DRIVE OPTIMISATION OF A PULSATILE TOTAL ARTIFICIAL HEART

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***Abstract* - Besides heart transplants total artificial hearts (TAHs) are the only possible therapy for terminal heart diseases. It is desirable to totally implant a TAH into the human thorax. The limited space in the thorax sets restrictions towards the TAH regarding weight and dimensions. Regardless of these restrictions the appropriate functionality must be ensured and blood damage by the TAH must be prevented. The presented TAH design is too heavy for implantation. Therefore the optimisation of the TAH drive, consisting of loss calculations based on Finite Element (FE) simulations and variation calculation for geometric, and the final results are presented in this paper.**

I. INTRODUCTION

TAHs are required for the therapy of terminal heart diseases. This is because hearts transplants are a restricted option due to the limited number of available human donor hearts. On the current market there is only one approved TAH [1], which has the disadvantage of extra corporal connections through the abdominal wall. Therefore, this increases the risk of infections and reduces the patients quality of life. That is the main reason why a totally implantable TAH-system is desirable.

An implementable system has rigorous restrictions in outer dimensions and weight due to the limited space in the human thorax. Additionally, blood damage caused by overheating and possible mechanical impact of the pump to the blood must be prevented. On the other side the TAH has to pump up to 7 liter of blood per minute against a medium aortic pressure of 100 mmHg. Due to these requirements a drive of a TAH has to be small sized and light weighted, provide enough force or torque for the blood pump and being highly efficient.

In [2] the development of a TAH at the RWTH Aachen University and its prototype (Fig. 1) are presented. This TAH is driven by a linear motor, which is based on a flux concentrating concept and is supplied by a dc current. On each side of the linear motor there is a pusher plate, which is directly connected to the motor, and a blood chamber. During the TAH operation the pusher plates drain the blood chambers and therefore pump the blood in a pulastile way. Besides the weight the mentioned requirements are achieved. This paper focuses on the weight reduction of the TAH by optimisation.

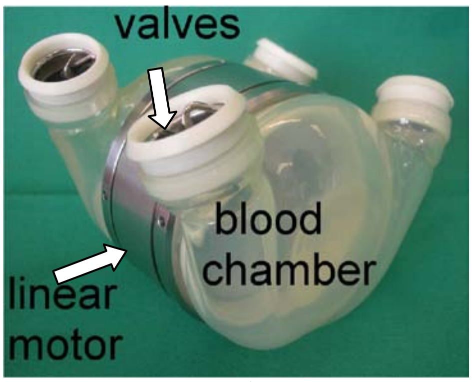

Fig. 1. Total Artificial Heart.

II. DRIVE OPTIMISATION

The drive motor is one of the main components of the TAH. When reducing its weight and dimensions while keeping the required forces, the resulting losses will rise when compared to the prototype. In [2] it is assumed that a overheating of the blood can be prevented by limiting the ohmic losses of the drive to 20 W.

A. Measurement of the force vs. displacement curve

For the drive optimisation a force vs. displacement curve is required. Therefore a blood chamber is connected to a mock loop, simulating the human blood circuits. The pusher plates are driven by a tensile testing machine, which also houses the force and position sensors. Additionally the flow and the pressure at the in- and outlet valves are measured. The pressure at the valves can be adjusted in the mock loop for simulating the operation conditions for the left and the right heart chamber. During the measurements the pumping frequency is changed to increase the blood flow.

For the left heart chamber the minimum required blood flow of 6 liter per minute against a medium aortic pressure of 100 mmHg is achieved at a frequency of 120 bpm (beats per minute) (Fig. 2). At this frequency the required force at the displacement of -18.5 mm reaches the maximum force value for all measurements. On the other side the amplitude of the

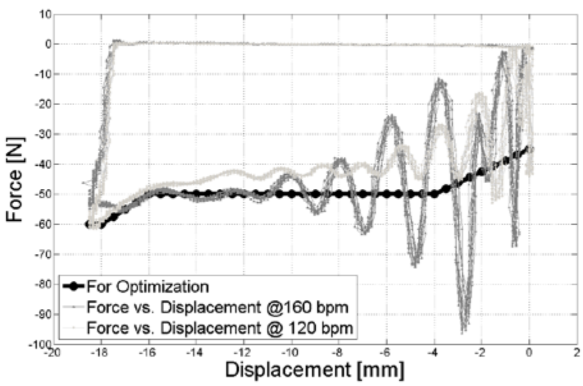

Fig. 2. Force vs. Displacement.

force fluctuations at the beginning reaches its maximum at a frequency of 160 bpm. These fluctuations are caused by oscillations of the fluid between the valves and the pusher plates. Hence, the chosen curve for the optimization considers these two cases.

B. Geometric optimisation

In this study, the drive motor of the TAH is optimised by variation of its geometric parameters. The coils are wounded with rectangular shaped copper wire to increase the copper fill factor. Due to the outer diameter of the outer permanent magnet, the remanence flux density of this NdFeB magnet is limited to 1.35 T, while the remanence flux density of the inner NdFeB magnet is 1.44 T.

