INVESTIGATING THE COMPROMISE OF ELECTRICAL AND HYDRAULIC REQUIREMENTS OF A ROTARY BLOOD PUMP MOTOR DRIVE

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***Abstract* - Ventricular assist devices (VADs) are commonly used to treat patients with heart failure by augmenting the output of the natural heart. These devices are designed to be as compact as possible to allow for placement within the patient's torso. Permanent magnet (PM) motors have been commonly used to drive VADs because of their high power density and compact size. This study determined the compromise between hydraulic and electrical efficiency when designing axial flux motors for VADs. Through analytical analysis a rotor diameter of Ø31.4mm was determined to be a good compromise between hydraulic efficiency, electrical efficiency and rotor size.**

I. INTRODUCTION

Due to the high incidence of cardiovascular disease (CVD) around the world, mechanical circulatory support (MCS) has been a focus of medical research for over 50 years and has evolved through a number of distinct technology generations. First generation devices feature displacement pumps with mechanical valves and pusher plates or membranes. These mechanical components used in these devices typically restricted their reliability and life expectancy. To overcome these challenges, continuous flow rotary pumps were proposed for use in blood pumps [1]. Rotary blood pumps are typically smaller in size and have a higher efficiency than displacement pumps allowing for a much less invasive patient treatment. In particular, rotary blood pumps have revolutionised the treatment of heart failure with the development of small implantable Ventricular Assist Devices (VADs) that can augment the output of a failing heart. These devices are designed to be as compact as possible to allow for implantation within the patient's torso.

Axial flux permanent magnet (PM) motors have been commonly used to drive VADs because of their high power density and compact size. In particular, rotary blood pumps with centrifugal type impellers often make use of axial flux permanent magnet motors due to the large axial surface area of the impeller [2].

The overall efficiency of rotary blood pumps is a combination of both hydraulic and motor efficiency, of which the torque component of each is dependent on the rotor diameter. Perturbations to the rotor diameter inherently change the hydraulic operating point and efficiency, consequently changing the torque requirement of the motor [3]. Likewise, the efficiency and torque production capacity of an axial flux motor is strongly dependent on rotor diameter. The purpose of this study is to investigate this intrinsic compromise between hydraulic and electrical systems and subsequently develop a small diameter axial flux motor that could be used in an implantable rotary blood pump.

II. METHOD

An initial motor and hydraulic system has previously been developed for use in a VAD. Extensive simulation and empirical testing of this motor and hydraulic design has previously been completed. The geometry of this initial design, particularly the rotor diameter, was not optimised for hydraulic and electrical efficiency. This previous motor and hydraulic design forms the starting point for this investigation.

The impeller is 38mm in diameter and has a design point of 5L/min against a head pressure of 100mmHg at 2600RPM. The motor shown in Fig. 1 and is a custom designed single sided BLDC axial flux drive. The rotor is made of ferromagnetic steel 9S20, which has a saturation flux density B_{sat} of approximately 1.7T. It houses 16 axially alternating magnetized, neodymium iron boron magnets (NdFeB) with a remanent induction B_r of 1.4T at 20^C. The stator is made of ferromagnetic steel 9S20 and contains 18 poles wound with rectangular copper wire. The motor was designed for a typical axial air-gap of 1mm.

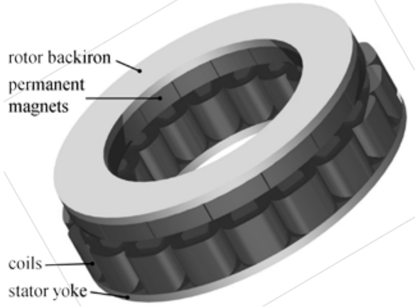

Fig. 1: Drive design parameter investigation.

Theoretical analytical analysis of both the hydraulic and electrical systems was performed [3, 4, 5]. The analytical models assume that all sizing parameters are held constant except for the free variable, namely rotor outside diameter.

Without loss of generality, the stator tooth outside diameter was chosen to be equal to the rotor outside diameter. Statistical data fitting was used to fit the analytical model parameters to the measured values of the existing hydraulic and motor design, signficanatly improving the accuracy of the model.

