XII-th International Workshop on Optimization and Inverse Problems in Electromagnetism
September 19 – 21, 2012, Ghent, Belgium

AUTONOMOUS AND IMPLANTABLE TOTAL ARTIFICIAL HEARTS – POTENTIAL OF NUMERICAL OPTIMIZATION IN THE DEVELOPMENT OF MEDICAL DRIVE SYSTEMS

André Pohlmann* and Kay Hameyer*

*RWTH Aachen University, Institute of Electrical Machines, D-52056, Aachen, Germany
E-mail: andre.pohlmann@iem.rwth-aachen.de

Abstract. Total Artificial Hearts (TAHs) can replace the human heart of patients suffering from heart failure. In order to enhance the quality of life for the patients, an autonomous and totally implantable TAH system is desirable. This paper focuses on the optimization of a linear actuator operating a TAH systems under the constraints given by the implantation requirements, which can be summarized as limited dimensions and weight, sufficient perfusion without blood damage and durability.

Keywords: Medical Engineering, Total Artificial Hearts, Linear Drives, Finite Elements Analysis

INTRODUCTION

Cardio Vascular Diseases are the mayor cause of death in industrialized countries. Due to availability problems, donor heart transplantation is only a limited option, if the drug based therapy of the patient fails. The demand of alternatives yielded the development of TAH systems. In order to enhance the quality of life of the patient, an autonomous and completely implantable TAH system is desirable. An autonomous TAH operation without any external components can only be ensured for a limited period of time, which is dependent on the capacity of the implanted battery. For charging the battery non invasive transcutaneous energy transmission (TET) systems should be applied, which have been described before [1]. For designing the TAH drive the following anatomical and physiological constraints are considered to allow for a device implantation:

a) Due to the limited space in the human thorax, the dimensions of the pump unit should not exceed 85 mm in diameter and 95 mm in length, allowing a motor height of 36 mm.
b) The total weight of the pump unit should be less than 800 g requiring a maximum drive weight of 500 g.
c) The average flow should amount up to 5 l/min against a medium systemic pressure of 95 mmHg and provide an additional overload capacity.
d) Electrical losses have to be less than 20 W to avoid blood and tissue damage due to excessive heat.
e) The drive has to generate a force of up to 60 N [2].

Figure 1. shows a TAH, developed at the RWTH Aachen University. It consists of a linear drive, two blood chambers with a volume of about 65 ml each and in/outlet valves regulating the blood flow. When considering flow losses, this TAH provides a perfusion of 6 l/min against a mean systemic pressure of 95 mmHg. In a previous work [3], the linear drive design shown in Figure 2. was the best drive concept for the described TAH. The drive is excited by an inner and an outer permanent magnet ring, constructed of NdFeB material. When compared to the remanent induction $B_{r,in}$ of the inner magnet ring, which amounts to 1.44 T, the remanent induction $B_{r,out}$ only averages to 1.35 T. This effect is causes by the magnetization process of the rings. Due to the limitations of the magnetization device used, only the ring with the smaller radius can be fully magnetized and the difference in remanence occurs. Above and beyond the magnets, pole shoes are attached, concentrating the flux in the air gap. They are constructed of an iron vanadium cobalt alloy, which has a saturation induction of 2.4 T. The mover consists of four separate coils, which can be supplied individually, to allow for a maximum force output at a minimum of copper losses. Each coil is hand-wounded with a rectangular copper wire. In this way a copper fill factor of 75 % is achieved. The prototype meets all implantation constraints except the weight limit (b). Therefore, a drive optimization yielding a weight reduction, by simultaneously matching all other specifications is performed.

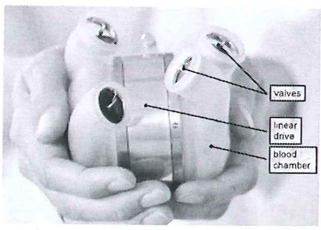

Figure 1. Total Artificial Heart (RWTH).

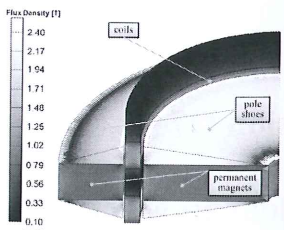

Figure 2. Linear Drive.

