. The designers of the DC motor, judging from experience, believe that the design variables are related to noise and vibration of motors. This analysis is done to show the effects that applicable design variables have on reaction force. Lastly, the test results along with improvement plans of the design variables, which can reduce the noise and vibration of DC motors, were presented.

2. DC Motor Modeling

The DC motor models that are constructed in this research are largely comprised of three parts : the armature assembly located in the central area of the motor that is supported by stator assembly and bracket assembly, the stay assembly, including the brush, which should be noted from a noise and a vibration aspect and which provides power to the armature. The shape for each part is shown in Fig. 1

To construct the actual dynamic properties of the DC motor, the dynamic model was constructed by using contact mechanisms. The contacts of this model are comprised of one ball bearing and one metal bearing mechanisms located at both ends of the armature, four mechanisms between the commutator and the brush, which receives power input, located on the lower center part of the armature.

Fig. 2 shows the make up of the entire DC motor model. The model is constituted with the following, including the contact mechanism, which is the most important factor in dynamic model of a DC motor.

① Ball bearing contact, ② Metal bearing contact, ③ Brush (4 units), and commutator contact constructed the contact mechanism, in order to construct clearance. It was modeled like this to enable a wider performance analysis for various cases. Through this model, the dynamic properties, which depend on the changes of clearance, can be inspected closely. In addition, the effects that friction coefficients and others have on the dynamic property of motors can be evaluated. Furthermore, the location of the shaft direction for ① and ② is changed so that the dynamic properties, which depend on the change in the shaft length of the armature, can be inspected closely.

④ The armature unbalance occurs during the production process, so it is generally calibrated by using balancing equipment. However, 100% balancing is impossible. This unbalance is related, especially, to motor vibration. In this model, the dummy unbalance mass is fixed to the armature, so by changing the dummy mass location from the shaft, the effects of unbalance mass on the noise and vibration can be evaluated.

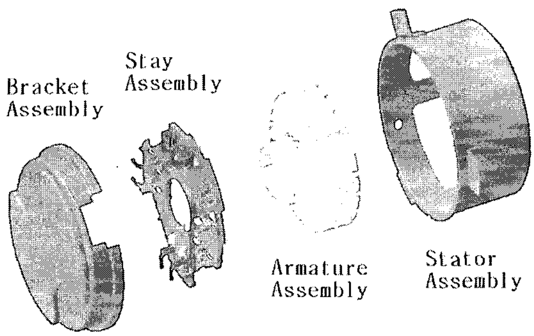

Fig. 1 CAD model of DC motor

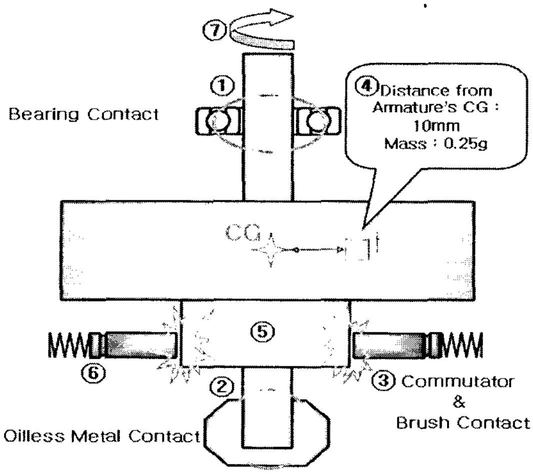

Fig. 2 Schematics of dynamic model

⑤ Fig. 3 shows the shape where the optional roundness is allocated with the cross section of the commutator. The cross section of the commutator uses random numbers to enable the construction of the desired roundness by a method that optionally stations each bar. As shown in the Fig. 3, 20 units of bars and slots were all constructed. If the conclusion may be mentioned beforehand, the roundness of the commutator acts as the biggest factor of the noise problem of this DC motor.

⑥ The brush is modeled with a translational joint and a spring, in order to construct the same dynamic properties as the actual DC motor. The four brushes have contoct with the commutator independent, and through this, the interactions between the brush and the commutator can be known. In addition, dynamic analysis is possible by employing the changes in stiffness of each spring.

