DESIGN OF NEW UNIVERSAL TURBINE-MOTOR FOR VACUUM CLEANERS

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This paper describes the design, prototyping and testing phases of a turbine motor used in domestic vacuum cleaners. The reference is a turbine-motor made in Asia, which is currently used on low cost, high production vacuum cleaners. The outcome of this research is producing a turbine-motor with a performance that is at least as that of the reference motor and has a competitive cost. Simulation results and experimental measurements are presented in comparative studies between the two turbine-motors.

Keywords: turbine-motor, vacuum cleaner

1. Introduction

A universal motor (UM) is a high-speed electrical machine that converts electrical power into mechanical power. The name "universal" refers to the fact that the motor can work in direct current and also in single-phase alternating current [1]. Although the home appliance industry is attempting to move into the electronically controlled motors [2], such as permanent magnet [3]-[4] or switched reluctance motors [5]-[7], UM is still widely used due to its reduced cost, good power to weight ratio [8]-[10].

Every modern house has a vacuum cleaner. These appliances reduce human effort while saving cleaning time. The operating principle consists of a flow of air from a high pressure to a low-pressure region [11]. This under pressure is created by a centrifugal fan, named the turbine, which spins at high speed. The turbine is powered by an electric motor [12]. This coupled centrifugal fan-motor group is named turbine-motor.

Nowadays, time is a precious resource for individuals and thus efficiency is key even when cleaning a house. Numerous automated and smart [13] cleaning robots such as vacuum or mop cleaners have been proposed [14]-[15]. This solution provides good performance, but only for light cleaning and a decluttered environment [16].

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Another option for fast cleaning is the cordless vertical vacuum cleaner. It has limited battery autonomy and provides inferior air power compared to the corded vacuum cleaners. A permanent magnet motor is used in some high-end products to increase the battery run time [17]. For intensive cleaning tasks, all the above-mentioned products still don’t replace the classic corded vacuum cleaner in terms of cost, air power and autonomy [18].

This paper focuses on designing, prototyping, and testing a new universal turbine-motor that can replace the one currently inside a corded vacuum cleaner. The simulation and experimental results are obtained and discussed in comparative studies.

2. Evaluation of the existing turbine-motor

The evaluated turbine-motor (Fig.1) is running in a low cost and high production vacuum cleaner dedicated to domestic use. The universal motor is coupled to a centrifugal fan on the lower side of the shaft. The centrifugal fan creates a vacuum that is used for air suction. On the other side of the shaft is placed the commutator and the cooling fan that pushes fresh air inside the motor. The motor is supplied directly by the main's AC voltage, 230V/50Hz using a filtering capacitor and a choke on the motor's cabling [19].

Fig. 1. The existing turbine motor

To have a deeper understanding of the motor, a transient magnetic field numerical simulation was done in Ansys Maxwell 2D. The stator and rotor lamination were measured, modeled in Catia v5, and imported in Maxwell.

After multiple simulation iterations, it was concluded that the lamination grade should be M800-50A. The motor windings were evaluated for the number of turns, resistance, and were introduced in the coupled electrical circuit. The mesh was generated taking care to have at least two layers of elements in the air gap and iteratively refined until no further improvements in performance were noticed.

The simulation was done considering a constant motion step and constant speed. The simulation time is equal to the period of the main's voltage Tp=0.02s and the time step Ts=10us. In the post processing of the simulation, the magnetic flux density map was obtained (Fig. 2) as well as the values of the mechanical and electrical power of the motor. The results will be analyzed in chapter 5.

