New Linear Motor Concepts for Artificial Hearts

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Total artificial hearts (TAHs), available in today's market, have the disadvantage of wear-prone components. Thus, their expectation of life is limited and the devices can only be used for temporary and not destination therapy. Durability- and wear-free operations are the critical requirements, as failure is an immediate threat to the patient's life. These attributes are combined in linear motors. In this paper, the potential of a linear motor as TAH's drive is shown by a prototype. On the basis of this prototype, different motor concepts are employed. The dimensions of each concept's geometry are first roughly determined by analytical optimization, and in a second step, more finely tuned by means of finite-element (FE) calculations. After optimization, two concepts achieve the requirements, provided by the natural heart of the human body. The first motor consists of moving coils and static permanent magnets, which are embedded in a flux concentrating geometry. To avoid the disadvantage of wear-prone power connection of the coils, the other concept consists of static coils and moving permanent magnets, arranged in a Halbach array. After constructing and testing both concepts in laboratory, animal experiments will follow to identify the superior one.

***Index Terms*—Flux concentration, Halbach array, linear motor, total artificial heart.**

I. Introduction

HEART failure has been the major cause of mortality in industrialized countries for the last several decades. If sufficient perfusion of the body cannot be maintained by medication, heart transplantation becomes the only therapy option. Due to a severe shortage in donor hearts, more and more patients die while waiting for a heart transplantation. In order to offer an alternative to those patients, total artificial hearts (TAHs) are being developed. Obviously, durability- and wear-free operations are critical requirements for life support systems, and especially TAHs, as failure is an immediate threat to the patient's life. In this paper, the application of linear motor concepts for TAHs by means of magnetic field simulations is studied. Previous drive concepts, based on rotary motors and a conversion gear mechanism, consisted of many moving components to drive the pusher plates. The MiniACcor [1], developed in Aachen, Germany, belongs to this category of TAHs, as well as Abiocor [5] and Magscrew TAH [6]. To achieve a five-year lifetime without maintenance and failure, the number of wear-prone parts has to be reduced to a minimum. A promising actuator type is a direct linear drive, as ideally only one part is moving. Fig. 1 illustrates the different parts of a prototype TAH with a linear direct drive. Analog to the natural heart, TAHs comprise two blood chambers (6, 7). To pump the blood into the aorta/pulmonary artery, these blood chambers are compressed by pusher plates (4). Additional specifications can also be listed. TAHs are implanted into the thorax in place of the weak natural heart. The available space is therefore limited. Additionally, high forces of up to 70 N are needed. Fig. 3 illustrates the amount of required forces over the stroke for right and left pump chamber (shaded area) along with the forces measured on the first prototype. Required forces for the left chamber have a negative sign as displacement direction is negative. Left forces are higher than right forces because pressure in the aorta is higher than in the pulmonary artery. Conventional linear drives are either too weak or too voluminous. Furthermore, the reduction of heat dissipation is an important challenge. Compact linear drives available on the market generate significant losses whereas it is commonly assumed that, for application in a TAH, heat losses larger than 20 W are not tolerated by the human body. As a proof of concept, a prototype has been designed and manufactured. Fig. 2 depicts the operation mode of the drive, as well as the direction of force and displacement.

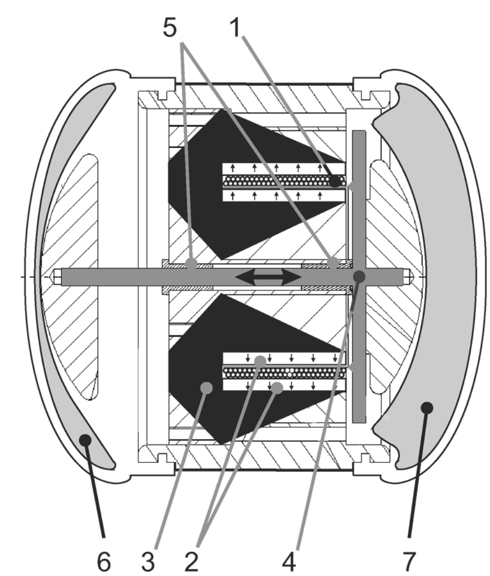

Fig. 1. Components of prototype TAH: 1 coil, 2 magnet rings, 3 back iron, 4 coil support with pusher plates, 5 bearings, 6 left pump chamber, and 7 right pump chamber.

