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RECENT ADVANCEMENTS IN PERMANENT MAGNET MOTORS TECHNOLOGY FOR MEDICAL APPLICATIONS

ABSTRACT *The paper discusses new constructions of permanent magnet (PM) brushless motors for medical and surgical devices, especially for implantable axial flow and centrifugal blood pumps. These motors usually have slotless stators and rotors integrated with pump impellers. Magnetic or hydrodynamic bearings are used because this type of bearings secures the longest life. Therapy, surgery and health care are, today, increasingly dependent on electrical and electronics engineering.*

Keywords: *mikro- PM brushless motors, new technologies in medicine, medical apparaturs and devices*

1. INTRODUCTION

When electricity was new, people had high hopes that it had curative powers. For example, *electropathy* (electrodes between patient's hands and ailing body part), very popular from 1850 to 1900, promised to cure most

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diseases and conditions, including mental illness. The 21st century biomedical engineering community has resurrected magnetic fields to treat depression, e.g., *magnetic seizure therapy* (high frequency, powerful electromagnets) or *transcranial magnetic stimulation* (strong pulse magnetic fields).

At present, many medical devices use small permanent magnet (PM) electric motors as, for example, high-quality pumps, centrifuges, infusion pumps, hemodialysis machines, precision handpieces and implantable devices (ventricular assist devices, pacemakers, defibrillators, nerve stimulators, etc). This paper focuses on very small PM brushless motors for *implantable devices*, in particular, motors for *rotary blood pumps*.

The most important choice for medical device designers is between ferromagnetic core and coreless motors. The elimination of the heavy iron offers such advantages as reduced mass, low electrical time constant, high power efficiency, zero cogging torque and low input current. Ferromagnetic core-free motors have become the rule in battery-operated or remotely situated devices where rapid cycling or long battery life is important.

Since the reliability of medical products is critical, the motor is considered a precision component rather than a commodity device [2]. Motors and actuators for medical applications must frequently endure hostile environments, caustic fluids, radiation, steam, elevated temperatures, vacuum, vibration and mechanical impact.

Improvements in motor capabilities have already helped medical device manufacturers bring such products as portable, disposable, and battery-operated instruments to market [2].

2. MATERIALS

PMs for medical devices should have high energy density, increased oxidation resistance and stable magnetization curves over extended periods of time. Miniaturization of brushless motors is possible due to availability of modern NdFeB PMs with remanence B_r up to 1.45 T, coercivity H_c over 1100 kA/m and $(BH)_{max}$ product about 400 kJ/m^3.

Compared with popular sintered bronze bearings and expensive stainless-steel ball bearings, sintered ceramic bearings provide up to 50 % more load-bearing capability in precision gearing systems. In the case of brushless motors, bearing life is the limiting factor, so that such motors can achieve lifetimes of 20,000 hours, or more, versus the 300 to 5000 hours that is typical for brush-type motors. For internal applications *hydrodynamic* or *magnetic bearings* are used because this type of bearing secures the longest life. In the case of a hydrodynamically levitated impeller, the pump impeller floats hydraulically into the top contact position. This position prevents *thrombus*, i.e., blood clot formation, by creating a washout effect at the bottom bearing area, a common stagnant region.

Incorporation of advanced plastic and composite components in motor and gearhead systems reduces cost, mass, and audible noise, and provides uniform products with short lead times [2].

Using hardened steels for shafts and cutting gears more precisely improves gear motor capabilities by decreasing backlash and lengthening gear life.

3. IMPLANTABLE BLOOD PUMPS

A *left ventricular assist device* (LVAD) is an electromechanical pump implanted inside the body and intended to assist a weak heart that cannot efficiently pump blood on its own. It is used by end-stage heart failure patients who are unable to receive a heart transplant due to donor availability, eligibility, or other factors.