A. Motor Sizing

The hydraulic analytical model was used to gerenerate the required torque and operating speed of the hydraulic system for a constant hydraulic output of 5L/min at 100mmHg, over a range of rotor diameters between Ø29mm and Ø40mm. The motor analytical model was used to calculate the torque generated for a constant input current over the same range of rotor diameters and at the appropraite rotation speed. The point at which the torque required by the hydraulics and the torque produced by the motor intersect indicates the new rotor diameter.

B. Simulation

The new motor was designed and simulated using Finite Element Method (FEM). Motor force, efficiency and core saturation were all determined from the simulation.

III. RESULTS

The analytical models were successfully generated and fitted to the previously collected data. Fig. 2 shows the analytical prediction of the operational speed to produce a constant pump output. As expected the rotational speed must increase to compensate for a smaller rotor diameter.

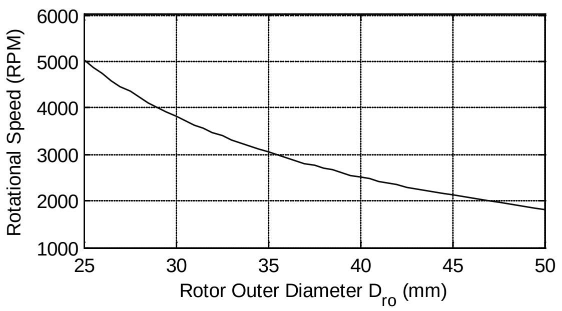

Fig.2. Required rotational speed to produce the constant hydraulic output for varying rotor outside diameters.

A. Motor Sizing

The torque required for the hydraulics and the torque produced by the motor was calcuated for rotor diameters between Ø29mm and Ø40mm and is shown in Fig. 3. The excitation current of the motor was kept constant at 1A regardless of the diameter, as this is the maximum desired operating current under steady state conditions.

As the outer diameter is reduced the torque capacity of the motor decreases approximatly linearly. The required torque also decreased, however at a fuction of the inverse square of the diameter. At 31.4mm the torque production of the motor at 1A equals the estimated required hydraulic torque.

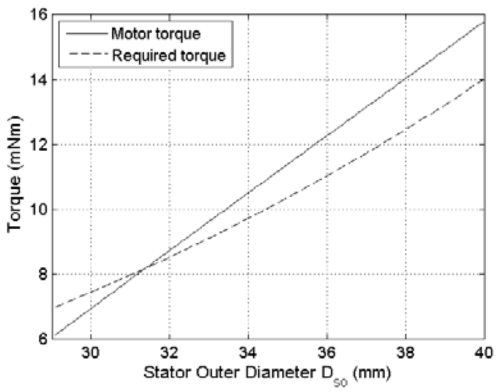

Fig.3. Comparison of torque required by the hydraulic system (dashed line) and torque production at 1A by the motor (solid line).

A new motor was designed with an outer diameter of 31.4mm and simulated using FEM. The simulation results did not indicate that the core would not saturate under normal operating conditions. It also returned a torque capacity 10% lower than what was predicted analytically.

IV. CONCLUSIONS

The study provides insight into the design process of a motor for an LVAD. A suitable compromise of Ø31.4mm outside diameter was found between torque generation and hydraulic performance whilst producing a small diameter pump. Initial FEM analysis indicates that this motor will be sufficient for the application. Future work will be focused on the construction and testing of the new motor and hydraulic pump. The general knowledge and techniques developed in this study, can assist the motor design for other rotary blood pumps.

REFERENCES

[1] D. Timms, “A review of clinical ventricular assist devices”, *Med. Eng. Phys.*, vol. 33, pp. 1041-1047, 2011.

[2] T. Masuzawa, *et al.*, “Magnetically suspended centrifugal blood pump with an axially levitated motor,” *Artif. Organs*, vol. 27, no. 7, pp. 631-638, 2003.

[3] A.J. Stepanoff, *Centrifugal and Axial Flow Pumps: Theory Design, and Application.* New York, Wiley, 1954.

[4] J. F. Gieras, R. Wang, M. J. Kamper, *Axial Flux Permanent Magnet Brushless Machines.* 2nd ed., Springer Verlag, 2008.

[5] D. Hanselmann, *Brushless Permanent Magnet Motor Design*, 2nd ed., The Writers’ Collective, 2006.