The prototype is axisymmetric. It consists of two radially magnetized cylindrical permanent magnets placed concentrically on both sides of a long thin coil. Back iron closes the magnetic circuit. The electrical contact for the movable coil is ensured by specially designed flat springs. The measured force

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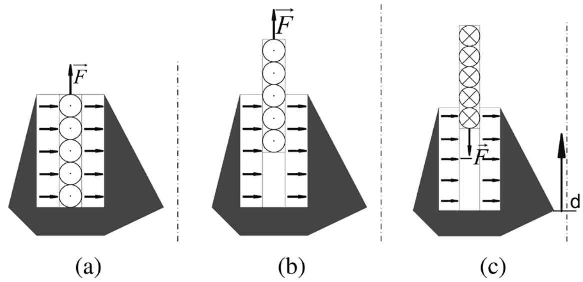

Fig. 2. Operation mode of prototype.

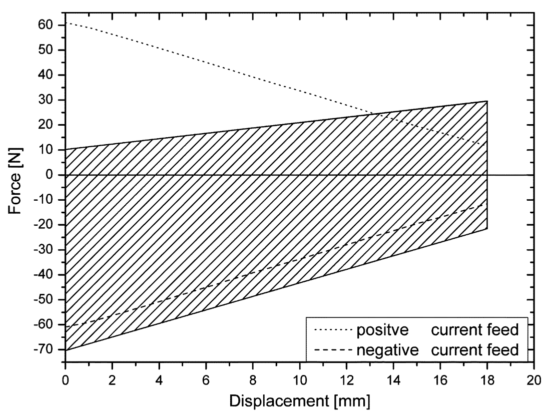

Fig. 3. Required force (shaded area) and measured force (lines)—displacement curve of prototype.

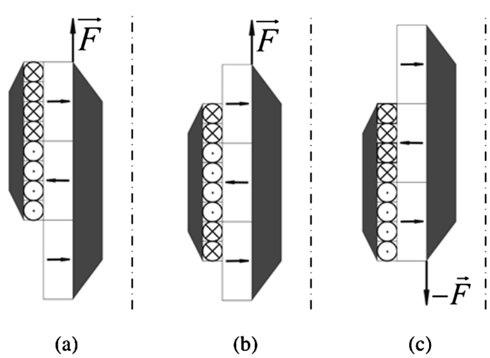

Fig. 4. Concept 1: operation mode.

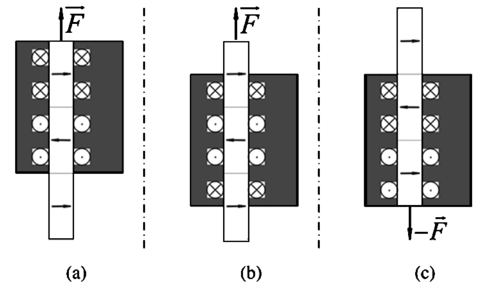

Fig. 5. Concept 2: operation mode.

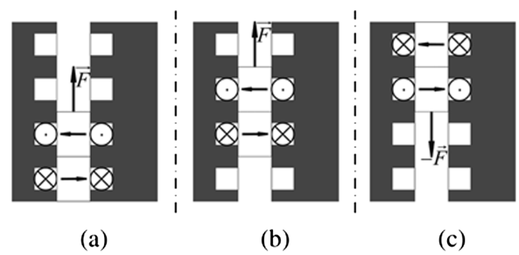

Fig. 6. Concept 3: operation mode.

