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Designing and Modelling A Ventricular Assistive Device

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Abstract : *An Increase In The Number Of Cardiac Patients And A Decrease In Number Of HeartDonors Has triggered The Development Of ArtificialHeartPump To Support The ProperFunctioning Of The Heart.This paperPresents Design Of MagneticallyLevitated (Maglev) Axial Magnetic Flux Brushless Direct CurrentMotor (Af-Bldc) For Axial Blood Flow VentricularAssistDevice (Vad).A ventricularassistdevice (VAD) is an electromechanicaldevice for assistingcardiac circulation, whichisusedeither to partially or to completely replace the function of afailingheart. The developeddevice has three phase Two axial flow Bldcmotors are placedsymmetrically and the rotors are coupled to the pump. The stator and rotor of the Bldcconsist a hole, sincemagnetic flux pathdoesn'tpassthrough the central part. In order to get large volume in pumpchamber and lower speed, the pumpimpellersmaybeplaced in thishole. Motor has passive magneticbearing, whichdoesn'tinvolve contact and friction, thusitminimize the blood damage. For minimizing the penetration of magneticfieldto blood, the axial magnetic fluxes are parallel to the direction of blood.*
Keywords –Axial Flux BLDC Motors(AF Bldc), Cardiovascular devices, Ventricular Assistive Devices (VAD)

1. INTRODUCTION

Cardiovascular disease (CVD) is a class of diseases that involve the heart or blood vessels. The last clinical therapy option for some patients, suffering from terminal heartdiseases, is donor heart transplantation. As the available number of donor organs isdecreasing, many patients die while waiting for a transplant.One of the suitable solution for the above problem is to use VAD, which assisting cardiac circulation. VADs are distinct from artificial hearts, which are designed to assume cardiac function, and generally require the removal of the patient's heart. Moreover, VADs are designed to assist either the right ventricle (RVAD) or the left ventricle (LVAD), or to assist both ventricles (BiVAD).The left-ventricle assistance device (LVAD) usually is the most common device applied to a defective heart. [1][2].

Left Ventricular Assist Devices (Lvads) Are Blood Pumps Used To Augment The Cardiac Output Of Patients With Left Heart Failure. These Devices Are Used Either As A Therapy To Allow The Patient‟s Heart To Recover, As A Temporary Support To The Patient Until A Heart Transplant Can Be Performed, Or Even As A Long Term Alternative To Heart Transplantation. Rotary Blood Pumps Offer Several Advantages Over The Pusher-Plate Type Pulsatile Pumps Because Of Their Simplicity, Low Cost, Small Size, And High Efficiency [3]. Control Of The Rotary Blood Pump Is Usually Maintained By Setting The Pump At A Fixed Speed Such That The Pump Can Provide Enough Blood Flow For The Patient‟s Organ Perfusion. However, Determination Of An Appropriate Pump Speed Setting To Achieve A Desired Blood Flow Rate Based On Patient‟s Body Demand Is Difficult. A High Pump Speed With Low Right Heart Return Can Cause Collapse Of The Left Atrium Or Left Ventricle, Thereby Damaging The Blood And The Heart Tissue. On The Other Hand, A Low Pump Speed At A High Arterial Pressure May Cause Retrograde Flow Into The Heart Through The Lvad Due To Its Valve-Less Design. . Moreover Regardless Of Pump Speed, An Improperly Fixed Conduit Can Lead To Blockage Of The Conduit Causing A Dangerous Flow Restriction Through The Device. For These Reasons, It Is Crucial To Monitor The Pump Flow To Determine A Proper Pump Speed Setting As Well As To Detect Potential Risk From Inappropriate Device Operation. Direct Flow Measurementwithin The Pump Would Require An Implantable Flow Transducer. This Is Undesirable For Long Term Implant Because Of The Risk Of Sensor Failure And The Need For Additional Wires Passing Into The Patient‟s Chest Cavity.