Motor driven pumps implanted in the human body must be free of *shaft seals*. This problem can be solved by embedding PMs in the pump rotor placed in a special enclosure and driven directly by the stator magnetic field. In this case the nonmagnetic air gap is large and high energy PMs are required.

Electromagnetic pumps for LVADs can be classified into three categories:

- 1st generation (1G), i.e., pulse pumps;
- 2nd generation (2G), i.e., rotary pumps with mechanical bearings;
- 3rd generation (3G), i.e., rotary pumps with magnetic or hydrodynamic bearings.

Electromagnetic 1G pumps were driven by electromagnets, linear oscillating motors or linear short-stroke actuators. The pump, integrated with a linear actuator, is heavy, large and noisy.

DeBakey 2G LVAD *axial flow rotary pump* manufactured by *MicroMed Technology, Inc*., Houston, TX, U.S.A., is driven by a novel PM brushless motor with magnets embedded in the blades of the impeller (Fig. 1). The inducer/impeller has six blades with eight PMs sealed in each blade and spins between 8,000 and 12,000 rpm [3]. This allows it to pump up to 10 liters of blood per minute. All parts are enclosed in a sealed titanium tube. The bearings are blood-immersed pivot bearings. The titanium inlet tube attaches to the left ventricle**.** The outlet tube is sewn to the aorta.

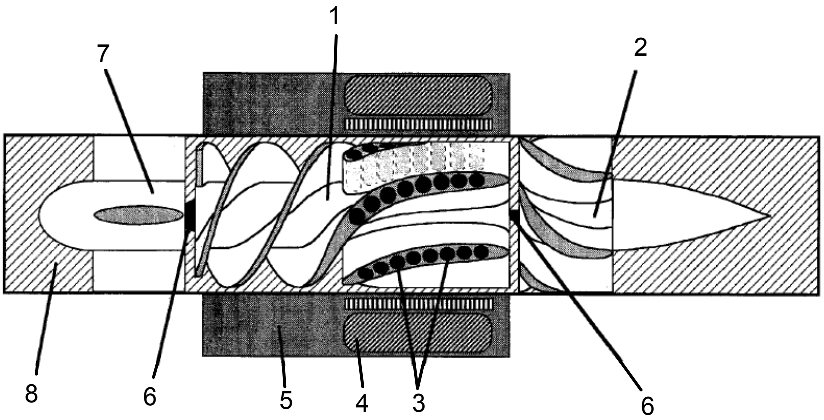

Fig. 1. Longitudinal section of DeBakey axial flow rotary blood pump: 1 – flow inducer/impeller, 2 – flow diffuser, 3 – PMs, 4 – stator winding, 5 – stator, 6 – bearing, 7 – flow straightener, 8 – flow housing

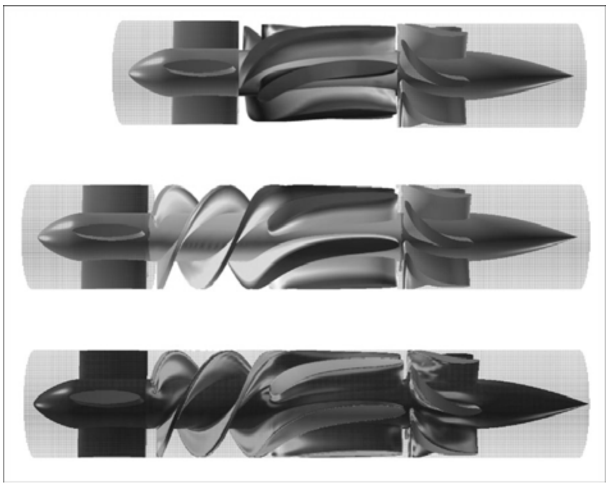

Fig. 2. DeBakey rotary pump: original design (top) and modifications by NASA researchers (middle and bottom image)

An inducer added by NASA researchers eliminates the dangerous back flow of blood by increasing pressure and making flow more continuous. The device is subjected to the highest pressure around the blade tips, shown in magenta (Fig. 2) .

