Abstract: - The brushless direct current motor is widely used in various industries because it has a long life, low noise, higher speed and higher torque, and is made easily smaller. Especially, due to its high torque output in a small size it is intensively applicable for small dental and surgical hand-pieces. Electromagnetic analysis has been carried out numerically to improve torque output and ripple of a hand-piece motor. Case studies on electromagnetic torque were carried out by changing numbers of coil wires from 11 to 30 wound and maximum motor torque was obtained with 20 wound wires at the electromagnetic angle of 90°. To reduce torque ripple of the motor, the changes in torque ripples for several slot shapes in a stator were evaluated and compared. The slot with circular holes and V-cut showed a good ripple performance.

Key-Words: - BLDC Motor, Motor Torque, Medical Hand-piece, Stator Coil, Ripple, FEM

1 Introduction

The small hand-pieces have been widely used to cure diseased teeth and tissues during various dental and surgical operations [1-3]. Most dental hand-pieces have adopted an air-turbine as a driving engine for last 30 years [4-9]. The hand-piece driven by an air-turbine, however, has a difficulty to obtain enough output torque and sometimes stops to rotate due to contamination of burrs. Recently, the research is underway to replace the air-turbine by a series of a gear train with an electric motor. The new hand-piece under development consists of a small driving BLDC (Brushless Direct Current) motor, a small high speed gear train and a small burr. The mating gears usually rotate at 50,000 - 200,000 rpm in order to transfer power to the end of a burr by way of a series of high-speed gear train. Because BLDC motors have several advantages over general brushed DC or induction motors, including more torque per weight, more torque per watt, increased reliability, reduced noise, longer lifetime (no brush and commutator erosion), elimination of ionizing sparks from the commutator, and overall reduction of electromagnetic interference, its applications are very broad in various industries.

Structural optimization was performed for magnetic devices in a magnetic field using a homogenization method [10-12]. A new configuration of a brushless DC motor without a permanent magnet was study by finite element analysis [13]. A design method of a single-phase brushless DC fan motor was studied to obtain optimal driving efficiency [14]. In addition, the research on the reduction of torque ripple was performed for synchronous reluctance motor using an asymmetric flux barrier arrangement [15]. Taguchi optimization method was applied in an effort to reduce torque ripple in interior permanent magnet motor [16]. The shape design of a hole in a motor rotor was carried out by drilling axial circular holes of optimal radius and position in the flux path of the rotor core. The torque curves of the optimized motor showed lower pulsating torque and higher average torque [17]. Structural optimization based on the level set method was formulated to reduce torque ripples by minimizing the difference between torque values at defined rotor positions and the constant target average torque value under the constrained material usage [18]. A new optimization technique was applied to design the rotor of interior permanent magnet motor which consists of a permanent magnet and ferromagnetic material for reducing the torque ripple. To express three different material properties (PM, FM, and air), a multi-phase level-set model representing two level-set functions was introduced and the concept of a phase-field model was incorporated to distribute
level-set functions for controlling the complexity of the structural boundaries [19].

There are little studies on the performance analyses of high speed small BLDC motors especially used for various medical hand-pieces for many kinds of medical operations. In this study, electromagnetic analyses have been performed using MAXWELL program in order to improve the torque outputs of the hand-piece BLDC motor. The electromagnetic numerical results have been compared with measured ones. Variations in motor torques were calculated according to changes in the number of winding coils and then the number of coils that can increase torque outputs was determined. In addition, the study on torque ripple was also done to obtain a good slot shape of a stator which could give lower torque ripple. The torque ripple refers to a periodic increase or decrease in output torque as the output shaft rotates. It is measured as the difference in maximum and minimum torque over one complete revolution, generally expressed as a percentage.

2 Motor Torque Analysis

Fig. 1 shows a BLDC motor assembly that is composed of a sensor, a rotor and a stator. The reference BLDC motor has a diameter of 20 mm and a length of 30.0 mm. The sensor controls the flow of an electric current by sensing a sequence, a position and a speed of the rotor. The rotor consists of a rotating shaft and a Nd-Fe-B permanent magnet with S and N poles, and the stator is composed of coils, slots, and a cover. As an electric current runs through the coil, an electromagnetic force occurs. Coils, slots and a cover are made of brass, Teflon and steel, respectively. The locations of key parts in the stator and the rotor are described in Fig. 2.

In Fig. 3, three coils marked as 1, 2 and 3 and a permanent magnet at central region are positioned. As the rotor spins, the current in stator coils varies and the direction of an electromagnetic field also changes. Fig. 4 shows how two directions of electromagnetic forces varies as electric current path shifts from coil to coil wound at the stator and the magnet rotor at the center rotates in 1/4 cycle.
Fig. 5 Directions of electromagnetic forces produced by the magnet (dotted arrow) and coils (solid arrow), where the “x” denotes current in and “●” denotes current out.