⑦ When a rated load is applied, a simple control algorithm is used to maintain rotational velocity of 2180 RPM. The situation, like in actual driving, is re-enacted by generating torque when the angular velocity decreases, by reading the angular velocity of the armature body, which ultimately compensates for the loss of torque caused by each contact.

The special feature of this model is that the contact mechanism has been applied to construct the dynamic properties of the actual DC motor. The contact motion analysis used a continuous analysis method (Curtis, 1983 ; Fenton et al., 1989 ; Feng and Kuslsk, 1994), and the calculation of the contact force used Hertz Contact Force model (Gear, 1971 ; Führer and Leimkuhler, 1989). Through dynamic analysis, the dynamic properties of the DC motor, along with five design variables that designers had the most interest in, were analyzed.

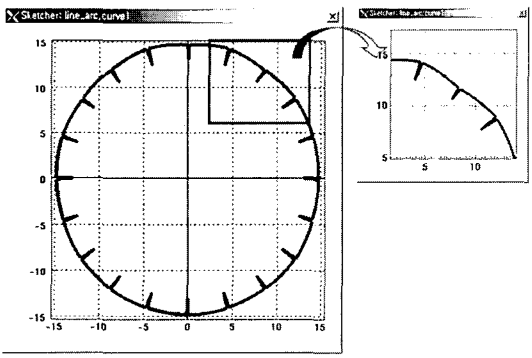

Fig. 3 The shape of commutator section

3. Analysis Result

While changing design variables, dynamic analysis that maintains armature with 2180 RPM during one second, was performed. From this dynamic analysis, the results that should be observed deeply is the brush reaction force and shaft reaction force, which can have major affects on noise and vibration. Here, the brush reaction force is the average value of RMS (Root Mean Square) in the vertical contact force, which is caused between the four brushes and the commutator. Shaft reaction force is the average value of RMS in the vertical contact force of the ball bearing and the metal bearing, which is connected to the shaft. The brush reaction force has a relatively large effect on noise. (Kang, 1995) Naturally, it also has an effect on vibration, caus- ed by the contact between the brush and commutator. On the other hand, the shaft reaction force has a relatively larger effect on vibration rather than noise. The armature shaft makes contact with each ball bearing and metal bearing, and it affects the vibration of the motor itself. However, since the shaft reaction force is also a result of unbalanced movement of the armature, this, of course, affects the noise as well. This was taken into consideration for each result.

3.1 Roundness of commutator

In this research, the height difference between the highest and the lowest bar, from 20 bars of the commutator, was defined as roundness. Fig. 4 is a graph that illustrates the reaction force of the brush and the shaft, according to the roundness of the commutator. All of the reaction force of the brush and the shaft increases as the roundness increases, and one can see that the brush reaction force increases rapidly with the critical point 0.11 mm as the base point. This means that brush noise

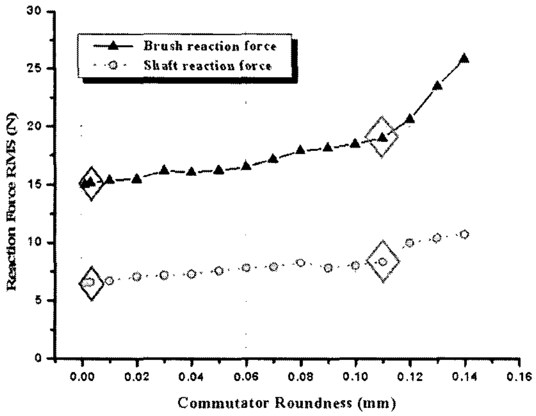

Fig. 4 Relationship between commutator roundness and reaction force

can increase rapidly. There is nearly no difference of reaction forces in the current design specifications (Max. 0.001~0.003 mm. roundness) and the ideal case (Zero roundness).

This shows the validity of the design specification in relation to the current roundness. The problem is that the changes in commutator roundness can be a direct cause of noise and vibration when the motors are used for long hours. Thus, in order to improve the performance of noise and vibration after the durability test, a method to prevent the wear of the commutator is urgently needed.