Recently more researches are focused on bearing less Magnetically Levitated Axial Magnetic Flux BLDC motor. The Axial blood flow VADs are used radial magnetic flux BLDC motors for pumping. In this type, magnetic flux is perpendicular to the direction of blood flow. In [4] a hybrid permanent magnet hydrodynamic bearing is designed. VAD drive leads to electriclosses, which might result in an overheating of blood, and a long durability. Thereforein [4]a hybrid permanent magnet hydrodynamic bearing is designed, which workspassively and contactless. Based on Finite Element simulations of magnetic fields,various permanent magnet topologies are studied in terms of axial forces and stiffness.

In [5] developed a small blood pump with a levitated rotor, and a design scheme for an axial-type self-bearing motor. This motor basically a disc motor and an axial magnetic bearing controls both the axial translation of the rotor and the rotation. In order to improve the radial support properties hydrodynamic bearing is included in the design of the motor. The designed motor in [5] has high efficiency (small continuous flow blood pump) delivering sufficient flow rate and pressure head. An electromagnetic and fluid finite element analysis based axial blood flow pump is designed in [6]. The characteristics of the magnetic bearings are evaluated by using electromagnetic finite element analysis. In [7] discuss about the effect of magnetic field on blood due to the presence of iron in blood hemoglobin. The design and optimization of the axial flux motor for blood application is described in [8]. In order to maximize the motor efficiency different motor design topologies are explained. A bearing less permanent magnet synchronous motor based on the Maxwell stress tensor method and suspension force modelling is proposed in [8].this proposed drive is verified by using finite element analysis. In [9-11] it explains magnetically levitated axial blood flow pump along with a new electromagnetic actuator. This electromagnetic actuator is for axial flow balancing. A sensor assembly for the control of rotor axial position is also presented in [11].

The main problem in the VAD is the damage of the blood due to high shear stress. This high shear stress is due to the small volume of pump chamber. To avoid this large volume of pump chamber than conventional VAD are required. So in this paper describes the larger volume pump chamber, which rotates at lower speed. Therefore shear stress can be reduced in blood. Here the magnetic field doesn't affect the blood because flux is not perpendicular to the blood flow.

This paper presents the design and modelling of the magnetically levitated axial flux BLDC motor for an axial blood flow VAD. This research takes inspiration from [12].This paper Presents Design Of Magnetically Levitated (Maglev) Axial Magnetic Flux Brushless Direct Current Motor (Af-Bldc) For Axial Blood Flow Ventricular Assist Device (Vad). The developed device has three phase Two axial flow Bldc motors are placed symmetrically and the rotors are coupled to the pump. The stator and rotor of the Bldc consist a hole, since magnetic flux path doesn't pass through the central part. In order to get large volume in pump chamber and lower speed, the pump impellers may be placed in this hole. ie in this design the chamber of the pump is bigger than the previously proposed normal axial VADs. Motor has passive magnetic bearing, which doesn't involve contact and friction, thus it minimize the blood damage. For minimizing the penetration of magnetic field to blood, the axial magnetic fluxes are parallel to the direction of blood.