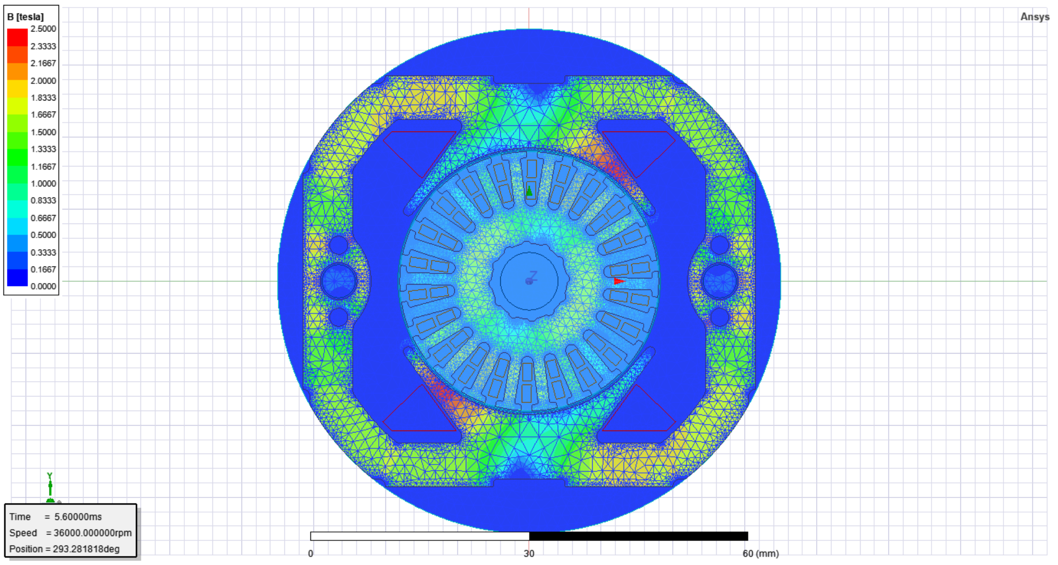

Fig. 2. Magnetic flux density of the existing motor

The motor was tested for pneumatic performance by obstructing the turbine inlet orifices. This simulates the usage of the vacuum cleaner, from an orifice of 50mm that corresponds to no obstruction to an orifice of 0mm when the inlet is completely sealed. From internal studies, it was deduced that the average usage of the vacuum cleaner on the carpet is equivalent to an orifice of 16mm, which is considered the nominal working point of the motor.

Table 1 presents the performance of the existing turbine-motor. The electrical parameters are as follows: voltage supply (U), input current (I) and electric power (Pel). The output parameters of the turbine are represented by speed (n), air flow (h), vacuum (q) and air power (Pair). The efficiency (Eff) is calculated as air power to electric power ratio.

Table 1

Electric and air data of the existing turbine motor

Orifice [mm]	U [V]	I [A]	Pel [W]	n [rpm]	h [mbar]	q [l/s]	Pair [W]	Eff [%]
50	230	4.13	926	33614	8.7	44.5	38	4.2
40	230	4.09	917	33600	17.5	40.3	70	7.6
30	230	4.04	906	33681	44.8	36.1	161	17.8
23	230	3.93	882	34170	91.6	30.0	275	31.2
19	230	3.78	848	35021	126.5	23.8	302	35.6
16	230	3.57	801	36203	141.3	17.8	252	31.5
13	230	3.34	750	37611	157.5	12.4	196	26.1
10	230	3.09	695	39215	166.8	7.6	127	18.2
6.5	230	2.87	648	40856	176.4	3.3	59	9.1
0	230	2.71	613	41986	186.8	0.0	0	0.0

The motor was tested on a hysteresis dynamometer without the turbine in an external laboratory (Fig. 3). The measurements were performed on the motor without the cooling fan to obtain the motor's mechanical power.

