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Rigorous design and implementation of an innovative electric generation unit for a portable self-powered lung air flow meter

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ABSTRACT

An innovative portable self-powered digital lung air flow meter with a useful electrical generation unit (EGU) is proposed, for the monitoring of asthma and the measurement of the expiratory strength, using an electrical signal generated by the EGU. The EGU must be able to provide sufficient electric power to the proposed surveying instrument when a blower uses the instrument. The EGU is composed of a pneumatic turbine and a highly effective generator. A pneumatic turbine is used, in the form of a Pelton turbine, which has less air resistance and allows increased mechanical power for generation. A coreless axial-flux permanent-magnet (AFPM) generator, which has the advantages of simpler construction, lower cogging torque, light weight and small size, is also used to measure expiratory strength in this paper. The experimental results show that the proposed EGU exhibits excellent performance and provides sufficient electrical power to the proposed portable self-powered equipment, without vibration and noise.

KEYWORDS

Axial-flux permanent-magnet generator;
Cogging torque;
Finite element method;
Lung air flow meter.

INTRODUCTION

Asthma occurs in the lower airways, from the trachea down to the alveoli (air sacs). Asthma is an expiratory problem, caused by a narrowing of the airways and an increase in airway resistance[1]. In order to monitor asthma, doctors generally use a peak expiratory flow meter. A digital lung air flow meter measures the patient's maximum ability to expel air from the lungs, or the peak expiratory flow rate (PEFR or PEF), as shouren in Figure 1[2,3].

For digital applications, an innovative portable digital self-powered lung air flow meter is proposed for the monitoring of asthma and the measurement of expiratory strength. The structure of the proposed meter,

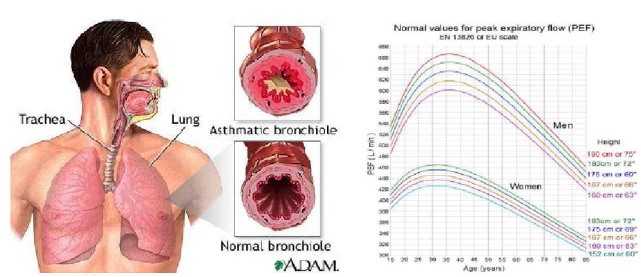
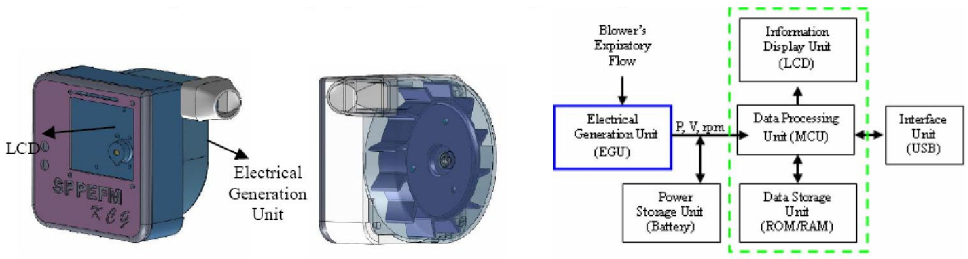


Figure 1 : Lung capacity and peak expiratory flow[1]

shown in Figure 2 composes six main units. These units can be form a single portable device that helps to diagnose and monitor asthma. Further, this proposed meter allows the use of the equipment anywhere, without of the need to recharge or change batteries. Another advantage of the machine is its reliability.



(a) The proposed equipment (b) Perspective drawing of the EGU (c) System structure

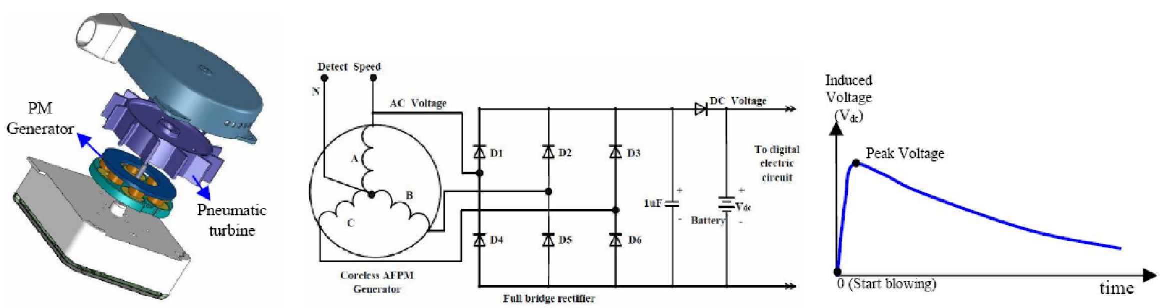
Figure 2 : The proposed self-powered digital lung air flow meter

However, in a self-powered digital lung air flow meter, the electric generation unit (EGU) is a main key component. The EGU not only serves as the digital signal generator for the presentation of air-flow data, but also acts as the energy source to recharge the batteries. This paper proposes an innovative EGU, with both a pneumatic turbine and a coreless AFPM generator, which provides sufficient electrical power to the proposed portable digital lung air flow meter.