Table 1 shows the results (results shows the before and the after) from the durability test on the three kinds of DC motors. The first group A1 is the test result that used the brush and the commutator of the existing model. Group B1 is the test result that used a different brush from group A1, and the brush of group B1 is a product which is used in other companies. This brush was obtained for benchmarking purposes, so the exact material constituents of the brush were not known. The last group A2 is the test result of using the commutator with low coefficients. The commutator of group A2 is the commutator of group A1 including lubrication oil. Through the test results above, the following fact was confirmed. First, the interesting result is that roundness of group A1, which has roundness above 0.11 mm, is noticeably bigger than that of

Table 1 Test results before and after durability test

Group	Before		After	
	Roundness [mm]	Noise [dB(A)]	Roundness [mm]	Noise [dB(A)]
A1	Max. 0.003	61.4	0.146	78.8
	Max. 0.003	58.8	0.140	78.6
	Max. 0.003	60.3	0.137	78.9
	Max. 0.003	59.0	0.148	79.5
B1	Max. 0.003	60.3	0.078	74.1
	Max. 0.003	56.8	0.042	73.6
A2	Max. 0.003	53.9	0.087	76.5
	Max. 0.003	52.1	0.067	71.1

the other two groups. This means that once the roundness grows, a vicious cycle of enlargement of roundness continues because of the increase in contact force between the brush and the commutator. This corresponds well to the analysis results in Fig. 4. In addition, the average sound pressure level of group A1 is around 5 dB(A) higher than other groups. According to this, a general fact in which roundness of the commutator is related to noise, had been verified by numerical value. Additionally, when considering the fact that the noise standard of DC motor, used as fans in common vehicles, was a maximum of 73~75 dB(A) after the durability test, it is clear that the roundness of the commutator should be managed below 0.11 mm even after a durability test. Through the results from the second group B1, it becomes known that the change in materials of the brush changes the degree and the tendency of the wear in the commutator; thus, the noise can be reduced. Lastly, by the result of group A2, it shows that by lowering the friction coefficient of the commutator, it also reduces the degree of the wear in the commutator; thus, noise of the brush can be reduced. These methods verified that even the initial noise could be reduced as well.

3.2 Armature unbalance

The content of the effects caused by changes in unbalance mass, explained during the dynamic modeling process, can be seen in Fig. 5. Unbalance mass below 0.2~0.25 gfcm is the current specification. A favorable tendency on the related vibration is shown because the shaft reaction force becomes less as the unbalance mass becomes less. Furthermore, it is predicted that the shaft reaction force will rapidly increase from 6 gfcm, which applies to the critical point. However, as in Fig. 6, this reaction force, centering on the average value, will repeatedly fluctuate. Therefore, it will look as though no big change of RMS value occurred up to the critical point, so in the case of unbalance mass, both RMS and peak value must be considered.

According to the effect analysis result from changes in unbalance mass, the current design specification is deemed applicable because the results of the current design and ideal case, that is zero unbalance mass, have nearly no difference in RMS or peak value.