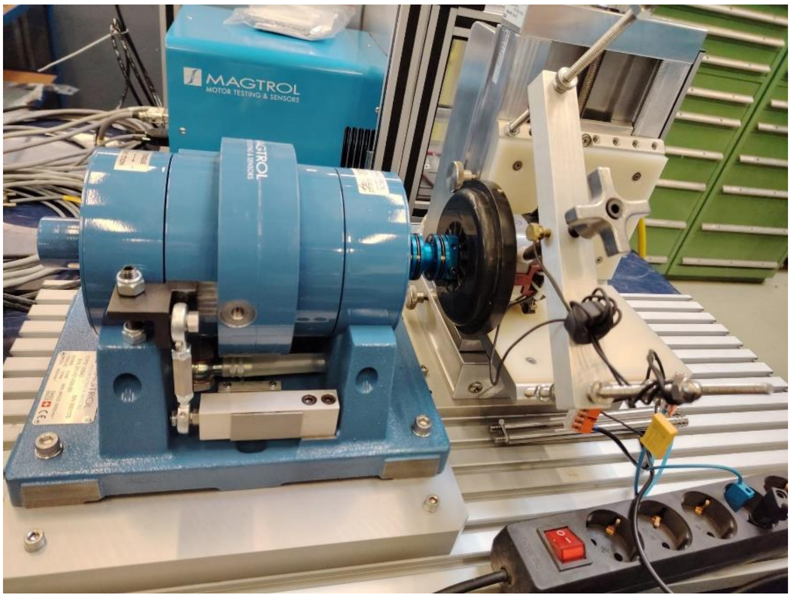

Fig. 3. Existing motor tested on dyno

Table 2 presents the dyno test results of the existing motor. The input parameters are: voltage (U), current (I) and electrical power (Pel). The measured mechanical data is: speed (n), torque (T) and mechanical power (Pmec). The efficiency (Eff) is defined as mechanical to electrical power ratio.

Table 2

Existing motor test on the dyno

Configuration	U [V]	I [A]	Pel [W]	n [rpm]	T [Nm]	Pmec [W]	Eff [%]
Motor without cooling fan	230	3.60	805	36207	0.147	553	68.6

The constant torque test at 0.147Nm proved to be well chosen. The motor speed was 36207 rpm which is very close to the 36203rpm from the air data test. Also the electric power of 805W is similar to the value of 801W measured on the air data test. All these considerations validate the setup for the measured mechanical power.

3. Design of a new turbine-motor

The new turbine-motor is designed considering that the air power at the orifice of 16mm should be minimum 250W and the electric power should be less than 800W. The turbine should be competitive in terms of price compared to the existing motor manufactured by the Asian supplier. All the technical improvements of the motor are dedicated to the reduction of the motor size, while maintaining the requested efficiency.

Three key design aspects were implemented into the new turbine-motor:

An improved cooling solution that consists of placing the commutator on the lower side of the turbine so that the heat generated by the commutator is evacuated faster, and a new cooling fan manufacturing process, making it by plastic injection instead of using metal sheet stamping. The lower temperatures obtained on the stator allowed a higher current density in the stator winding. The wire gauge was reduced, thus obtaining a material cost reduction for the aluminum stator wire. The required winding slot is smaller, and the additional space was dedicated to the iron core, reducing iron losses.

An improved magnetic circuit obtained using a new way of assembling the motor by replacing the two screws that pass through the stator yoke and hold together the front and rear shields. The new end shields have screws on the outside of the stator and four additional centering pins that ensure the motor alignment. The same motor torque is obtained with a stack height reduction from 25mm to only 18mm.

A new turbine cover was simulated in a CFD software, which has an increased efficiency in transforming the air power into mechanical work. Using this new turbine cover lowers the required motor torque.

The prototype of the new turbine motor with 3D printed end shields, turbine cover and cooling fan is presented in Fig. 4.

Fig. 4. Prototype of new turbine motor

The magnetic flux density map of the new lamination shape is simulated and presented in Fig. 5.