DRIVE OPTIMIZATION

The drive of the TAH is optimized in such a way, that the required force is provided, while the resulting losses are in the range of 10 W and the weight is as low as possible. This approach will automatically reduce the dimensions of the drive as well. For this optimization Finite Element Analysis (FEA) is applied to determine the magnetic flux density in the drive. The local field distribution is required for the determination of the optimum coils supply and therefore for the estimation of the resulting losses. Both, the weight and the dimensions are depending on the geometry and the construction of the drive. Before starting the optimization a force displacement curve for evacuating the blood chambers is measured to obtain the required force profile (Figure 3). For this measurement, the human body has been simulated by a circulatory mock loop.

The optimization is achieved by applying a parameter variation. Here, a limited number of objective variables is selected to study their influence on the distribution of the flux density and the weight of the drive. In this case the parameters, inner and outer diameter, thickness of the coils and air gap and the radial positioning of the mover are considered. Exemplary the approach is explained by the positioning of the mover. By reducing the inner coil diameter in steps of 2 and 4 mm, the mover is repositioned in radial direction. Thus, a small increase of the volume of the permanent magnets is performed while simultaneously decreasing the magnetic resistance of the air gap, resulting in an increase of the air gap flux density. Furthermore, the coil's resistance is reduced, improving the ohmic losses. On the other hand the active wire length l is decreasing, causing an increase of coil current to achieve the required forces. Figure 4 shows the weight vs. losses characteristic for three mover positions. Additionally, the outer diameter of the drive is reduced in steps of 1 mm. The intersections between the three curves indicate when changing the radial mover position is beneficial.

RESULTS AND CONCLUSIONS

The numerical optimization yielded a reduction of the weight for the prototype by 27%. According to Table 1, which compares the prototype and the optimized drive, this is achieved by reducing the outer diameter by 12 mm and the coil thickness by 1 mm. Although the average losses have been increased from 8 W to 12.2 W, the loss limit of 20 W has not been completely exploited. Therefore, a further optimization of the drive geometry, yielding a further increase in the losses of the drive, is possible. But concerning the drive all implantation specifications are fulfilled. The results have been validated by invitro and invivo testing.

REFERENCES

[1] H. Miura, S. Arai, Y. Kakubari, F. Sato, H. Matsuki, T. Sato. "Improvement of the transcutaneous energy transmission system utilizing ferrite cored coils for artificial hearts". IEEE J MAG, Bd. 2, Nr. 10 S. 3578–3580, Oct. 2006.

[2] A. Pohlmann, M. Leßmann, T. Finocchiaro, A. Fritschi, T. Schmitz-Rode, and K. Hameyer, "Drive optimization of a pulsatile Total Artificial Heart", in: the XXI symposium electromagnetic phenomena in nonlinear circuits, EPNC 2010, pages 65-66, 2010.

[3] M. Lessmann, T. Finocchiaro, U. Steinseifer, T. Schmitz-Rode and K. Hameyer, "Concepts and designs of life support systems." IET Science, Measurement & Technology 2008, 2(6): 499-505.

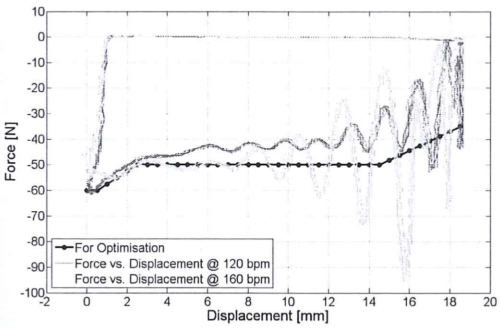

Figure 3. Measured Force Displacement Characteristic.

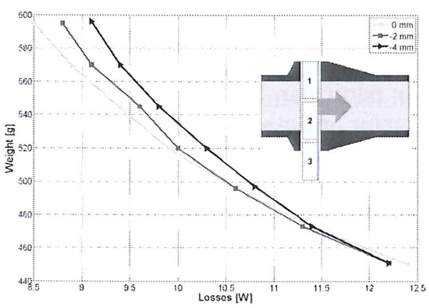

Figure 4. Variation of the coil position.

Table 1. Results of drive optimization.

Parameter	Prototype	Optimised Drive	Variation
Outer diameter	85 mm	73 mm	- 14.1 %
Coil thickness	3 mm	2 mm	- 33 %
Drive weight	616 g	450 g	-26.9 %
Losses	8 W	12.2 W	+ 52.5 %