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THEORETICAL AND EXPERIMENTAL STUDY OF UNIVERSAL MOTOR FOR VACUUM CLEANERS

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ABSTRACT

This paper presents the experimental and theoretical studies of universal motors for vacuum cleaners. The mathematical model of the universal motor is formed at first and MATLAB-SIMULINK model is developed. This model utilises the electromechanical parameters of the motors. For this purpose, methods to measure the electrical and mechanical parameters of the equivalent circuit are proposed and parameter measurement tests are conducted. A computer programme, which is called UMSIM, is developed to calculate the performance of the motor. The theoretical performance characteristics are computed. In parallel, the finite element analysis is achieved by using Infolytica's MAGNET 5.2 programme and the measured inductance values are verified. Later the performance tests are conducted on MAGTROL dynamic-loading test system. The input current, input power, output power, output torque and efficiency values are recorded. Finally the experimental and theoretical results are presented together. It is shown that, the simulation model is capable to calculate the dynamic performance of universal motors successfully.

1. INTRODUCTION

It is known that, universal motors(UM) operate with DC and single phase AC supplies, and have performance characteristics similar to those of series DC motors [1,2]. UMs are widely used in appliance industry. The washing machine, mixer, blender, electrical knife, hair drier, sewing machine, drill and vacuum cleaner are well known examples. The objective of this study is to develop a method to predict the performance of universal motors and to check the validly of the theoretical study on two types of vacuum cleaner motors. The first type of motor which has rated speed around 20-25,000 rpm is used in wet and try type of cleaner. The second type of motor is known as dry only type of which speed is approximately 40-50,000 rpm.

Despite its widespread use and the difficulties in mathematical modelling for accurate performance computation, UMs receive little attention from academicians. This study commences with SIMULINK based generalised dynamic modelling of UMs for performance computation. In parallel, MAGNET 5.2 Finite Element Program (FEM) is used for the computation of the magnetic field and calculation of mutual and self inductance, which are used as data for the generalised model mentioned above. A computer program is developed for performance prediction, which is called UMSIM.

It is an universal fact that, drive motors in appliance industry should be reliable, light, silent and cost effective. Generally the operation speed is around 25,000 rpm for vacuum cleaners. High speed UMs offer advantageous over the low speed types for vacuum cleaners. There is almost no published information in the literature on high speed motors. This study presents the theoretical and experimental study of universal motors for speeds up to 50,000 rpm. Various test motors are designed and manufactured, measured performance values are compared with the those of predictions.

2. GENERALISED MACHINE MODEL

The lumped-parameter equivalent circuit of the UM is developed in the following manner. The field and armature quantities are represented with f and a subscript [3]:

$$V_a = r_a \cdot i_a + p\lambda_a \quad (1)$$

$$V_f = r_f \cdot i_f + p\lambda_f \quad (2)$$

$$\lambda_a = L_{aa} \cdot i_a + L_{af} \cdot i_f \quad (3)$$

$$\lambda_f = L_{fa} \cdot i_a + L_{ff} \cdot i_f \quad (4)$$

where, p denotes derivative operator, V_f stator voltage (volt), r_a total rotor resistance including brushes (ohm), r_f total stator resistance (ohm), i_a rotor current (ampere), i_f stator current (ampere), L_{aa} rotor self inductance (henry), $L_{af} = L_{fa}$

mutual inductance between stator and rotor (henry), L_{ff} stator self inductance (henry)

Inductances vary with rotor position θ_r as,

$$L_{aa}=\frac{L_{\max}+L_{\min}}{2}+\frac{L_{\max}-L_{\min}}{2}\cdot\cos(2\theta_r) \qquad (5)$$

$$L_{af}=L_{fa}=-L\cdot\cos(\theta_r) \qquad (6)$$

$$L=\frac{N_a\cdot N_f}{\Re_{af}} \qquad (7)$$

$L_{\max}$ and $L_{\min}$ reflect the maximum and minimum values of rotor self inductance, respectively. N_a and N_f are the rotor and stator number of turns. The reluctance is represented by $\Re$.