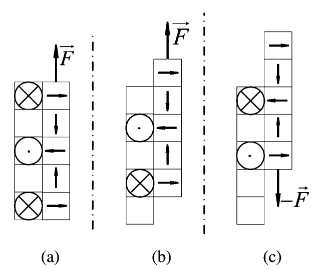

Fig. 7. Concept 4: operation mode.

at 20-W copper losses is displayed in Fig. 3 as a function of displacement. Although in a wide range forces are too low and weight exceeds limitations, the prototype demonstrates that it is possible to realize a TAH with a linear direct drive if the device is well optimized. Main fields of optimization are improved geometry and materials.

II. Development Approach

An actuator always consists of a stator and a mover. Either the magnets or the coils can be part of the stator or mover. To achieve a higher reliability, it is useful to avoid a moving coil, because the electrical contacts for the coil (e.g., springs) are additional, wear-prone parts. On the other hand, a moving coil can dissipate heat by conduction via the pump diaphragm to the flowing blood. In a static coil concept, heat is mainly transferred to the surrounding tissue.

As their impact on the human body is not well known, both principles, moving coil and moving magnets, are investigated.

Therefore, five concepts have been studied under comparable conditions.

In a first step, the magnetic field in the air gap has been determined by analytical calculations based on a magnetic equivalent circuit. Iron cross sections are designed so as to bring the magnetic material close to saturation. The force was calculated and the ratio between the thickness of coil and the thickness of magnets was varied, holding the effective magnetic air gap constant, consisting of the air gaps', the coil's, and the permanent magnets' heights.

The dimensions of each concept's geometry were first roughly determined by analytical optimization, and in a second step, more finely tuned by means of finite-element (FE) calculations with the package iMOOSE [4]. Furthermore, plots of induction highlighted areas within the iron where flux density was below saturation. Hence, an optimal point for reduction in weight and size was determined. After optimization, the force versus displacement curve was calculated for each concept.

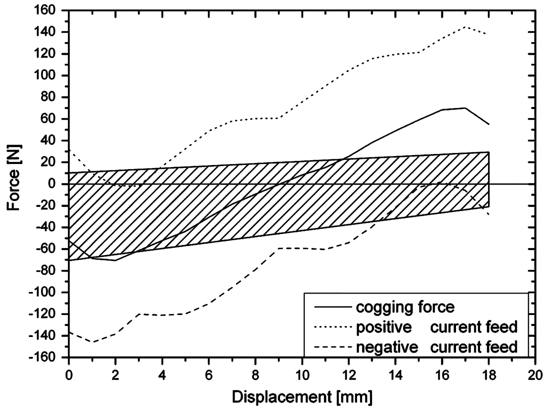

Fig. 8. Concept 1: force-displacement curve.

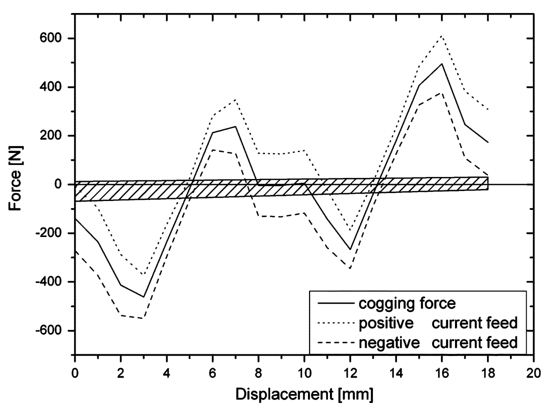

Fig. 9. Concept 2: force-displacement curve.

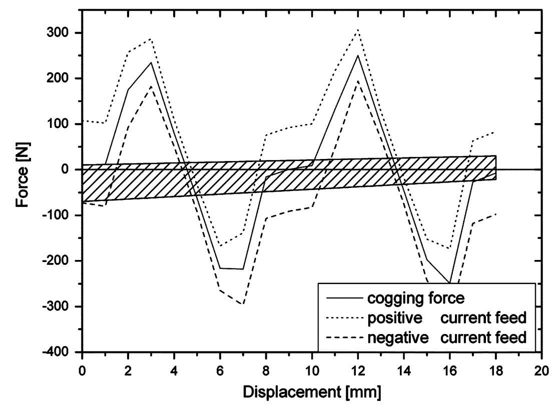

Fig. 10. Concept 3: force-displacement curve.