CHARACTERISTICS OF THE PROPOSED ELECTRICAL GENERATION UNIT

A practical EGU is composed of a pneumatic turbine and a highly effective generator, as shown in Figure 3(a). The former behaves like a wind turbine and the latter is a high-quality permanent-magnet (PM) generator. The equivalent circuit model for the proposed electrical power generation unit is shown in Figure 3(b). Figure 3(c) is the curve for the DC output voltage of the EGU.

In order to maintain an unhindered airway for expiratory flow without obvious airway resistance and accurately measure the peak expiratory flow, a pneumatic turbine cannot assume the structure of a HAWT or VAWT that is usually used in wind power[4]. Hence, the pneumatic turbine must be redesigned to meet the needs of the proposed meter.



(a) Generation unit (b) Equivalent circuit model (c) Ideal induced voltage profile

Figure 3 : Electrical power generation unit

Currently, the axial-flux permanent-magnet (AFPM) machine is an attractive alternative to the radial-flux machines used in wind-turbine applications[5-7]. In a coreless AFPM generator, the permanent magnet (PM) replaces the field winding, so the copper losses are eliminated. Furthermore, the stator is made from a non-magnetic non-conducting material with a lightweight structure, such as PEEK engineering plastic, so iron losses are also eliminated. Therefore, coreless AFPM generators have the advantages of simpler construction, lower weight and size for the same performance, reduced losses and higher efficiency[7].

PNEUMATIC TURBINE

A Pelton turbine is used as the pneumatic turbine.

The mechanical power of the Pelton turbine model is dependent on the drag forces from the airflow. The drag force produced is caused by the pressure difference between the airflow hitting the inner part of the blades and the air blowing against the back of the blades. When there is an airflow with speed v (m/s), the kinetic energy available is:

$$E_{af} = \frac{1}{2} M v^2 \qquad (1)$$

To convert the kinetic energy, E_{af}, to mechanical power at the interval, t, the airflow power, P_{af}, can be expressed as follows:

$$P_{af} = \frac{1}{2} \rho A v^3 \qquad (2)$$

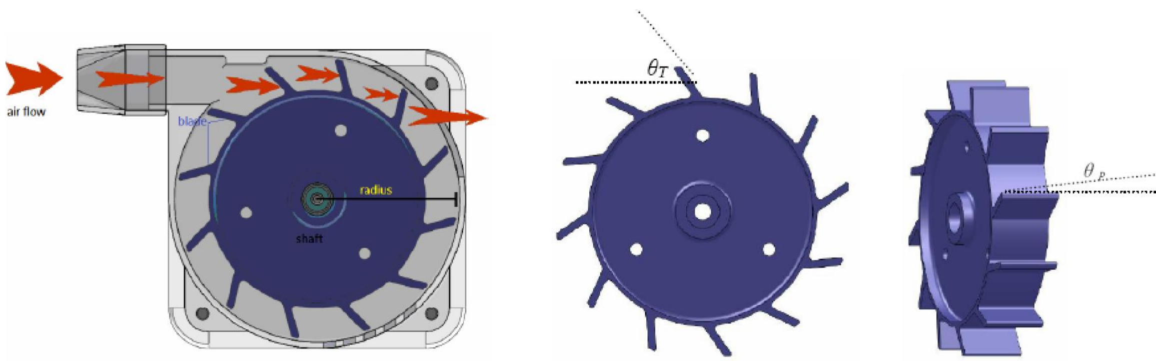
At standard temperature and pressure (STP = 273K and 101.3 KPa), the air density, ρ, is equal to 1.294, so the power of the airflow is proportional to the air density, the area of the segment of airflow being considered and the airflow speed.

In (2), the mechanical power generated can be calculated, but it should be noted that the pneumatic turbine cannot convert all of the airflow power into mechanical power, for generation, because some of the airflow energy is consumed in pressure changes across the turbine blades. This pressure change causes a decrease in velocity and therefore usable energy. Therefore, the mechanical power (P_m) and torque (T_m) can be re-expressed respectively as

$$P_m = \eta C_p P_{af} = \frac{1}{2} \eta C_p \rho A v^3 \qquad (3)$$

$$T_m = P_m / \omega_m \qquad (4)$$

In (4), ωm is the rotating speed of turbine and η and Cp are the efficiency coefficient and the performance coefficient of the pneumatic turbine, respectively. The performance coefficient depends on airflow speed, the rotational speed of the turbine and blade parameters such as the pitch angle (θ_P) and the angle of attack (θ_T), as shown as Figure 4. The pitch angle is the angle between the line perpendicular to the blades' motion and the chord line of the blade. The angle of attack is the angle between the relative airflow velocity and the centerline of the blade.