Since stator self inductance does depend upon the rotor position,

$$L_{ff}=\frac{N_f^{\,2}}{\Re_f}=const. \qquad (8)$$

α is the angle of brush shift if there is any,

$$L_{aa2}=\frac{L_{\max}+L_{\min}}{2}-\frac{L_{\max}-L_{\min}}{2}\cdot\cos(2\alpha) \qquad (9)$$

$$L_{aa1}=(L_{\min}-L_{\max})\cdot\sin(2\alpha) \qquad (10)$$

$$L_{af1}=L\cdot\cos(\alpha) \qquad (11)$$

$$L_{af2}=L\cdot\sin(\alpha) \qquad (12)$$

$$V_a=r_a\cdot i_a-w_r\cdot L_{aa1}\cdot i_a+L_{aa2}\cdot\frac{di_a}{dt}+w_r\cdot L_{af1}\cdot i_f$$
$$+L_{af2}^{r}\cdot\frac{di_f}{dt} \qquad (13)$$

$$V_f=r_f\cdot i_f+L_{fa}\cdot\frac{di_a}{dt}+L_{ff}\cdot\frac{di_f}{dt} \qquad (14)$$

Considering (13) and (14),

$$V_t=V_a+V_f \qquad (15)$$

The generalised equivalent circuit of the UM is shown in Figure1.

The following well-known electromechanical equations are used in simulation package.

$$T_e=K\cdot\Phi\cdot i_a \qquad (16)$$

$$K=\frac{Z\cdot p}{2\cdot\pi\cdot a}=\frac{N_a}{\pi} \qquad (17)$$

$$T_e=J\cdot\frac{dw}{dt}+B\cdot w+T_L \qquad (18)$$

where J inertia (Nms^2), B friction coefficient (Nms), K torque coefficient, T_L load torque (Nm).

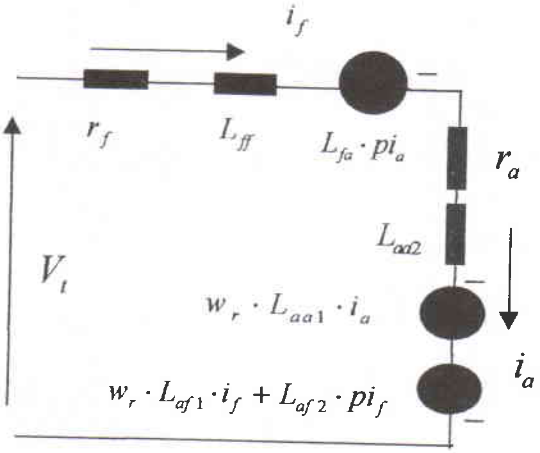

Figure 1. Generalised equivalent circuit of UM.

3. MAGNETIC FIELD ANALYSIS

The electromagnetic field analysis is achieved by using two-dimensional finite element program MAGNET 5.2 [4].

The cross-section of the magnetic network is drawn by using AutoCAD program and transferred to finite element (FEM) file [5]. The magnetic and electrical properties of the core is given as data to MAGNET 5.2 as well as the required electrical and magnetic properties. As a result of successive analysis for various loading conditions, and for various stator and rotor excitations the flux densities are computed and plotted. The flux lines are depicted in Figure 2 for test motor A under rated current. The deviation of the resultant flux from vertical axes is approximately 30^0 which gives the phase shift requirement of the brushes. The FEM analysis has yielded the torque, force, mutual and self inductance and iron losses of the designed motors. Similarly the electromagnetic field analysis of motor B is achieved by using

MAGNET 5.2 FEM package of Infolytica. The flux lines of motor B is shown in Figure 3. The magnetic field analysis is not only important to calculate the mutual and self inductance values of the universal motors, but also very important to prevent excessive saturation and to achieve uniform flux density distribution in various parts of the magnetic core.

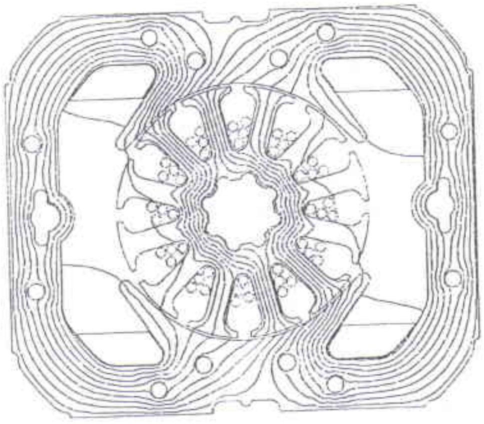

Figure 2. Flux lines of motor A.