Fig. 6 FE model of a BLDC motor

A direction of an electromagnetic force produced by the central magnet is denoted as a dotted arrow and that by stator coils is represented by a solid arrow. The marks “x” and “●” at slots denote current in and out, respectively. Figs. 5(a), (b), (c) and (d) show the angles between two electromagnetic forces- 90°, 120°, 60° and 90°.

The angle between the magnetic field directions of a rotor and a stator always exists between 60 and 120 degrees. The largest motor torque occurs at 90 degree and the smallest torque occurs at 60 or 120 degree. The largest and smallest torques were calculated using MAXWELL.

Fig. 6 shows a finite element model of a BLDC motor constructed by 3-noded elements. The vector potential at the outer circumference of the motor cross-section was set to be zero. The coercive force of the magnet is 10,500 Oe (Oersted) and the remanence is 14,000 Gauss. The rotor and a cover are made of SUS303F and their magnet permeability is 1.0. As the current of 2.5A runs through a coil and 12 coils are wound around a slot, the total current is 30A.

The magnetic flux density is the largest at both sides as shown in Fig. 7. The maximum motor torque on the magnetic rotor was 21.50 N-mm at 90° in-between stator and rotor electromagnetic forces and the minimum torque was 19.95 N-mm at 60° or 120°. The average measured torque of a real BLDC motor is 20.46 N-mm at 28,000 rpm and 60W of a power output. The numerical analysis predicts the torque output accurately.

A parametric study was performed in an effort to improve the torque output by changing the number of coils and the shape of a stator. The torque outputs of the BLDC motor were calculated on the basis of the cross-sectional area of one coil, as the number of coils increases. To add more coils, more space is required without increase in a motor diameter. The outer diameter of the motor and R1 in Fig. 4 are, therefore, fixed and Rx can increase to secure more space for coils. The area of a single coil cross-section is 0.513 mm² and one slot occupies 50° and two bunches of coils exist as in Fig. 4. The number of coils can be related with the space parameter, Rx, as in Eq. (1).

\[ 0.153mm^2 \times \text{number of coils} = \pi \left( R_2^2 - R_1^2 \right) \frac{50}{360} \]  

Fig. 4 shows a quarter dimensions of a present BLDC motor used for a parametric study. There are 12 coil wires in one bunch of coils and the required cross-sectional area for a single wire is 0.153 mm². The motor torque was calculated as the number of coil wires varied at the angles of 60° and 90° between the electromagnetic field directions of a
rotor and a stator. The coil area changes proportionally as the number of coil wires varies. As the number of coil wires increases, the area also increases and the thickness of a motor cover decreases. Figs. 8 and 9 show the motor torque outputs per a unit mm calculated by using MAXWELL on the different number of coil wires from 11 to 30 at 60 and 90 degrees. The maximum motor torque was obtained with 20 wound wires in the both cases of electromagnetic angles as shown in Figs. 8 and 9. The trend in torque variations is that the torque increases as the wire number increases up to 20 and then it decreases gradually even though the wire number increases. As expected, the torques at 90° is higher than those at 60°.

3 Ripple Analysis
A motor ripple is defined as a difference between maximum and minimum motor torques, and occurs due to the variation in torque per one revolution. The torque ripple is evaluated based on the following equation [22],

\[
\frac{T_{\text{max}} - T_{\text{min}}}{T_{\text{max}} + T_{\text{min}}} \times 100(\%) = \text{Torque Ripple}
\]

where \(T_{\text{max}}\) and \(T_{\text{min}}\) denote maximum and minimum torques, respectively.

In an effort to reduce the torque ripple, four different cases of slot shapes in a stator were designed and the torque ripples were compared. The computed torque ripple for the current slot with 20 coils is 7.8%. The 4 cases of design changes in a
slot configuration are depicted in Fig. 10. The calculated torque ripples for cases 1, 2, 3 and 4 are 6.75%, 7.85%, 7.20%, and 6.10%, respectively. The slot shape that combined the cases 1 and 3 gives less torque ripple.

4 Conclusion

Through electromagnetic modelling and analyses, how to improve the torque output of a hand-piece BLDC motor has been studied. The average torque calculated from the existing reference motor was 20.73N-mm and the measured torque was 20.46 N-mm. The analysis method can be thought to be, therefore, accurate from the fact that the numerical result correlates with measured one. In an effort to improve the torque of the reference motor further, some case studies on the electromagnetic torque were performed regarding to various numbers of coil wires from 11 to 30 wound and the maximum motor torque was obtained with 20 wound wires at the electromagnetic angle of 90°. To reduce torque ripple of the motor, the changes in torque ripples for several slot shapes in a stator were evaluated and compared. The slot with circular holes and V-cut showed a good ripple performance.

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