2.1 Pump Design

The Blood System Is The Main Transport System For Fuel Supply And Disposal Of Body By-Product. It Serves For Distribution Of Food Contents From The Digestive System And Of Oxygen From The Respiratory System To The Body Cells. It Also Serves As Transport System For The Disposing Of By-Products Like Co2 In The Combustion Process. Heart Is The Main Component Of Cardiac Vascular System. It Includes The Pulmonary Circulation, A "Loop" Through The Lungs Where Blood Is Oxygenated; And The Systemic Circulation, A "Loop" Through The Rest Of The Body To Provide Oxygenated Blood. The Systemic Circulation Can Also Be Seen To Function In Two Parts–A Macro Circulation And A Microcirculation. An Average Adult Contains Five To Six Quarts (Roughly 4.7 To 5.7 Liters) Of Blood, Accounting For Approximately 7% Of Their Total Body Weight. The Heart Pumps Oxygenated Blood To The Body And Deoxygenated Blood To The Lungs. In The Human Heart There Is One Atrium And One Ventricle For Each Circulation, And With Both A Systemic And A Pulmonary Circulation There Are Four Chambers In Total: Left Atrium, Left Ventricle, Right Atrium And Right Ventricle. The Right Atrium Is The Upper Chamber Of The Right Side Of The Heart. The Blood That Is Returned To The Right Atrium Is Deoxygenated (Poor In Oxygen) And Passed Into The Right Ventricle To Be Pumped Through The Pulmonary Artery To The Lungs For ReOxygenation And Removal Of Carbon Dioxide. The Left Atrium Receives Newly Oxygenated Blood From The Lungs As Well As The Pulmonary Vein Which Is Passed Into The Strong Left Ventricle To Be Pumped Through The Aorta To The Different Organs Of The Body. Cardiac Output (Known As „Q‟) Is A Measure Of The Amount Of Blood That Is Pumped Out Of The Heart In One Minute. „Q‟ Specifically Refers To The Amount Of Blood Pumped Out Of The Left Ventricle As This Is The Ventricle That Supplies Blood To The Muscles And Organs Of The Body. Cardiac Output Is Made Up Of Two Components, Heart Rate (Hr) And Stroke Volume (Sv). Heart Rate (Hr) Refers To The Number Of Times The Heart Beats Every Minute (Bpm). Stroke Volume (Sv) Refers To The Quantity Of Blood Pumped Out Of The Left Ventricle With Every Heart Beat. The Exact Volumes Are Not Easily Measured, So They Are Often Estimated Based On What We Know About Stroke Volume And The Factors That It Affects Such As Blood Pressure Which We Can Measure. The Equation For Cardiac Output Is: Q = Hr X Sv Blood Pressure (Bp) Is A Measure Of The Force Being Exerted On The Walls Of Arteries As Blood Is Pumped Out Of The Heart.The Maximum Pressure During Ventricular Contraction Is Called The Systolic Pressure. The Lowest Pressure That Remains In The Artery Before The Ventricular Contraction Is Called Diastolic Pressure. Ideally, We Should All Have A Blood Pressure Below 120

Over 80 (120/80). This Is The Ideal Blood Pressure For People Wishing To Have Good Health.Since Variation In The Pressure Is Difficult During Design We Take Average Of Pressure (100mmhg).

The Heart Can Be Described By Simple Model Of A Pump. The Heart Muscles Contracts Which Cause Decrease In The Volume Of Respective Heart Chambers.Amount Of Work Done By Heart Muscle Can Be Calculated By Force F Of The Muscle,

$\Delta W = \int F.Dr$(1)

The Work Can Be Expressed In Terms Of Pressure P Exerted On The Surface Area A Of The Heart Chamber.

$\Delta W = \int (F/A)\, A.Dr$(2)

$\Delta W = \int FAdV$(3)

$\Delta W = \int PdV$(4)

$$\Delta W = \int_{V1}^{V2} PdV \quad (5)$$

$\Delta W = P(V2 - V1)$(6)

V2 − V1 Is The Volume Of Pumped Blood During Each Compression P Is The Average Pressure. Change In Work Done ΔWis Given By, ΔW =Average Pressure * Stroke Volume. The Power or Work Rate Depends on the Frequency Of Theheartbeat.

Output Power Required To Pump = $(\Delta W/t)$ (7)

During The Calculation Of The Input Power Of The Motor Of The Motor We Have To Consider The Blood Flow Conditions, Flow Resistance, Viscosity And Turbulence. Blood Flows Only If There Is Pressure Difference Between Points Along A Tube Originates A Flow F.

F A ΔP(8)

Flow Is Determined By Average Velocity (V) Of Particle and Area Of Cross Section (A) Is Given By,

F = A*V(9)

According To Law Of Continuity Flow Is A Constant.Therefore Average Velocity Is Inversely Proportional To Square Of The Radius Of The Tube. The Resistance R Of The Flow F Is Determined By The Pressure Difference Between The Tubes. The Resistance Can Be Calculated By The Following Relations.