An example of 3G axial rotary blood pump is the *Streamliner*, developed at University of Pittsburgh, PA, U.S.A. [1]. The design objective was to magnetically levitate and rotate a pump impeller in the bloodstream while minimizing pump size, blood damage, battery size, and system weight.

The *Streamliner* topology is shown in Fig. 3 (U.S. patent 6,244,835). The stator (32) has a slotless core and toroidal winding. PMs (34) constitute the rotor excitation system. The key design elements are a cylindrical magnetically levitated rotating impeller (12), which is supported on PM radial bearings (9 and 10). The inner races of these bearings are fixed and supported by the outflow hub (18) and the inlet stator blades (20). The axial position of the impeller is actuated by the coils (38 and 40) interacting with the outer race magnets of the bearing (9). Sensing of the axial position is accomplished with eddy-current sensor probes (26 and 28). The outputs of these sensors are summed to render pitching motions of the impeller unobservable and decoupled from the axial feedback loop. Although the rotor is magnetically controlled in six degrees of freedom, only two degrees of freedom are actively controlled: axial and rotational motion. A 3D image of the *Streamliner* is shown in Fig. 4.

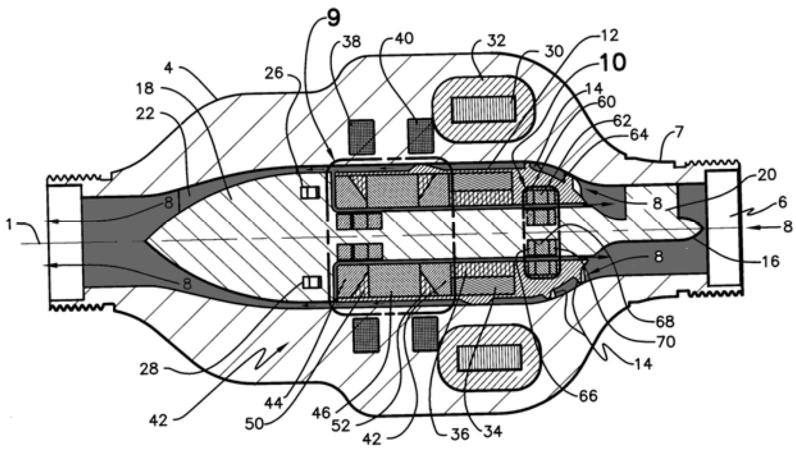

Fig. 3. Longitudinal section of *Streamliner* axial rotary blood pump with magnetic bearings according to U.S Patent No. 6,244,835. Description in the text

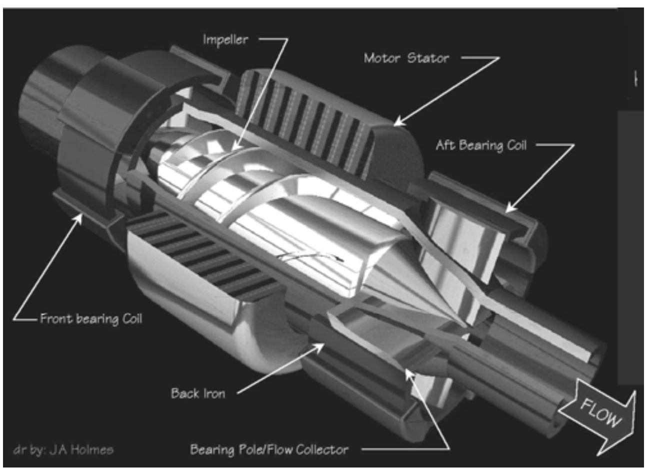

Fig. 4. Computer generated 3D image of the *Streamliner* blood pump

The *DuraHeart*® 3G LVAD developed by *Terumo Corporation*, Tokyo, Japan, combines *centrifugal pump* with *magnetic levitation* technologies (Figs 5 and 6). Magnetic levitation allows the impeller to be suspended within the blood chamber by electromagnets and position sensors. The three-phase, 8-pole, axial flux PM brushless motor with slotless stator resembles a floppy disk drive spindle motor (Fig. 5). NdFeB PMs are integrated with the impeller. The output power of the motor is 4.5 W, speed 2000 rpm and torque 0.0215 Nm [3].