4. Testing the new turbine motor

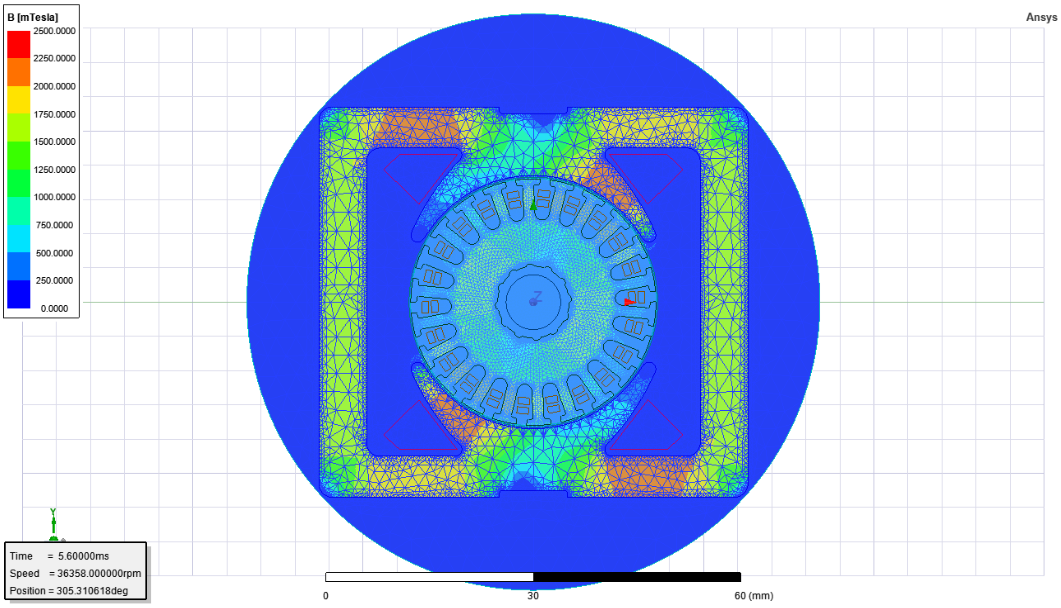

Fig. 5. Magnetic flux density of new motor

The air data of the prototyped turbine was measured and the results are shown in Table 3.

Table 3

Air data measurement of the new turbine motor

Orifice [mm]	U [V]	I [A]	Pel [W]	n [rpm]	h [mbar]	q [l/s]	Pair [W]	Eff [%]
50	230	3.88	873	33165	8.1	42.8	34.6	3.9
40	230	3.87	870	33110	16.5	39.1	64.4	7.4
30	230	3.84	863	33410	42.9	35.3	151.8	17.6
23	230	9.71	834	33992	90.1	29.8	268.7	32.2
19	230	3.53	794	34933	124.6	23.7	295.7	37.2
16	230	3.33	748	36358	143.4	18.0	258.0	34.5
13	230	3.06	690	38162	164.1	12.6	208.1	30.1
10	230	2.79	629	40222	175.4	7.7	136.5	21.6
6.5	230	2.54	577	42093	190.3	3.4	65.8	11.4
0	230	2.38	540	44324	202.5	0.0	0.0	0.0

Analyzing the measured results for orifice opening of 16mm, an improvement of total efficiency of 3% can be observed.

5. Simulation and testing results

Table 4 shows the electromagnetic field simulation data obtained for the electrical and mechanical power. The results are compared with the measured air data and dyno test. N/A (not applicable) is an abbreviation used when the data is not applicable to the test. For example, orifice is not applicable for dyno test and mechanic power is not measured on the air data test.

Table 4

Comparison between simulations and measurements

Motor	Measurement	Orifice [mm]	n[rpm]	Pel[W]	Pmec[W]	Eff [%] El-mec	Pair[W]	Eff [%] El-Air
Actual	Air data	16	36203	801	N/A	N/A	252	31.5
Actual	Dyno/ no fan	N/A	36207	805	553	68.6	N/A	N/A
Actual	Sim.	N/A	36203	802	542	68.0	N/A	N/A
New	Air data	16	36358	748	N/A	N/A	258	34.5
New	Sim.	N/A	36358	763	514	67.3	N/A	N/A

The air data measurement is the most reliable way of testing as the motor is running in its natural condition. The dyno test of the existing motor provides very good correlation between measured and simulated data for electrical power (0.5% deviation) and motor speed (0.01% deviation). This confirms that the working point of the motor is well chosen for the dyno test (i.e., the load torque is right) and the motor shaft is properly aligned to the dyno shaft. This test provides the mechanical power at the shaft of the motor. This value is the verification key for the electromagnetic field simulation. As the deviation is only 2%, it confirms the simulation is accurate, and the numerical model can be used to design the new motor.