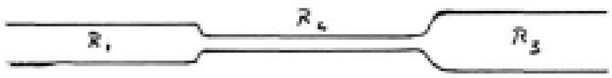

Figure 1 Tubes In Series

Rtotal=R1+R2+R3(10)

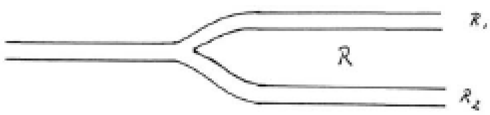

Figure 2 Tubes In Parallel

$$\frac{1}{R_{Total}} = \frac{1}{R_1} + \frac{1}{R_2} \quad (11)$$

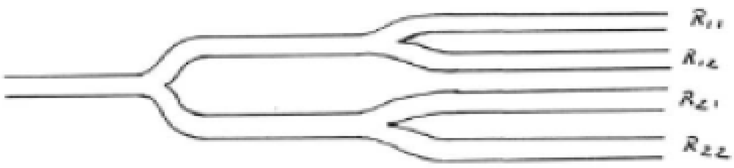

Figure 3 Tubes In Parallel

$$\frac{1}{R_{Total}} = \frac{1}{R_{11}} + \frac{1}{R_{12}} + \frac{1}{R_{21}} + \frac{1}{R_{22}} \quad (12)$$

By Using The Expression For The Flow In The Case Of Branching We Obtain Relation Between The Main Flow F And The Branch Flows F1 And F2.

F = F1 + F2(13)

Flow Resistance Can Be Calculated By,

R = (ΔP/)(14)

Viscosity Is Temperature Dependent Which Reflects Friction Between The Fluid Components. The Velocity Profile For Viscous Or Laminar Flow Is As Shown In The Figure 4.

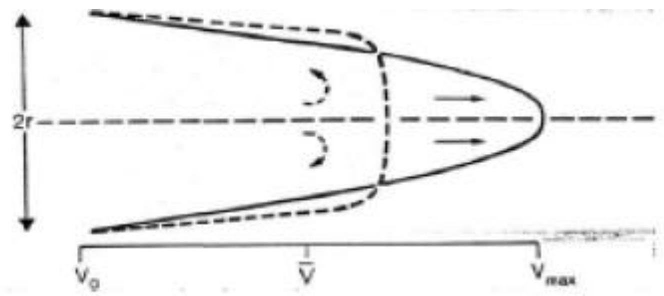

Figure 4 Velocity Profile

Figure 4 is the Velocity Profile For Viscous Or Laminar Flow, here Velocity Is Maximum Along Center Axis Of The Tube And The Velocity At The Adjacent Tube Walls Is Zero. Flow Is Determined By Viscosity Of Fluid Θ.

$F = (\pi r4/\Delta P\ 8\vartheta L)$ (15)

If Velocity Of Fluid Increases Above A Critical Velocity Laminar Flow Is Turbulent.During Turbulence Linear Relation Between Pressure And Flow Becomes Invalid. Turbulence Is Less Efficient So More Work Is Required For The Heart. Critical Velocity Of Turbulence Depends On Viscosity Of The Fluid, Densityρ, Average Velocity V, Radius Of The Tube R,

$N_R = (2\rho r V/\vartheta)$ (16)

Flow Will Be Laminar If TheReynolds's Number Is Less Than 2000.Flow Will Be Turbulent If The Reynolds's Number Is Greater Than 3000.