(a) Structure (b) Angle of attack (θ_a) (c) Pitch angle (θ_P)

Figure 4 : Structure of a pneumatic turbine

CORELESS AFPM GENERATOR

A single-sided coreless axial-flux permanent magnet (AFPM) generator is designed for the proposed device, as shown in Figure 5(a). This is cost effective, reliable and simple to manufacture[4]. The proposed coreless AFPM generator uses one steel rotor disc and one non-magnetic non-conducting stator disc. The former carries the NdFeB permanent magnets, arranged circumferentially around the rotor in a N-S-N-S arrangement, as shown in Figure 5(a). The latter uses PEEK engineering plastic carrying coils to eliminate the cogging torque and to reduce the iron loss. The pneumatic turbine is then integrated with the rotor disc of the AFPM generator. The magnetic flux loop of the 6-slot 8-pole coreless AFPM generator is shown in Figure 5(b). The instantaneous induced electromotive force (EMF) of each phase is

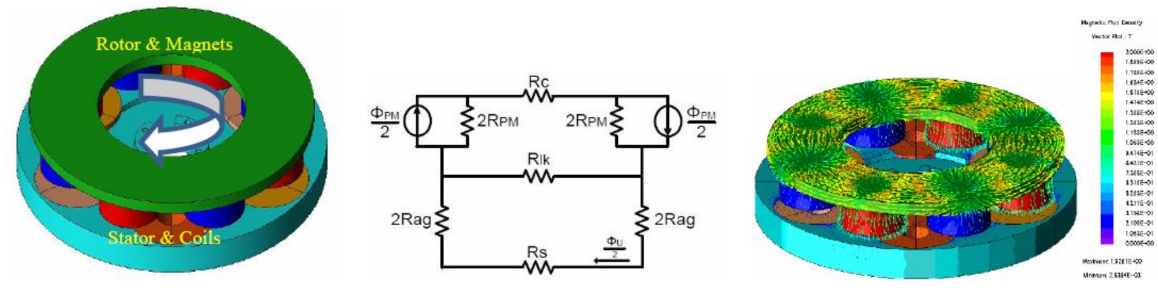
$$e_{ph}(t) = \sum_{C=1} N_c A_u B_u \omega \sin \omega t \qquad (5)$$

where, B_u is the air-gap magnetic flux density.

Figure 5(c) also shows a simulated 3-D air-gap flux density distribution for the proposed AFPM machine, used to predict the induced EMF of the stator windings[8]. Figure 6 shows the outlines of flux density at different measurment position.

IMPLEMENTATION AND PERFORMANCE TESTING

TABLE 1 shows the geometric parameters of the proposed coreless AFPM generator. The proposed



(a) 6s8p Coreless AFPM Generator (b) lumped magnetic circuit (c) Air-gap flux density using 3-D FEM

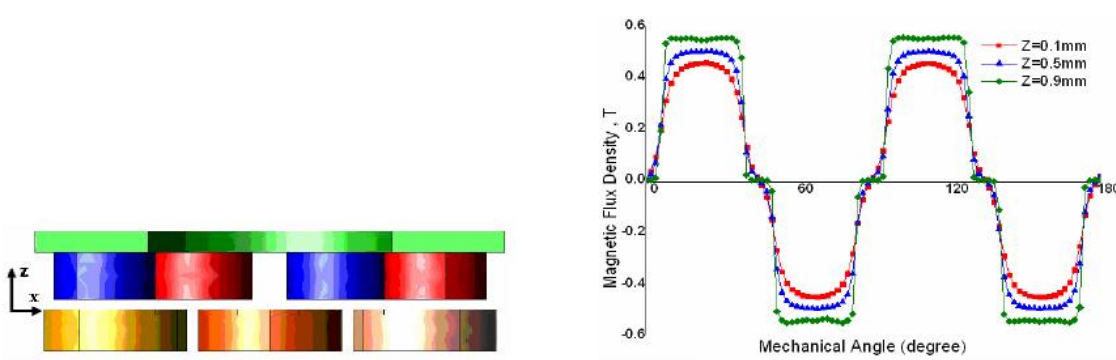
Figure 5 : Electrical power generation unit

pneumatic turbine and the coreless AFPM generator are assembled to form an EGU. Figure 6 shows the prototype of the proposed EGU.

