Analysis and Solution on Squeak Noise of Small Permanent Magnet DC Brush Motors in Variable Speed Applications

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The phenomenon of squeaking noise based on noise spectra data during the running up of small permanent magnet DC (PMDC) brush motor is analyzed. From the analysis, it is found that apart from some mechanical issues, the major contributor of the squeaking noise of PMDC is the unbalanced magnetic radial force. In this study, the unbalanced magnetic radial force is simulated using finite element analysis (FEA). A simple but effective method to reduce the noise is proposed. The improved method is validated by test results.

Index Terms—Finite element analysis, permanent magnet, PMDC motor, squeak noise, unbalanced magnetic radial force.

I. INTRODUCTION

Permanent magnet direct current (PMDC) brush motors employing a 3-slot and 2-pole configuration are very popular in small power drives as, for example, the seat-belt tension adjuster, door-locker and water pump in automobiles as well as the driving motors in electric toys, due to their simple structure, compacted size, low cost and mature manufacture process. Usually, it works without speed control and the DC supply is applied directly to the PMDC motors. Therefore there are essentially two operating conditions which are, simply, the ON and OFF modes. But with the advent of power electronics, coupled with the requirements for energy saving and user comfort, more and more speed controllers are being used in conjunction with these simple PMDC motors. Therefore they are now operated from power electronic controllers over a much wider speed range compared to those driven from simple ON-OFF controllers.

Typically, when a motor accelerates, the motor noise increases smoothly. But when a simple 3-slot, 2-pole commercial PMDC motor is tested, it is observed that the motor begins to produce an unbearably loud squeaking noise over a specific range of speed. Once the motor accelerates further away from that noisy speed, the abnormal noise and vibration disappear sharply and such observation is consistent with what one expects from resonance. In the industry such noise is broadly referred as the squeaking noise. The question is whether the squeaky noise are produced because of mechanical resonance or electromagnetic resonance.

Based on noise spectral analysis, the authors found that apart from some mechanical issues, such as the shaft strength and bearing system, the main reason for the production of this squeaky noise is attributed to the presence of unbalanced magnetic radial force [1-7], which is caused by the asymmetrical airgap field distribution in the motor being studied. In order to ascertain the findings from the noise spectral analysis, finite element analysis (FEA) is used to study the magnetic field pattern of the motor [8-10].

II. SQUEAKING NOISE PHENOMENON DESCRIPTION AND ITS SPECTRAL ANALYSIS

The motor running-up test circuit is shown in Fig. 1. To ensure there is no high switching noises due to PWM converters upon the operation of the DC controller, only a variable DC power supply is used, i.e., during running up, the DC voltage supply is increased manually and linearly.

![Fig. 1. PMDC running-up test circuit](image)

The recorded $V-I$ (voltage-current) characteristics during run-up is as shown in Fig. 2. It is observed in Fig. 2 that there are current fluctuations at a critical speed (i.e., 13000 rpm), which is highlighted by a circle in the figure. Fig. 3 shows the noise spectrum of the motor during running up. From Fig. 3, one notices that at this critical speed, its noise spectrum of the motor is increased sharply too, which is also highlighted by a circle. Fig. 4 is its separate harmonic spectrum. It is found that the 1st and the 3rd order noises are the dominant components. In particular, when the vibration of the motor increases...
suddenly and produces the squeaking noise at 13000 rpm, the 3rd order harmonic are also increasing sharply, just as highlighted by the circles in Fig. 3 and Fig. 4. As the rotation speed approaches 16000 rpm, the abnormal noise disappears suddenly, and its vibrations in all three directions disappear too. From the observation, it can be seen that the 3rd order harmonic force plays a major role in the generation of the squeaking noise. Traditionally, cogging torque is considered to be one of the root causes of the squeaking noise, but in this case, i.e., for the PMDC motor with 3-slot, 2-pole configuration as shown in Fig. 6, the main order of the cogging torque are the 6th order, not 3rd order, as shown in Fig. 5.