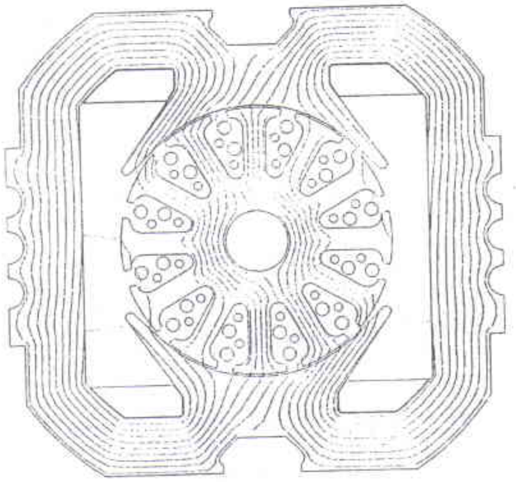

Figure 3. Flux lines of motor B.

4. THE MEASUREMENT OF MOTOR PARAMETERS

In order to obtain performance characteristics of UMs by using the developed simulation program UMSIM, the following motor parameters must be known [6,7,8].

- Useful flux,
- Motor resistance,
- Stator self inductance,
- The maximum and minimum values of the rotor self inductance,
- The mutual inductance between stator and rotor,
- Mechanical losses, friction coefficient and inertia of the rotor
- Shift in neutral line.

As a result of the number of experiments, of which details are not given here, these values are obtained. For design study however, there would be no motor to test, thus FEM and other computational methods should give accurate results for these parameters. The Table 1,2,3 and 4. gives the stator and rotor flux and inductance values computed by FEM DC and FEM AC models and the measured inductance values for motor A and B.

Table1.The measured and computed flux for motor A.

	$\Phi_{ff}(mWb)$	$\Phi_{\max}(mWb)$	$\Phi_{\min}(mWb)$
DC	0.7459	0.5464	0.5139
AC	0.5732	0.42	0.4135
EXP.	0.67	0.5	0.398

Table 2. The measured and computed inductance for motor A.

	$L_{ff}(H)$	$L_{\max}(H)$	$L_{\min}(H)$
DC	0.0507	0.0175	0.0164
AC	0.039	0.01345	0.0131
EXP.	0.045	0.0162	0.0128

It is seen that the correct inductance values are between the two FEM methods. The maximum disparity is 28 percent for DC and 17 percent for AC measurement.

Table3.The measured and computed flux for motor B

	$\Phi_{ff}(mWb)$	$\Phi_{\max}(mWb)$	$\Phi_{\min}(mWb)$
AC	0.381	0.278	0.275
EXP.	0.409	0.352	0.313

Table 4. The measured and computed inductance for motor B.

	$L_{ff}(H)$	$L_{\max}(H)$	$L_{\min}(H)$
AC	0.036	0.015	0.0148
EXP.	0.039	0.019	0.0169

5. DEVELOPMENT OF THE UMSIM SIMULATION PACKAGE

Generalised lumped parameter equations and dynamic mechanical equations describe in Section 2 are used to develop a SIMULINK based simulation package which is called UMSIM by us [9]. The saturation is taken into account by using the FEM oriented inductance calculations. The look up tables are prepared for flux and inductance variations with current form [10,11]. In order to compute and plot the dynamic performance of the motor, friction coefficient, inertia, mechanical losses, and speed information are also given as data to the UMSIM program. In Figure 4 the block diagram of the UMSIM is presented. In Figure 5,6,7 and 8 the speed and output torque versus time functions are depicted for A and B test motors.

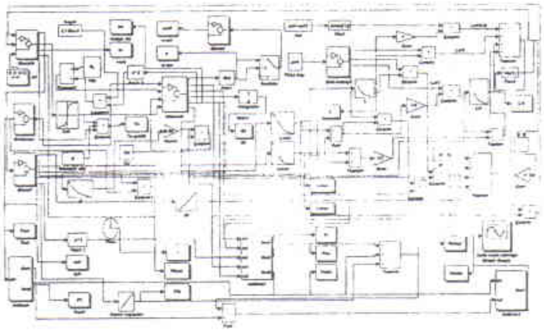

Figure 4. UMSIM block diagram.

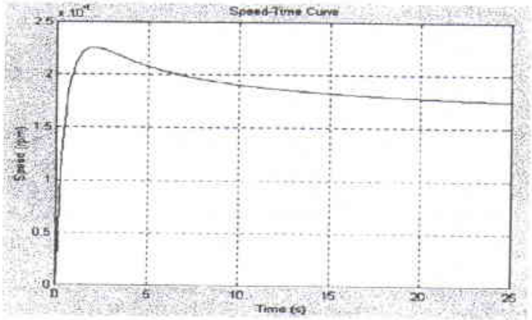

Figure 5.Speed-Time curve for motor A.