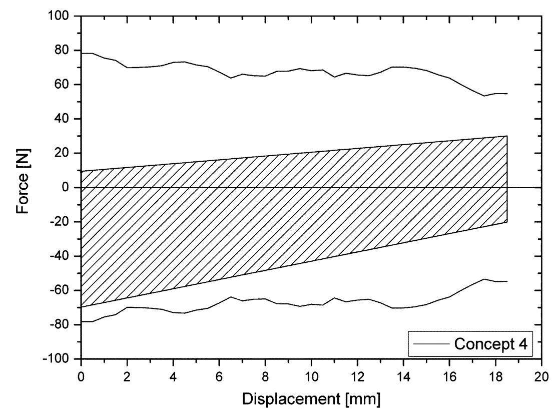

Fig. 11. Concept 4: force-displacement curve.

All data were collected at an operation point corresponding to 20 W of copper losses for positive and negative current. Cogging torque was computed with no current in the coils.

III. Results

Concept 1 (Fig. 4): The mover consists of three radially magnetized magnets and back iron. The static coils also comprise back iron. Fig. 8 displays the force displacement for the whole stroke.

Concept 2 (Fig. 5): There are two static components. The slotted iron yoke with coils is the static part. The mover is made of three radially magnetized magnets. This concept has a high force density because of the small effective magnetic air gap. The results of the force over displacement simulation are shown in Fig. 9. In this concept, high force ripple and high cogging forces can be observed.

Concept 3 (Fig. 6): To reduce size and end effect forces, the concept of Fig. 6 was developed. The stator part is the same as in concept 2. The mover part consists of two instead of three magnets. The height of the magnets is reduced in such a manner that they do not leave the iron yoke.

The results of this concept demonstrate that there is still a considerable cogging force (Fig. 10). Wang *et al.* [2] proposed to skew the back iron part connected to the coil assembly or the permanent magnets. However, complexity of construction prohibits this approach.

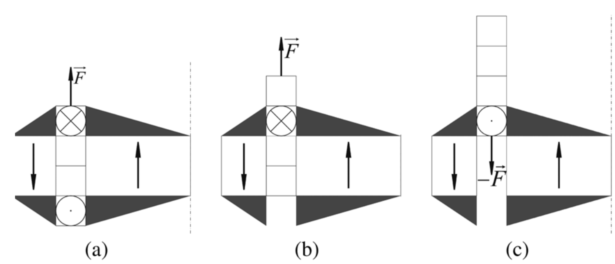

Fig. 12. Concept 5: operation mode.

Concept 4 (Fig. 7): To completely avoid cogging forces without increasing complexity of the device, an ironless drive has been set up. The magnets are aligned in a special manner known as Halbach array [3]. Through this alignment, the magnetic flux density is augmented on the left/outer side, while it is partially cancelled on the right/inner side of the magnets. Fig. 14(a) shows a plot of the flux density in this concept. Back iron is not required in this configuration. The moving magnets are surrounded by a segmented coil. Only those parts of the coil, penetrated by high radial flux, are powered. These coils are placed opposite to the radially magnetized magnets. The force-displacement curve for concept four is shown in Fig. 11. The force ripple can be reduced by increasing the number of coils.

Concept 5 (Fig. 12): Force density and efficiency of a drive can be improved by maximizing air gap flux density. Hence,

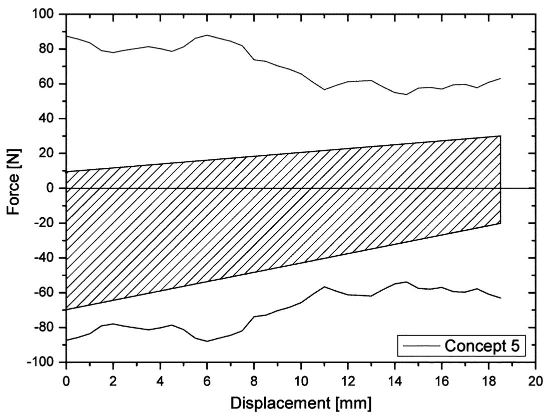

Fig. 13. Concept 5: force-displacement curve.