TABLE 1 : Geometric parameters of the proposed AFPM generator

Phase	3 (Y)	Air-gap (mm)	0.5
Pole	8	Stator diameter (mm)	50
Slot	6	Rotor diameter (mm)	46
Rotor yoke	S45C	Coil turns	900
Stator	PEEK	Speed(rpm)	300~1500
Magnet	NEOMAX-35		

Using the results of practical experiments, Figure 7 shows the induced voltage profile with no-load at a rated speed of 600rpm. The peak value of the induced voltage, determined by 3-D FEM, is 5.36 (V) and the practical test voltage is 5.8 (V). Figure 8(a) and Figure 8(b) respectively show the peak values of the induced voltages with no-load and heavy-load (100Ω/phase) at different speeds. The solid line is the induced voltage, determined by 3-D FEM, and the dotted line is the induced voltage, determined by practical tests. As can be seen in Figure 8, the results for the practical tests are almost the same as those for the simulation using 3-D FEM.



(a) Measurement position (b) Outlines of flux density at different position

Figure 6 : Air-gap flux density

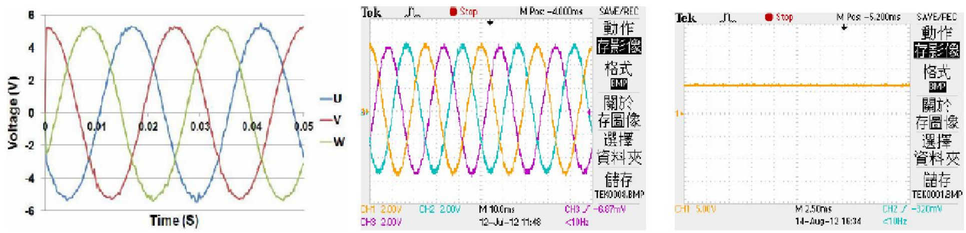
Figure 9 shows a practical induced voltage profile generated by a blower. The result of the practical test is almost the same as the ideal induced voltage profile shown in Figure 3(c).

The results of these experiments and comparisons show that the proposed design is feasible and that the coreless AFPM generator can provide sufficient electrical power for the portable digital lung air flow meter.

An EGU that is free of cogging torque, small, lightweight, low-speed and that has low vibration and noise and high efficiency, provides sufficient electric power to the proposed equipment. The proposed EGU composes

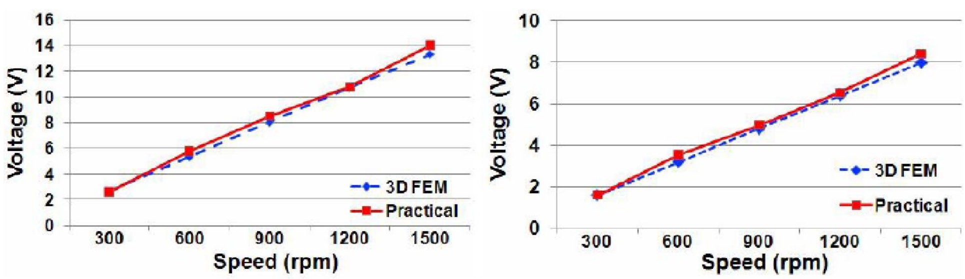
(a) LCD Panel, rotor and stator (b)The assembled equipment

Figure 7 : Prototype of the proposed equipment



(a) Simulation using 3-D FEM (b) AC voltage (c)DC voltage

Figure 8 : Induced voltage profile with no-load (600 rpm)



(a) no-load (b) with a heavy-load of 100Ω/phase

Figure 9 : Induced voltages at different speeds

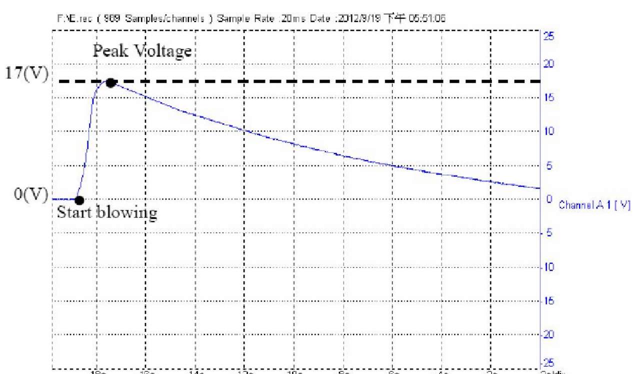


Figure 10 : Induced voltage profile generated by a blower (measured using a Sefram DAS600)

a pneumatic turbine and a highly effective generator. The pneumatic turbine, in the form of a Pelton turbine, generates mechanical power. A single-sided coreless axial-flux permanent-magnet (AFPM) generator also provides sufficient electrical power to the proposed meter. The experimental results show that the proposed EGU has excellent performance and that it provides sufficient electrical power to the proposed self-powered equipment, without vibration and noise. Since the proposed EGU exhibits excellent performance, it form the basis of a self-powered digital water flow meter, in future work.

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