For this reason the applied optimisation method is a combination of calculations varying the geometric parameters and the determination of the resulting losses and weight. In this way the parameter, which should be first used to reduce the weight of the drive, while keeping the ohmic losses low, is computed. A comparison of the results yields a hierarchic order of the geometric parameters for a small weight losses ratio. For this computation the inner and outer diameter of the drive, the thickness of the coils and of the air gap respectively and the inner diameter of the air gap were considered.

The first step of the calculation of the ohmic losses is a FEM simulation of the static flux density distribution in the drive (Fig. 3) under no load condition. Then the flux density distribution is used to determine the ideal dc current supply of the four coils. According to [3] the optimal output

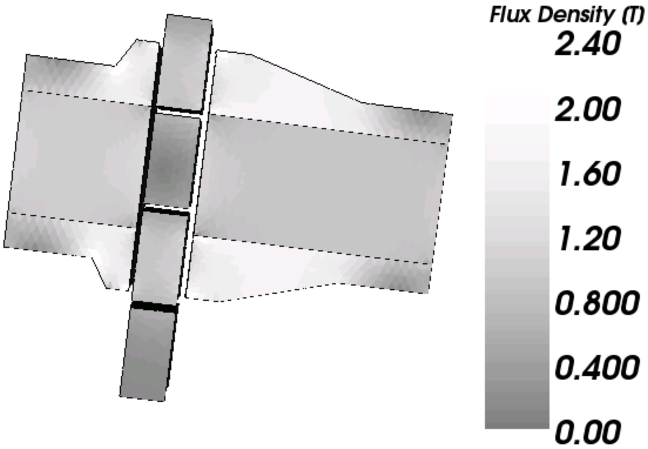

Fig. 3. Flux distribution in TAH.

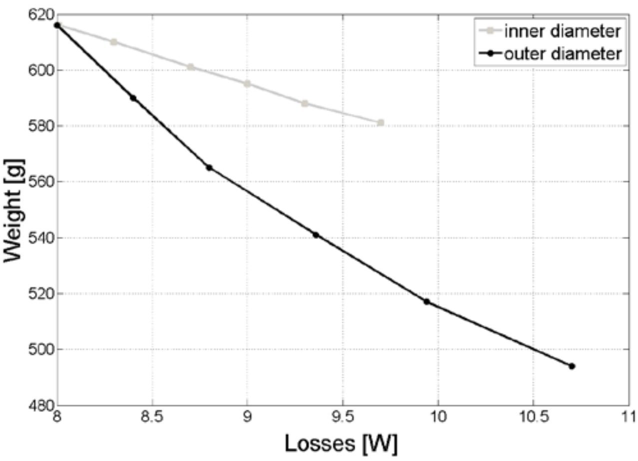

Fig. 4. Weight vs. Losses.

force can be obtained by the Lorentz force equation:

$$F(x) = I(x) \cdot (\vec{l} \times \vec{B}(x)) \qquad (1)$$

As the required output force F(x), the flux density distribution B(x) and the length l of the coils are known, eq. 1 is used to determine the ideal current supply and to calculate the resulting ohmic losses. As the geometric parameters are known, the weight of the drive can be calculated by the volumes of the used materials.

III. RESULTS

In Fig. 4 the weight vs. losses diagram for variations of the inner and outer diameter of the TAH drive is drawn. It can be seen, that the variation of the outer diameter yields a better weight losses ratio when compared to variations of the inner diameter. All the other geometric parameter will be evaluated during the optimisation in the full paper.

Table I lists the results of the geometric optimisation of the drive. Its weight is reduced by 16.1% or 99g respectively. The outer diameter is reduced by 9.4 % resp. 8 mm. As expected, the ohmic losses rise in total by 35% resp. 2.8 W when compared to the prototype.

IV. CONCLUSIONS

The requirements and limitations of a totally implantable TAH for the therapy of terminal heart diseases were discussed. Then the required forces to ensure a good blood perfusion of the human body were defined in a force vs. displacement curve. Finally the drive of the presented TAH was optimised in terms of weight and losses.

Compared to the prototype, the weight and dimensions have been significantly reduced by the optimisation. The resulting losses are far below 20 W, which were assumed to be the critical limit for blood damage. Therefore a further optimisation potential is expected.

Compared to the 400g of the natural heart, the TAH consisting of the drive, the blood pump (blood chamber and pusher plates) and the housing is still to heavy. But the experiences in the transplantation of TAH's have shown that a TAH weight of 800g is realistic. With respect to the results obtained, it can be stated that this aim seems to be in a reachable range.

TABLE I
COMPARISON OF PROTOTYPE AND OPTIMIZED GEOMETRY.

Parameter	Prototype	Optimized Drive	Variation [%]
Outer diameter	85 mm	77 mm	- 9.4 %
Inner diameter	14 mm	16 mm	+ 14.3 %
Weight	616 g	517 g	- 16.1 %
Losses	8 W	10.8 W	+ 35 %

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[3] H. Lu, J. Zhu, Z. Lin and Y. Guo, "*A Miniature Short Stroker Linear Actuator-Design and Analysis*." IEEE Transactions on Magnetics, Vol. 44, No.4,pp. 497-504, April 2008.