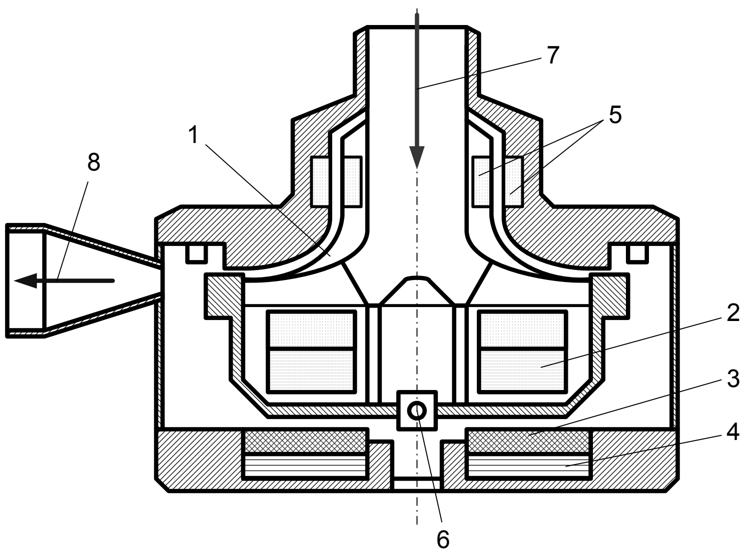

Fig. 5. DuraHeart® centrifugal rotary pump with axial flux PM brushless motor and magnetic levitation bearings: 1 – impeller, 2 – PM, 3 – stator winding, 4 – stator core, 5 – magnetic suspension, 6 – ceramic pivot, 7 – inlet, 8 – outlet

Fig. 6. Exploded view of DuraHeart® centrifugal rotary pump. Courtesy of *Terumo Corporation*, Tokyo, Japan

An axial flux slotless motor integrated with a centrifugal blood pump is shown in Figs. 7 and 8. The so-called *VentrAssist*™ manufactured now by Australian company *Ventracor* is a new cardiac LVAD which has only one moving part – a hydrodynamically suspended impeller integrated with a PM rotor. The hydrodynamic forces act on tapered edges of the four blades. The stator of the brushless electric motor is of slotless type and has only upper and lower coils. The three coil winding and four pole rotor use the second harmonic of the magnetic field wave to produce the torque. To provide redundancy, body coils and cover coils are connected in parallel so that the motor still can run even if one coil is damaged.

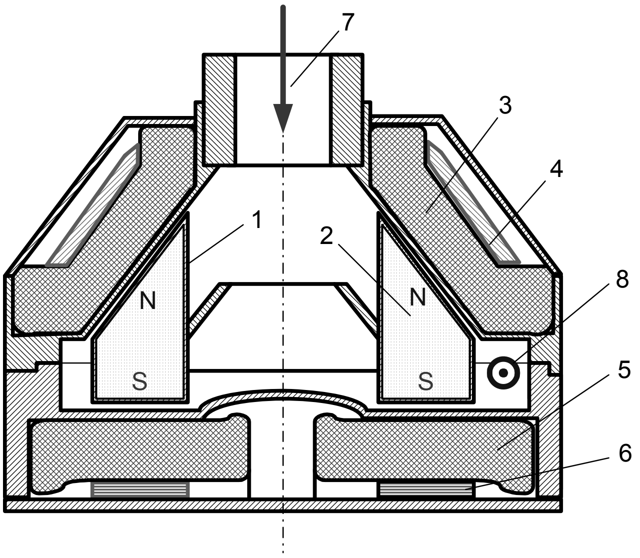

Fig. 7. Longitudinal section of *VentrAssist*™ hydrodynamically levitated centrifugal blood pump: 1 – impeller, 2 – PM, 3 – body coil, 4 – body yoke, 5 – cover coil, 6 – cover yoke, 7 – inlet, 8 – outlet