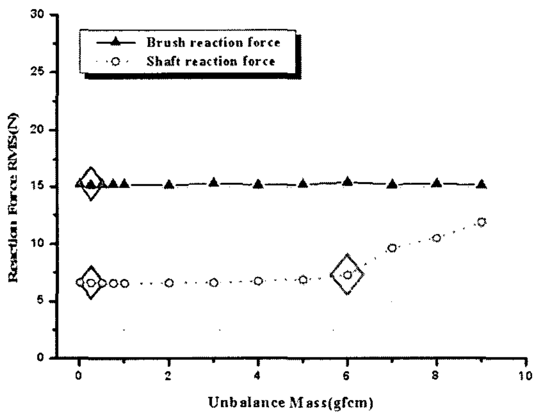

Fig. 5 Relationship between unbalance mass and reaction force

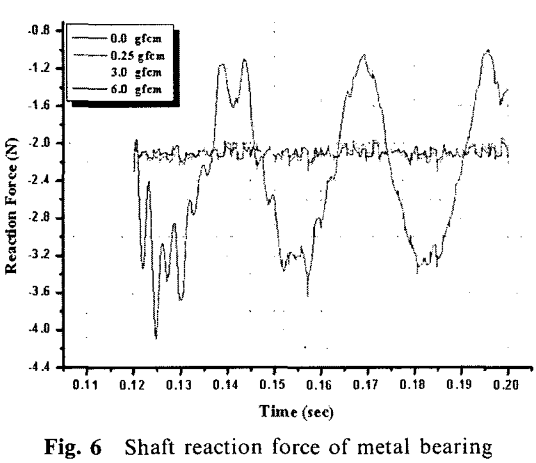

Fig. 6 Shaft reaction force of metal bearing

3.3 Spring stiffness

The reaction force is the same as Fig. 7 when changing the current standard of the brush spring stiffness to 60, 80, 120, 140%. A conclusion can be derived that the brush reaction decreases, as the value of the spring stiffness decreases ; therefore, it is favorable for noise reduction.

However, when the spring stiffness is very small, the contact between the commutator and the brush cannot be maintained, so a problem of supplying power may occur. Such instances should be taken into consideration when developing a design. In addition, when the motor is used for long hours, wear in the commutator and the brush occurs inevitably ; therefore, such problems should be taken into consideration when deci-

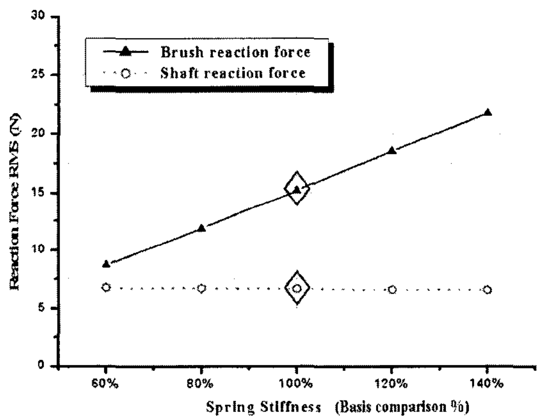

Fig. 7 Relationship between all spring stiffness and reaction force

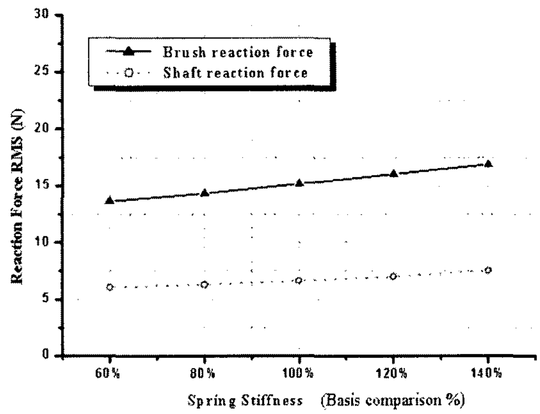

Fig. 8 Relationship between only 1 spring stiffness and reaction force

ding spring stiffness and free length. Upon examination, the current spring stiffness was adequately small, so a further reduction of the spring stiffness was impossible.

As in Fig. 8, in the case of changing only single brush spring stiffness, it shows a tendency where, as the stiffness decreases, so does the reaction force of the brush, due to the asymmetry of stiffness.

3.4 Armature shaft length and bearing clearance

The reaction forces, which were caused in the case of changes in armature shaft length and bearing clearance, were deemed to have nearly no change, like in Figs. 9~10 After a thorough inspection of the data, the shaft reaction force tended to become less as the shaft length and the bearing slot/clearance became less, so it is predicted to be favorable for noise problems, but this effect will be insignificant, due to the small change of reaction forces.

The horizontal shaft in Fig. 9 means the changed lensth from the original shaft length, and the horizontal shaft in Fig. 10 means nine cases, by classifying and combining the three clearances as the minimum, intermediate, maximum, which the ball bearing and the metal bearing have, within the tolerance limits. The case 1 is minimum + minimum, Case 2 is minimum + intermediate, ⋯, and Case 9 is Maximum + maximum.