The newly designed turbine-motor has very good air data results, keeping under consideration that to order to keep the price competitive the 25 mm stack height of the existing turbine-motor was reduced to 18 mm. The electrical power consumption is 52W below the target of 800W and the air power is 8W above the 250W target. These improvements increased the efficiency of converting electrical to air power, by 3%. As the new motor was not tested on the dyno due to project time constraints, the only way to calibrate the simulation was using the electrical power. The deviation between the real electrical power consumption and the simulated value was 2%. This small deviation shows that the simulation model is very robust and can be used in any new motor case.

6. Conclusions

In this paper a new turbine motor for vacuum cleaners was designed, prototyped and tested. The main features of the design are:

An improved cooling solution was proposed. The new turbine-motor has the commutator placed on the turbine side. This allows the heat to be dissipated without passing through the motor. The upper end shield covers the stator facilitating cooling airflow through the stator and rotor. The cooling fan shape was redesigned to produce more airflow.

An improved magnetic circuit takes advantage of the mounting screws not passing through the stator, making the effective yoke wider. The improved cooling solution allowed for a smaller stator wire gauge and created more space for increased stator pole area.

A new turbine cover was proposed. The new design consists in an increased diameter and a smaller number of scoops with increased area. These solutions reduced the turbulence in the airflow and increased the turbine efficiency.

The main goal of the project was to keep the electric performance with a competitive material cost. The price target was achieved and the efficiency of the new turbine-motor (for an orifice opening of 16mm) is 3% higher than the existing motor. The reduction in size resulted in a lighter motor that is better for the user when vacuum cleaning. The new turbine motor will begin the manufacturing phase and the design concept will be extended to other vacuum cleaner turbines.

R E F E R E N C E S

[1]. *B. Korousic-Seljak, G. Papa, B. Benedicic and T. Kmecl*, "Improving the technical quality of a universal motor using an evolutionary approach," Proceedings 27th EUROMICRO Conference. 2001: A Net Odyssey, Warsaw, Poland, 2001, pp. 287-293.

[2]. *A. Oprea and D. Floricau*, "Field Oriented Control of Permanent Magnet Synchronous Motor with Graphical User Interface," 2021 12th International Symposium on Advanced Topics in Electrical Engineering (ATEE), Bucharest, Romania, 2021, pp. 1-4.

[3]. *O. Craiu, T. I. Ichim and L. Popescu*, "FEM study of a synchronous motor with different permanent magnet topologies," U.P.B. Sci. Bull., Series C, **vol. 85**, Iss. 1, 2023.

[4]. *S. Ok and D. H. Lee*, "Sensorless Control of High-Speed BLDC Motor for Vacuum Cleaner Using Sliding Mode Observer," 2022 IEEE 5th Student Conference on Electric Machines and Systems (SCEMS), Busan, Republic of Korea, 2022, pp. 1-4.

[5]. *Z. Yang, F. Shang, I. P. Brown and M. Krishnamurthy*, "Comparative Study of Interior Permanent Magnet, Induction, and Switched Reluctance Motor Drives for EV and HEV Applications," IEEE Transactions on Transportation Electrification, **vol. 1**, no. 3, pp. 245-254, Oct. 2015.

[6]. *N. Majlesi, S. M. S. Nejad and A. Rashidi*, "Multi-Physics Electromagnetic-Mechanical Analysis of a High-Speed Switched Reluctance Motor for Vacuum Cleaner Application," 2024 32nd International Conference on Electrical Engineering (ICEE), Tehran, Islamic Republic of Iran, 2024, pp. 1-6.