Fig. 8. Computer generated 3D image of *VentrAssist*™ centrifugal blood pump

The housing and impeller shell are made of titanium alloy Ti-6Al-4V. Vacodym 510 HR NdFEB PMs are embedded into imepller. To reduce the reluctance for the magnetic flux, laminated silicon steel return paths (yokes) are designed.

The 2D FEM simulation of the magnetic field distribution is shown in Figs 9 and 10. The measured performance characteristics are shown in Figs. 11 and 12 [3]. For output power between 3 and 7 W and speed between 2000 and 2500 rpm, the efficiency is from 45 to 48 % (Fig. 11). At 3 W and 2250 rpm the winding losses are 1.7 W, eddy current losses in titanium 1.0 W and losses in laminated yokes are 0.7 W [3]. At load torque 0.03 Nm the fundamental phase current is 0.72 A (Fig. 12).

The device weighs 298 g and measures 60 mm in diameter, making it suitable for both children and adults.

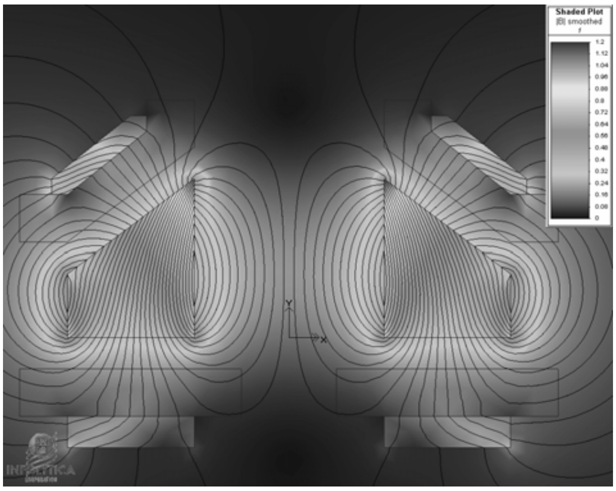

Fig. 9. Magnetic flux (contour plot) and magnetic flux density (shaded plot) excited by NdFeB PMs at no load

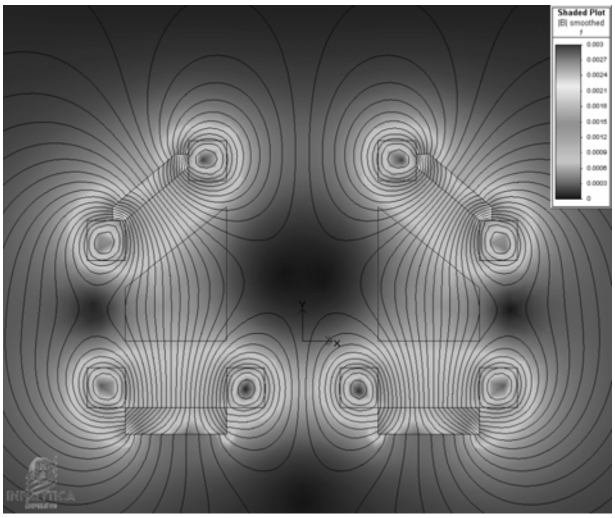

Fig. 10. Magnetic flux (contour plot) and magnetic flux density (shaded plot) excited by armature (stator) coils