6. PERFORMANCE MEASUREMENT

By using a test facility which is capable of measuring the dynamic performance values of the test motor A the input power, output power, efficiency, input current and output torque valued with respect to speed are recorded and plotted. These curves are shown in Figure 9 and 10 for motor A and B .

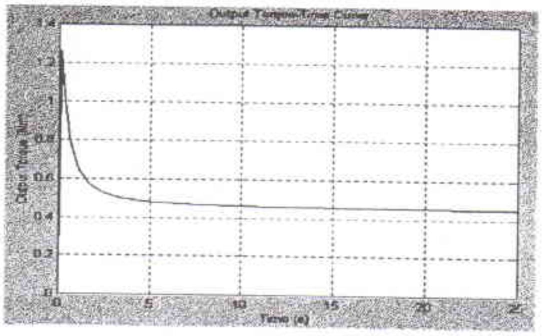

Figure 6. Output Torque-Time curve for motor A

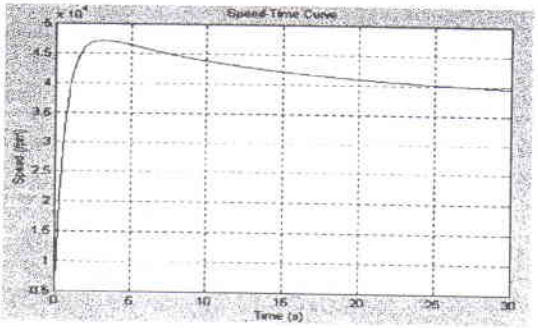

Figure 7.Speed-Time curve for motor B.

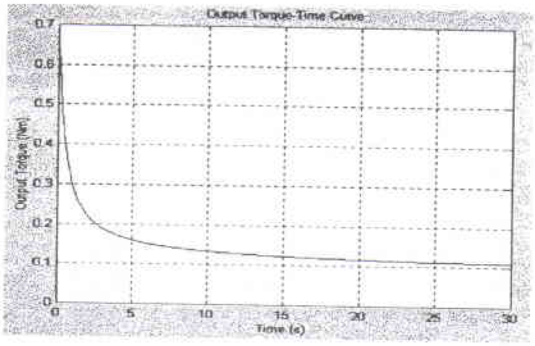

Figure 8. Output Torque-Time curve for motor B

7. THE COMPERASION BETWEEN THEORETICAL AND EXPERİMENTAL PERFORMANCE CHARACTERISTICS

In order to achieve a good design methodology, one has to rely upon to the predicted performance values. Therefore it is very important to have agreement between experimental and theoretical performance characteristics. Computational results obtained from UMSIM simulation program are compared with the experimental results for the test motor A. It is seen in Figure 11, 12 and 13 that the theoretical and

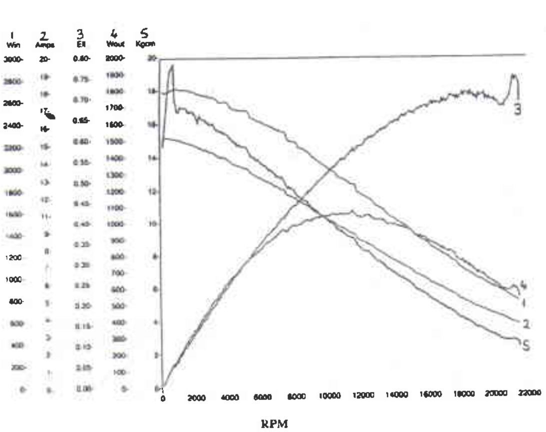

Figure 9.Experimental performance values of the test motor A.

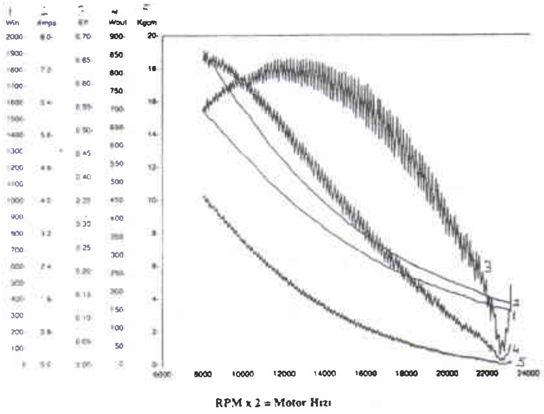

Figure 10.Experimental performance values of the test motor B.

experimental torque, current, input power and output power versus speed curves are in good agreement for motor A. The experimental and theoretical performance curves for motor B are presented in Figure 14,15 and 16. It is seen that, for high speed motor (B) the disparity is observed at low speeds. Nevertheless these figures verify that the developed simulation package (UMSIM) for universal motors is successfully calculate the performance characteristics. This program would be a useful step for design optimisation of universal motors which is a subject of other publication [13].