[7] S. Roopa, H. B. Manju, M. Shadab, J. Nikhil and N. S. Nithin, "Design of Voice Automated Floor Cleaning Robot," 2023 12th International Conference on Advanced Computing (ICoAC), Chennai, India, 2023, pp. 1-7.

[8]. *R. N. Tuncay, M. Yilmaz and C. Onculoglu*, "The design methodology to develop new-generation universal-motors for vacuum cleaners," IEEE International Electric Machines and Drives Conference, Cambridge, 2001, pp. 926-930.

[9]. *C. D. Oancea, V. C. Petre and V. A. Boicea*, "Educational and Experimental Study for Evaluation of an Universal Motor," 2019 11th International Symposium on Advanced Topics in Electrical Engineering (ATEE), Bucharest, 2019, pp. 1-4.

[10]. *Jun-Young Lim, Yun-Chul Jung, Sang-Young Kim and Jung-Chul Kim*, "Single phase switched reluctance motor for vacuum cleaner," 2001 IEEE International Symposium on Industrial Electronics Proceedings, Pusan, South Korea, 2001, **vol.2**, pp. 1393-1400.

[11]. *S. B. Alam, S. S. Islam, M. R. Uddin and K. M. Salim*, "48V Three-Phase Induction Motor Development for a Portable Industrial Vacuum Cleaner by using LV VFD Controller," 2020 11th International Conference on Electrical and Computer Engineering (ICECE), Dhaka, Bangladesh, 2020, pp. 254-257.

[12]. *S. Ok and D. -H. Lee*, "Sensorless Control of High-Speed BLDC Motor for Vacuum Cleaner Using Sliding Mode Observer," 2022 IEEE 5th Student Conference on Electric Machines and Systems (SCEMS), Busan, Korea, Republic of, 2022, pp. 1-4.

[13] *M. I. Hasan*, "Scheme and Construction of a Smart Vacuum Cleaner Robot," 2023 Third International Conference on Advances in Electrical, Computing, Communication and Sustainable Technologies (ICAECT), Bhilai, India, 2023, pp. 1-6.

[14] *K. Saravanan, E. Siva Prasanna, R. Sattish, R. Udhaya Abinesh and P. Anandakumar*, "Automatic Floor Cleaning Robot," 2022 IEEE International Conference on Data Science and Information System (ICDSIS), Hassan, India, 2022, pp. 1-5.

[15] *H. -Y. Park and J. -M. Lee,* "Development of a Floor-Mopping Robot," 2019 19th International Conference on Control, Automation and Systems (ICCAS), Jeju, Korea (South), 2019, pp. 678-680.

[16] *W. H. C. Wickramaarachchi, M. A. P. Chamikara and R. A. C. H. Ratnayake*, "Towards implementing efficient autonomous vacuum cleaning systems," 2017 IEEE International Conference on Industrial and Information Systems (ICIIS), Peradeniya, Sri Lanka, 2017, pp. 1-6.
[17] *M. Xu, Z. Qiu and Z. Wang*, "Research on weakening control strategy of permanent magnet synchronous motor of high speed vacuum cleaner based on sliding mode observer," 2023 International Conference on Computers, Information Processing and Advanced Education (CIPAE), Ottawa, ON, Canada, 2023, pp. 562-568.
[18] *Y. Niwa and Y. Akiyama*, "Third harmonic restraint technique for the cleaner universal motor under power controller," 2009 International Conference on Power Electronics and Drive Systems (PEDS), Taipei, Taiwan, 2009, pp. 1470-1475.
[19]. *D. Olaru and D. Floricau*, "Design procedure for the input/output filter circuits used for single phase AC choppers", U.P.B. Sci. Bull., Series C, **vol. 69**, No. 3, 2007.