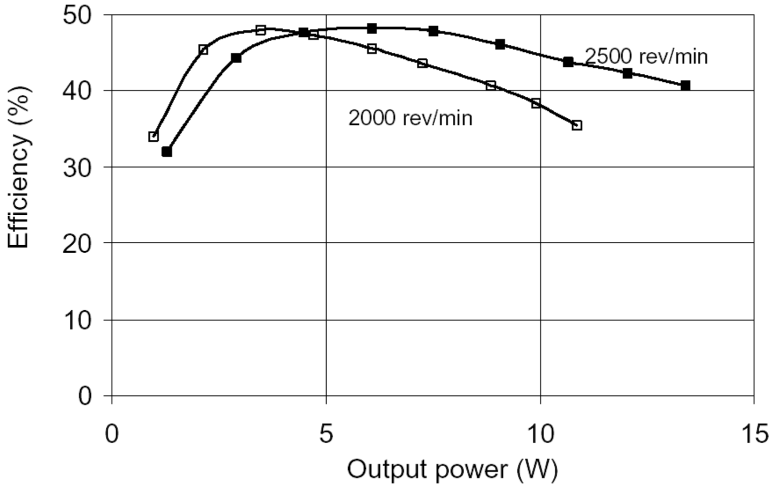

Fig. 11. Efficiency of VentrAssist™ BA2-4 pump driven by a six-step sensorless inverter [3]

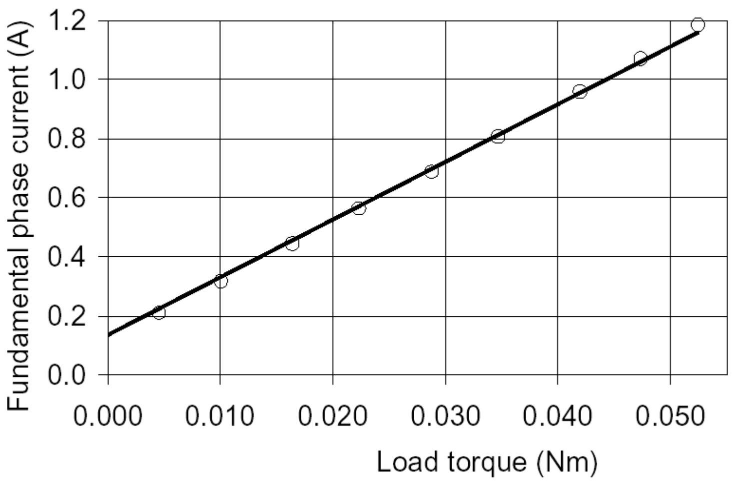

Fig. 12. Fundamental phase current calculated on the basis of EMF (solid line) and obtained from laboratory tests (circles) [3]

4. OTHER APPLICATIONS OF MINIATURE MOTORS

A brushless motor with planetary gearhead and outer diameter below 2 mm has many potential applications such as motorized catheters (Fig. 13), minimally invasive surgical devices, implantable drug-delivery systems and artificial organs [6]. An *ultrasound catheter* shown in Fig. 13 consists of a catheter head with an ultrasound transducer on the motor/gearhead unit and a catheter tube for the power supply and data wires. The site to be examined can be reached via cavities like arteries or the ureter. The supply of power and data to and from the transmit/receive head is provided via slip rings. The stator of the brushless motor is a coreless type with skewed winding. The rotor has a 2-pole NdFeB PMs on a continuous spindle. The outer diameter is 1.9 mm, length of motor alone is 5.5 mm and together with gearhead is 9.6 mm (Fig. 14). The output power is 0.13 W, no-load speed 100 000 rpm, no-load current 0.032 A, maximum current 0.2 A (thermal limit), maximum torque 0.012 mNm and efficiency 26.7 % [6]. The high-precision rotary speed setting allows analysis of the received ultrasound echoes to create a complex ultrasound image.

Small PM brushless motors are also used in motorized lightweight *surgery grippers* [4] and *surgical robotic systems* [5].