2.2 Axial flux BLDC pump

Permanent magnet BLDC motor has a compact structure and this provides additional magnetic flux. According to the flux directions, this motors are classified in to Axial flow and radial flow BLDC motors Excellent low speedperformance and high torque generating capacity are inherent natures of the Axial flow BLDC Motor. ie thiskind of motor can be designed for higher torque-to-weight ratio with high efficiency. Axial Flux motors differ from the other types of the motors not for the magnetconstruction shape but the flux direction and the shape of the motor. Flux goesthrough the radially from the rotor axe. The inherent features of PMs, such as high efficiency, high compactness and wideoperation speed range, make these machines suitable for direct drive applications. In directdrive applications, the shaft of the machine is directly coupled to the shaft of the application,thus avoiding the gearbox, which leads to more efficient and compact solutions. The highpower of current magnet materials may decrease the size of the machine in comparison withthe classic induction machines. Furthermore, PM machines have a magnetized motor, so thatthe consumption of electrical energy is decreased. These machines are able to work at lowspeed, which is very interesting for direct drive low speed applicationsIn axial flux machines flux goes throughthe axe direction. Also shape of the motor is rather disc type. The figure 5 below shows the Axial flux BLDC motor. Axial flux machines can be designed as rotor is outside the stator. With this typeof design disc type loads can be coupled with the motor. Sometimes motor iscompletely inserted into load. In the proposed design, rotors are symmetrically placed on both sides of the pump unit. Central part of the BLDC motor is hole, so there is no flux is passes through it. This is the main advantages of the proposed Axial flux BLDC motor based VAD. A pipe is placed in the central hole of the motor, thus it allows passingVAD blood flow through it.

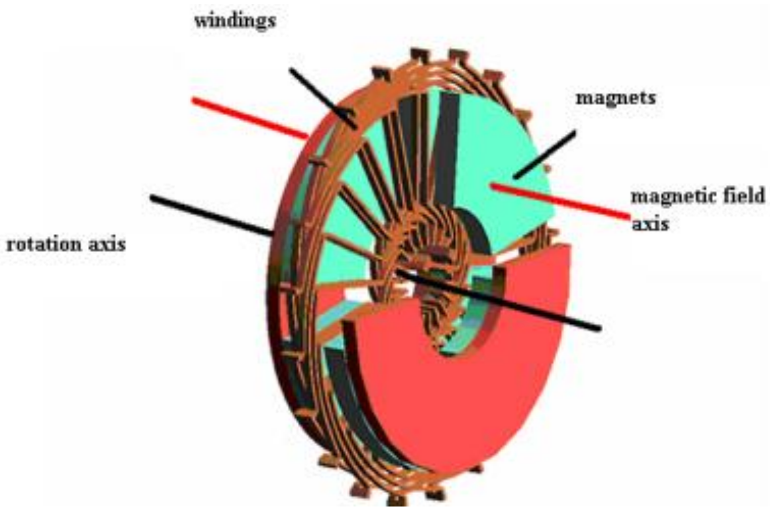

Figure 5 Axial flux brushless dc motors

The flux path of the axial flux BLDC Motor [12] is shown in Fig.6.

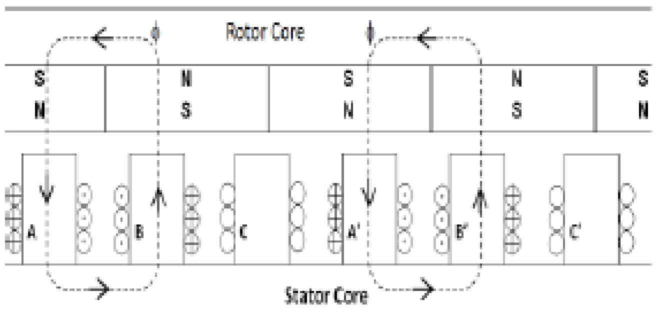

Figure 6. Flux path of AF-BLDC motor

According to the rotor position, phases are switched in sequential order. A hall effect sensor is used for sensing the rotor position. For each phase excitation rotor is rotates by 30 degree. The core reluctance and magnetic permeability of the core is assumed as zero and infinite respectively. Let $S_g$and $S_m$be the air gap and permanent magnet reluctance respectively. These are calculated by using equation (17) [12]

$$S_g = \frac{L_g}{\mu_0 A} : S_m = \frac{L_m}{\mu_m A} \quad (17)$$

Where$L_g$is the airgaplength and Lm is the permanent magnet length. A is the surface area of the stator pole. If the permeabilities$\mu_0 = \mu_m$ then the total reluctance will be

$$S_t = S_g + S_m = \frac{L_m + L_g}{\mu_0 A} \quad (18)$$

Here resistivity$\rho_O = \frac{1}{R_0} = \frac{\mu_0 A}{L_g + L_m}$ (19)