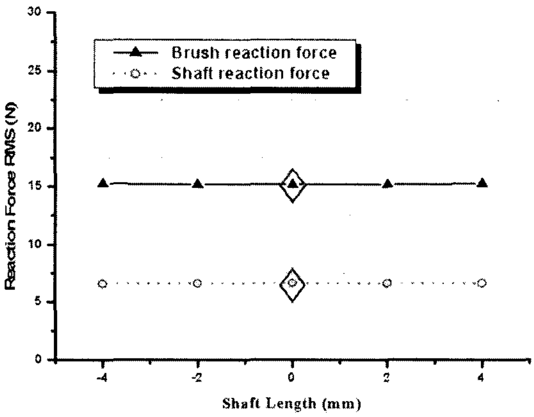

Fig. 9 Relationship between shaft length and reaction force

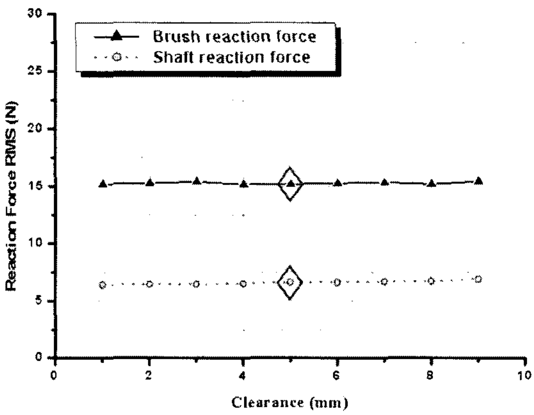

Fig. 10 Relationship between bearing clearance and reaction force

4. Conclusion

This research developed multibody dynamic models that can analyze the dynamic properties of DC motors, and various simulations were performed to understand the affects that each design variables have on noise and vibration, and the research results are as follows.

(1) It is predicted that the noise/vibration will be improved by the five design variables stated above, which will reduce reaction force, as the variables gets smaller ; however, such effects are insignificant. Thus, when making the above design variable lower than the current standard, it is deemed not to have major benefits when considering the quality expenses.

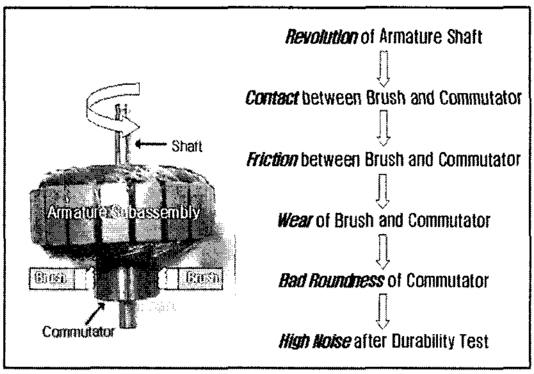

Fig. 11 Main reason of DC motor brush noise

(2) Since DC motors in vehicles are continually used during the lifespan of vehicles, the noise after durability must be considered in the initial designing stages. From this aspect, the following fact should be stressed upon : from the five design variables stated above, only the roundness of the commutator is the variable that can change before and after durability. The following fact was taken in consideration : based on analysis results, the brush reaction force increases according to changes in roundness, and this change is rapid, especially after critical points. Additionally, another fact was taken into consideration : based on test results, when brush reaction force increases, so does the noise of the brush. After these facts were taken into consideration, it was verified that through the process in Fig. 11, the roundness of the commutator was the main cause that generates brush noise of DC motors. In conclusion, it was deemed that the desired noise performance could only be assured by keeping the roundness of the commutator below a fixed level, even after durability. For this model, it should be kept below 0.1～0.11 mm.

(3) It was verified by tests that the change in brush materials and the decrease of the friction coefficient of the commutator, stopping the roundness from rapidly deteriorating, by stabilizing the wear of the commutator, and ultimately, stopping the increase in brush noise. Researches to clarify the relationship between the design variables, which is related to materials or friction coefficients, and noise is still progressing.

In conclusion, through a DC motor dynamic model and analysis, the reduction effect in noise/vibration of design variables were numerically valued, and a method to reduce noise was proposed. Such a dynamic modeling process and analysis method is deemed an expanded application to various DC motor researches.

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