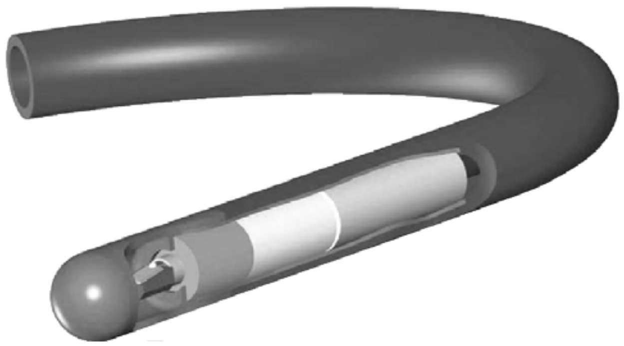

Fig. 13. Ultrasound motorized catheter [6]

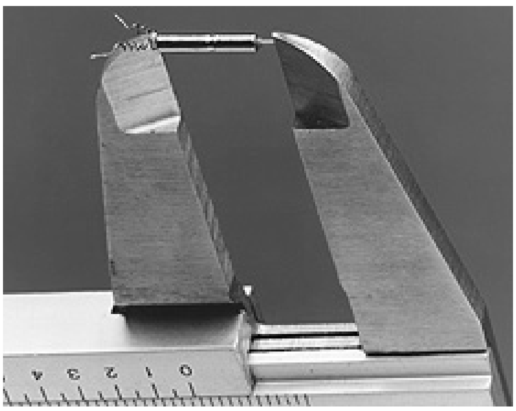

Fig. 14. 1.9-mm diameter PM brushless motor. Photo courtesy of *Faulhaber GmbH*, Schonaich, Germany

5. MEMS

Based on semiconductor processing technology, the MEMS promises micrometer-range sensors and actuators. While University researchers in numerous publications have presented successful results in this area, the reality is that the physics of the micro world are not necessarily the same as those of the macro world and the cost of manufacturing MEMS products is higher than that of traditional motor technologies [2]. Other aggravating problems are that very small motors are difficult to interface with other components, have very little usable power, and are tremendously inefficient. They sometimes require very high voltage (100 to 300 V dc) to operate and are very difficult to assemble.

Nevertheless, working prototypes of hybrid MEMS motors are being produced today and some versions will probably soon be available to customers on a limited basis. MEMS micromachining techniques are used to produce some of the motor and gearing parts. More traditional micromotor technologies are used to solve the assembly, lubrication, and power issues.

6. CONTROL

In *open-loop control*, when power is applied to the motor, it performs some turning, running, or incremental motion, disregarding the reference position. Motors for medical devices mostly require *closed loop control*. For example, in a typical surgical device, such as drill or saw, the feedback that controls a motor may be a physician who is applying physical pressure to change the speed. To provide greater consistency, or to allow a machine to perform a procedure inaccessible to human hands, it is desirable to integrate a feedback device into the instrument.

In *distributed control systems* the entire servo system, (i.e., motor, gearhead, feedback device and microprocessor) is situated at the point where the work is done and is connected to a host system by a few wires. Eliminating multiple wires in traditional control systems, induced noise in the system, wiring costs and complexity are reduced by a factor of three or four.

7. MANUFACTURING

Computer *numerical control production* and assembly equipment has enabled motor manufacturers to hold tolerances in the micrometer range, maintain consistency from piece to piece, and customize products in small quantities.

8. CONCLUSIONS

Today, therapy, surgery and health care are increasingly dependent on electrical and electronics engineering. Many medical devices require miniature and high power/torque density electric motors. In terms of miniaturization, high power density, high efficiency, low heat dissipation, reliability, lifetime and fault tolerance, the best motors for medical applications are PM brushless motors. Modern PM brushless motors for LVADs and other surgical devices are characterized by:

- integration of PM rotor with impeller or other rotating part;
- large air gap requiring high energy density PMs;
- slotless or coreless stator;
- elimination of shaft seals by embedding PMs in the pump rotor and using a special enclosure;
- reduced winding, core and eddy current losses to keep the operating temperature of the motor parts below the temperature of human blood, i.e., +36.8°C;
- utilization of one of higher harmonic MMF waves of the stator winding to produce the electromagnetic torque.