8. CONCLUSION

This study presents the theoretical and experimental study on universal motors in general vacuum cleaner motors in particular. The theoretical study commences with a generalised equivalent circuit concept and continues with a simulation package which facilitates the computation of the time variant performance characteristics. The transient and steady state solutions are obtained by taking the saturation of the motor into account. A FEM analysis is successfully applied to calculate the two-dimensional flux density values of the motor. The FEM package will be a useful tool for design optimisation as well as calculation of the inductance values which are used as input for UMSIM.

The experimental study is conducted to record the dynamic performance characteristics of the test motor. Finally, it is shown that theoretical results are very good agreement with those of experiments. This is the evidence of the validity of the simulation program developed.

This study also provides the fundamentals for design and optimisation of universal motors which is still very demanding in appliance industry.

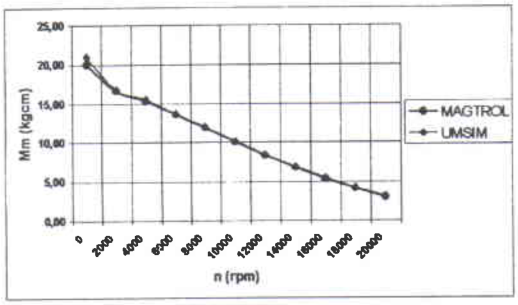

Figure 11.Exp.and theoretical torque-speed curve (A)

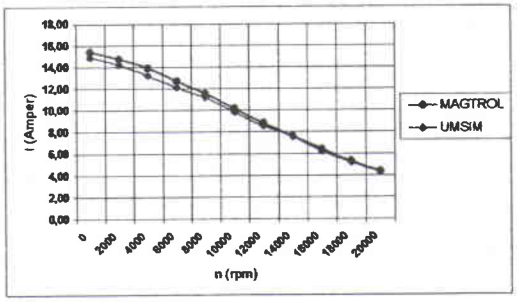

Figure12.Exp.and theoretical current-speed curve (A)

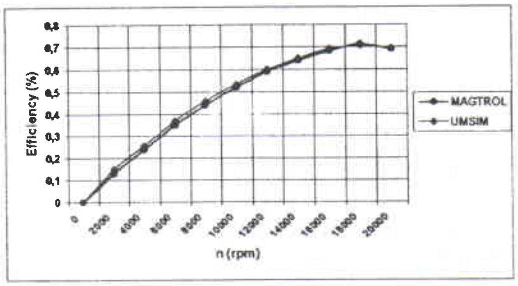

Figure 13 Exp.and theoretical eff-speed curve (A)

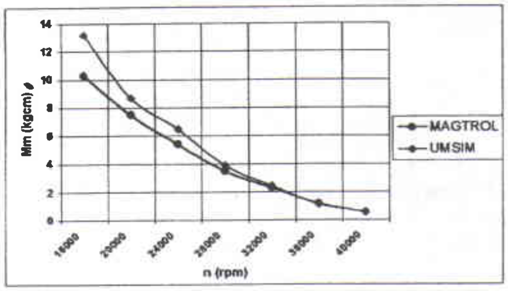

Figure 14 Exp.and theoretical torque-speed curve (B)

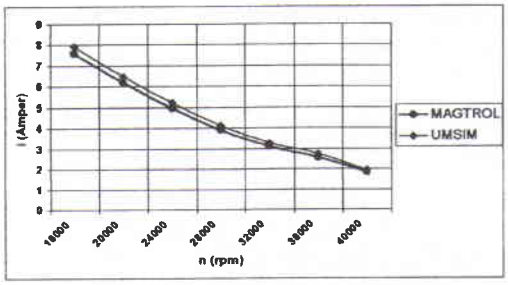

Figure 15 Exp.and theoretical current-speed curve (B)

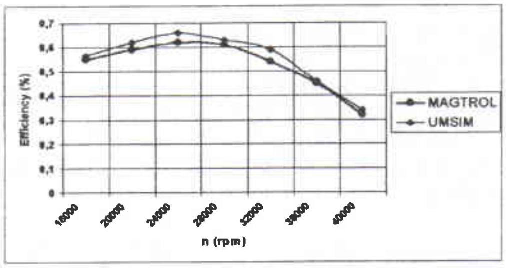

Figure 16 Exp.and theoretical eff-speed curve (B)

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