From the magnetic field analysis, it is found that for this kind of motor design, its magnetic field distribution in the airgap is asymmetrical. Fig. 6 shows the field flux line distributions at no-load, and Fig. 7 shows its field distribution in the airgap. It can be seen that the open circuit flux distribution in the airgap is fairly non-uniform, i.e., there is a pit in the negative field in Fig. 7 due to the slot opening, but for the positive side, no such pit is found. Such asymmetrical field pattern will result in unbalanced radial magnetic pulls on the rotor, which is indeed the main contributor of the squeaking noise.
III. UNBALANCED RADIAL FORCE AND FEA ANALYSIS

Unbalanced radial magnetic force is defined as the resultant global magnetic force acting on the rotor due to an asymmetric magnetic field distribution in the airgap. It can be obtained either analytically or by FEA using Maxwell’s stress tensor method. The force components acting on a rotor, namely $F_x$ and $F_y$, can be computed by evaluating the following expressions [11-12]:

$$F_x = \frac{r l_a}{2 \mu_0} \int_{\theta_0}^{\theta} \left( \left[ B_y^2 - B_0^2 \right] \cos \theta - 2 B_y B_0 \sin \theta \right) d\theta,$$

(1)

$$F_y = \frac{r l_a}{2 \mu_0} \int_{\theta_0}^{\theta} \left( \left[ B_y^2 - B_0^2 \right] \sin \theta - 2 B_y B_0 \cos \theta \right) d\theta,$$

(2)

where $\theta$ is the rotor rotational angle, $l_a$ is the rotor’s axial length, and $r$ is the radius in the middle of the airgap.

Therefore, the resultant magnetic force can be obtained from FEA simulation. The dashed lines in Fig. 8 depict the unbalanced radial magnetic force acting on the motor. Obviously, there is a high unbalanced magnetic force along the airgap, and its rotating frequency is 3 times that of the rotor rotating speed. Therefore, there will be 3rd order magnetic forces acting on the rotor, and if the force shares the same resonance frequency with the rotor, the force will be magnified, and strong vibration and squeaking noise will appear. Therefore, apart from some mechanical issues, such as the bearing, shaft and mechanical deficiencies, etc., the best way to decrease the squeaking noise of PMDC brush motor is to lower the unbalanced magnetic radial force.

IV. PROPOSED SOLUTION

From the above analysis, it is believed that the unbalanced radial magnetic force is generated by the asymmetrical field distribution in the airgap, therefore it will be highly attenuated when the field distribution becomes symmetrical. For example, the unbalanced magnetic radial force will be zero for the PMDC motors with an 8-slot, 2-pole configuration. But this configuration design necessitate changes in the commutator and brush; and for small PMDC motors, usually it is impossible to have such configuration due to space limitation.

Consequently, an alternative design with one dummy slot cut in the center of the rotor tooth is proposed. With this design, the field distribution becomes symmetrical, just as
shown in Fig. 9. Correspondingly, the resultant magnetic force is as shown in solid lines in Fig. 8. Obviously, the unbalanced magnetic force with the proposed design has been reduced substantially to about one tenth of that of the original ones as shown in the dashed line.

Also these unbalanced radial forces in Fig. 8 can be drawn in Fig. 10 with a loci format. It is worth noting that the smaller the radius of the loci, the lower are unbalanced radial forces. And for symmetrical slots design, such as the 8-slot, 2-pole configuration, its loci will be concentric on the center point, i.e., there is no unbalanced radial force on the rotor.

\[ B_{\text{airgap}} \]

Fig. 9. Field distribution in the airgap

\[ \begin{align*}
1 & \quad 0.8 \\
0.6 & \quad 0.4 \\
0.2 & \quad -2 \\
-0.2 & \quad -0.5 \\
-0.6 & \quad -0.8 \\
-1 & \quad -1
\end{align*} \]

\[ \text{Fv1} \quad \text{Fv0} \]

Fig. 10. Improved noise harmonic during running-up

V. CONCLUSION

In this paper, based on the noise spectrum, the squeaking noise phenomenon of a small permanent magnet DC brush motor during running up is analyzed in details. It is found that the 3\textsuperscript{rd} harmonic magnetic force plays a major role in the production of the squeaking noise in small PMDC brush motors. In this study FEA is employed to analyze the field distribution and compute the unbalanced magnetic force acting on the rotor. It is confirmed, experimentally, that the squeaking noise can be attenuated substantially if the motor is designed to have low unbalanced radial forces.

Fig. 11 (a) is the noise spectrum of the proposed rotor design during run-up. It can be seen that the squeaking noise disappears. Fig. 11 (b) shows that the 3\textsuperscript{rd} order harmonic has decreased sharply.

\[ \text{Autospectrum(noise)} - \text{Input- run up1 - slice (Real)} \]

(b) The 1\textsuperscript{st} and 3\textsuperscript{rd} noise harmonics

Fig. 11. Improved noise spectrum during running-up

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