The total mmf of the magnetic circuit is

Ni=$H_m L_m + H_g L_g$ (20)

Magnetic flux $\Phi = B_m a_m = B_g a_g$ (21)

Magnetic flux density is obtained from equation (21)

$$B_m = -\mu_0 (\frac{a_g}{a_m}) (\frac{L_m}{L_g}) H_m + \frac{\mu_0 N}{L_g} (\frac{a_g}{a_m}) I \quad (22)$$

From this current to be applied I = $B_m + \mu_0 (\frac{a_g L_m}{a_m L_g}) H_m * (\frac{a_m L_g}{\mu_0 N A_g})$ (23)

Let $F_r$and$D_r$be the radial force and the diameter of the rotor respectively. Torque can be calculated [12]by using

T= $D_r * F_r$ (24)

Where Frand Fais given by

Fr= I(LxB_g)e_r^-(25)

Fa = $\frac{B_g^2 \; A}{\mu_0 \, 2} e_a^-$ (26)

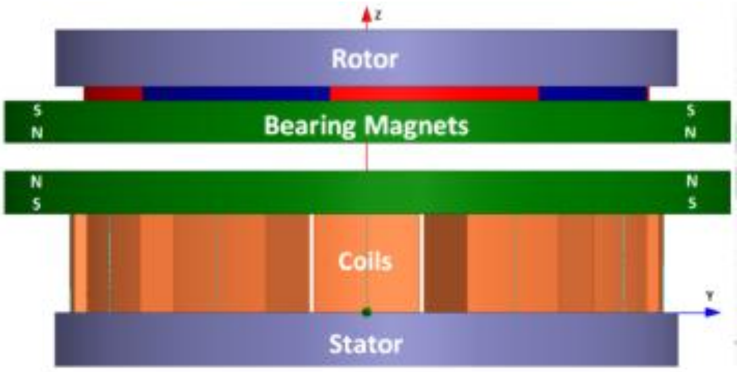

Fig.7. Magnetic levitated design of BLDC Motor (Courtesy : **Prof.Ahmet FENERCIOGˇLU)**

Here Axial force is the pull force of the rotor. This axial force must be compensated, otherwise it will creates friction and blockage in magnetic bearing motors. This design consists of symmetrically placed twin motor and passive bearing magnets for compensating the axial forces developed by the motor. In the operation of the motor, the rotor will be pushed in reverse direction depending on the motor speed and viscosity due to dynamics of the pumped liquid. The magnetic levitated design of the axial flux BLDC motor is shown in fig 7[12].

3 Conclusion

The Efficiency Of The Heart Pump Is Very Low (12-20%) So Due To This Variation In The Efficiency We Take Average Value Of Efficiency As 15%. The Mechanical Power Required For Pumping Blood Is ~1.3 Watts. So The Required Motor Has to Supply an Input Power (~13 Watts) To Provide This Mechanical Power, Since The Mechanical Efficiency Of Heart Is very low, Af-Bldc Motor Design Was Proposed For Axial Blood Flow VADs With Magnetic Bearing.The inherent features of this motor are it has high efficiency, miniature size and high compactness make these machines suitable for direct drive applications. The developeddevice has three phase twin axial flow Bldcmotors are placedsymmetricallyfor balancing the axial pull forces. The stator and rotor of the Bldcconsist a hole, sincemagnetic flux pathdoesn'tpassthrough the central part. In order to get large volume in pumpchamber and lower speed, the pumpimpellersmaybeplaced in thishole. Motor has passive magneticbearing, whichdoesn'tinvolve contact and friction, thusitminimize the blood damage. The blood damage due to shear stress isminimizedwiththisbearinglesspump design.

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