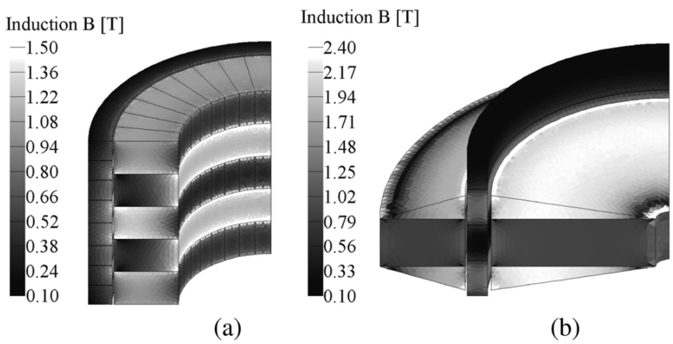

Fig. 14. Concepts 4 and 5: flux density.

in concept 5, flux concentration is the main objective. Due to geometrical requirements the coil has to be part of the mover, while the magnets and back iron are placed in the stator. The magnets are axially magnetized and the pole shoes guide the flux into the radial direction. The flux density of this concept is plotted in Fig. 14(b).

As the pole shoes are made of Vacoflux[1] with a saturation induction of 2.35 T, air gap flux density can be maximized. Current is only applied to coil segments located between the pole shoes. With this concept, height and weight can be reduced. As maximal force is only needed at one end of stroke, Fig. 12(a), additional coil segments placed beneath the coil assembly can be left out in concepts 4 and 5 due to TAH's requirements in Fig. 3. Additional segments would avoid the decreasing maximum force observed in Fig. 13, but they also would add unnecessary weight.

IV. Discussion

The results of concept 1 show that cogging force is ± 70 N, while Lorentz force component is between 60 and 80 N. The resulting force after superposition of Lorentz and Maxwell forces as depicted in Fig. 8 does not fulfil the requirements.

Concept 2 achieves very high force densities, shown in Fig. 9. Here cogging forces are ± 480 N. The Lorentz force component is between 50 and 140 N. Due to geometrical requirements, the magnet has to leave the static environment and the cogging forces reach unacceptable high levels.

In concept 3, the objective was to minimize the cogging force induced by the end effects of concept 2 by reducing magnet length. Here the magnet stays within the back iron and end effect forces are reduced. However, remaining cogging forces amount to 250 N. The Lorentz force range is between 30 and 90 N. The high cogging forces anticipate the use of this concept.

To avoid cogging forces, concept 4 uses a Halbach array of magnets. The maximum force is between 78 N at the beginning of the stroke and 55 N at the end. At every displacement point, the force meets the requirements. Consequently, this concept can be used as a direct drive for a TAH with moving magnets and static coils.

Concept 5 follows the idea of maximal flux concentration. Just as for concept 4, the maximum force is above requirements over the whole stroke. In summary, this concept can be used as a direct drive for a TAH with static magnets and moving coils.

V. Conclusion

Based on magnetic force simulation, two concepts for a direct linear drive for a TAH have been developed that accomplish force, weight, and size requirements.

Both demonstrate very good results in force simulation. Concept 5 with moving coils has a small height and weight and a high force density. A minor disadvantage is the ware-prone connection of the moving coils. Concept 4 with moving magnets has a small diameter, easy construction, and statically connectable coils, but a higher weight compared to the moving coils concept. In the future, both concepts will be constructed in order to validate the results of FEM simulation. The new prototypes will be connected to a circulatory mock loop simulator and tested under realistic conditions. In this simulator power requirements, heat dissipation and endurance can be evaluated. After successful laboratory tests, animal experiments will be conducted.

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[1]Iron–cobalt–alloy made by VACUUMSCHMELZE GmbH (Hanau, Germany).