Reliability, long lifetime, fault tolerance, low operating temperature and resistance to hostile environment are the most important design problems.

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POSTĘP W TECHNOLOGII SILNIKÓW ELEKTRYCZNYCH O MAGNESACH TRWAŁYCH STOSOWANYCH W URZĄDZENIACH MEDYCZNYCH

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STRESZCZENIE *Obecnie wiele urządzeń medycznych oraz chirurgicznych wymaga wysokiej jakości małych silników elektrycznych o magnesach trwałych. W artykule omówiono nowe silniki bezszczotkowe o magnesach trwałych stosowane w urządzeniach zainstalowanych chirurgicznie wewnątrzustrojowo, w szczególności silniki do pompowania krwi.*

Silniki pracujące wewnątrz ciała ludzkiego muszą odznaczać się bardzo małym ciężarem, bardzo dużą niezawodnością, temperatura pracy nie przekraczająca temperatury krwi ludzkiej, możliwością pracy w środowiskach agresywnych chemicznie oraz tolerowaniem przypadkowych uszkodzeń. Jako magnesy trwałe stosuje się NdFeB o najwyższej osiągalnej energii, obudowy stojana i wirnika ze stopów tytanowych, łożyska magnetyczne lub hydrodynamiczne oraz nowe tworzywa sztuczne i kompozyty na pozostałe elementy.

Urządzenie do wspomagania lewej komory serca (LVAD) jest pompa elektromechaniczna implantowana wewnątrz klatki piersiowej, która umożliwia pracę serca nie będącego w stanie pompować krwi samodzielnie. Pacjent z wszczepionym LVAD oczekuje w tym czasie na znalezienie odpowiedniego dawcy oraz transplantacje serca.

Rysunek 1 oraz 2 przedstawia pompę elektromechaniczną rotacyjną DeBakey'a o przepływie osiowym w której silnik bezszczotkowy jest zintegrowany z wirnikiem pompy. Magnesy trwale umieszczone są w sześciu łopatkach impelera. Łożyska osiowe są zanurzone w krwi.

Pompa o przepływie osiowym Streamliner (rys. 3 oraz 4) działa podobnie, ale zamiast łożysk mechanicznych posiada łożyska magnetyczne. Pole magnetyczne nie tylko napędza impeler, ale również unosi go magnetycznie. Uzwojenie stojana jest uzwojeniem toroidalnym.

Pompa centryfugalna (odśrodkowa) Terumo DuraHeart® (rys. 5 oraz 6) o łożyskach magnetycznych posiada trójfazowy, ośmiobiegunowy silnik bezszczotkowy tarczowy (strumień osiowy) o magnesach trwałych neodymowych zintegrowany z impelerem. Przy prędkości 2000 obr/min moc na wale wynosi 4.5 W oraz moment obrotowy 0.,0215 Nm.

W pompie centryfugalnej VentrAssist™ silnik bezszczotkowy o magnesach trwałych jest silnikiem o strumieniu magnetycznym osiowym, magnesach trapezowych oraz cewkach stojana umieszczonych po obydwu stronach wirnika. Cztery magnesy neodymowe w obudowie ze stopu tytanowego są jednocześnie czterema łopatkami impelera. Bezżłobkowy stojan posiada trzy cewki gorne oraz trzy cewki dolne. Sprawność silnika nie przekracza 48 % przy prędkości 2000 do 2500 obr/min oraz mocy 3 do 7 W. Rozkład pola

magnetycznego wirnika oraz stojana przedstawiono na rys. 9 i 10. Przebiegi charakterystyk sprawności oraz prądu fazowego stojana w zależności od obciążenia są wykreślone na rys. 11 oraz 12.

Artykuł jest zakończony wnioskami wynikającymi z dotychczasowych doświadczeń w konstrukcji małych silników bezszczotkowych pracujących wewnątrzustrojowo.