Maglev pumps sustain the wounded heart

Engineers aim to reduce strokes among artificial-heart users with magnetic bearings and computer optimization

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For decades, engineers have attempted to design implantable artificial hearts and LVADs (left ventricular assist devices), but with only mixed success. The same devices that save many of those suffering from life-threatening heart disease-by assisting their heart until a suitable donor organ becomes available-can damage the blood it pumps, causing a 15% incidence of strokes in patients. And each LVAD failure means another perilous surgery for the patient.

Fortunately, two devices that minimize these potentially harmful side effects have made the breakthrough to animal testing and may become clinically available in the next few years. Both replace standard blood-lubricated bearings with magnetic bearings that promise to improve pump reliability, extend operating life, and minimize blood damage.

Magnetically levitated propellers distinguish these from clinically available devices. Because conventional bearings suffer from friction and wear-and opportunities for clotting and infection-these maglev designs suspend the rotor in a magnetic field. Moreover, these maglev pumps are intended as permanent alternatives to a transplant-an important attribute given the shortage of donor organs.

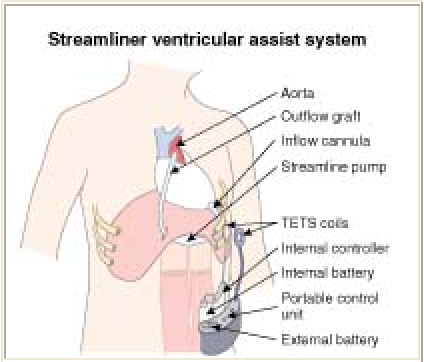
An axial-flow approach

Streamliner, the first magnetic bearing LVAD to reach animal testing in July of 1998, is named for the way it provides minimal disturbance to blood flow. Developed at the McGowan Center for Artificial Organ Development, a subdivision of the Department of Surgery at the University of Pittsburgh School of Medicine, Streamliner is meant to work inside the human body at approximately 7,500 rpm, supplementing the action of a weak or damaged heart. Like some LVADs already on the market, it sucks blood from the left ventricle and delivers it to the aorta.

"The current occurrence rate of strokes in patients with existing devices is unacceptable," says James Antaki, design team leader and director of artificial heart research for the McGowan Center. "To provide a device that saves someone's life, yet causes them to stroke is a real disservice to the patient." That's why Antaki says the key challenges in designing Streamliner were minimizing blood damage and thrombosis, or blood clotting. In fact, explains Antaki, we address all three legs of the thrombosis triangle by:

- Treating the LVAD's materials to resist clotting
- Providing a flow that is minimally disturbed
- And treating the blood with drugs to prevent uncontrolled clotting

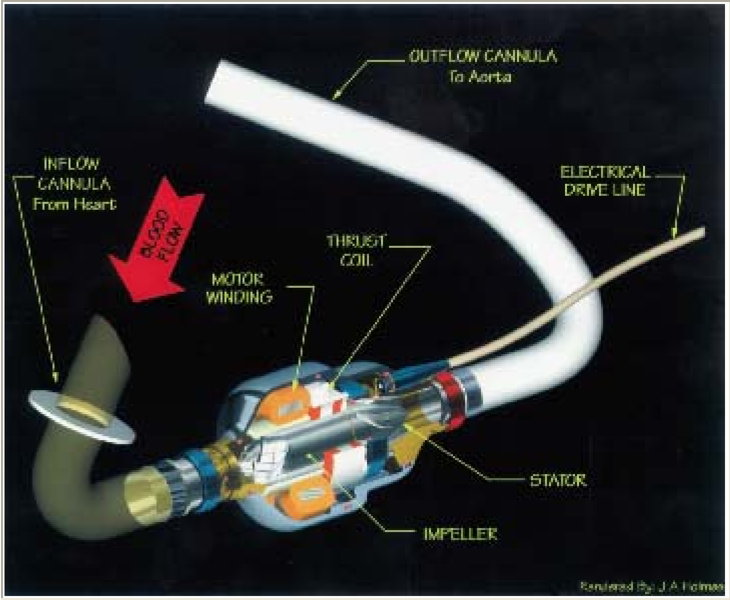
Brad Paden, co-founder of Magnetic Moments LLC (Goleta, CA) and associate professor of mechanical engineering at UC Santa Barbara, heads up the Streamliner's electromechanical design. Magnetic Moments designed the custom brushless dc motor and magnetic suspension system, while the McGowan Center focused on the computational fluid design of the impeller, flow visualization and modification of the fluid flow paths, and blood damage analysis.



Supplementing the action of a weak or damaged heart by sucking blood from the left ventricle and delivering it to the aorta, the Streamliner heart-assist device with a magnetically suspended impeller may become a permanent alternative to an organ transplant.

In the interest of reducing the number of components to improve reliability and save space, the impeller is not only the pumping component, but also serves as the permanent magnet (PM) rotor and contains the outer races of the PM bearing. Two permanent-magnet bearings provide passive radial support for the rotor, and an active feedback-controlled voice-coil thrust bearing positions it in the axial direction. Electromagnetic interactions between system components in such close proximity complicate the rotor's magnetic suspension. "In addition to the forces of the feedback-controlled magnetic thrust bearing, the PM radial bearings, and the field coil that stabilizes and rotates the rotor," explains Paden, "the PM radial bearings are unstable in the axial direction, making for a fast unstable mode in the uncontrolled system. The rotating motor PM interacts with the fixed magnetic components, and the thrust magnets interact with the motor stator. All of these interactions are accounted for and minimized through design, analysis, and experiment."

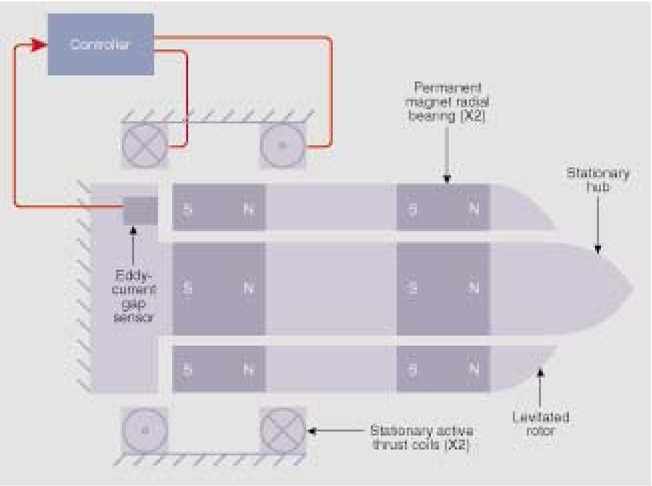
"The magnetic attraction between the motor rotor and the motor stator creates a negative stiffness," explains Paden, "which is dominated by the PM radial bearing stiffness." The negative stiffness of the 3-phase dc brushless motor is reduced with the toroidal winding, which maximizes the distance between the motor rotor magnets and the stator iron. Another advantage of the toroidally wound motor is its low torque ripple. Since the power required for magnetic levitation is largely dissipated in the thrust-bearing coil, engineers optimized its force-per-root-watt metric using ANSYS finite element analysis software. The pole geometry, magnet, and coil dimensions are all optimized using ANSYS and Excel's standard non-linear solver to achieve high performance in this actuator. "The quiescent coil dissipation is a mere 0.5W and 1.5W during pumping at physiologic pressures and flows," says Paden.



Streamliner, named for its minimally disturbed blood flow, was the first magnetic bearing heart-assist device to reach animal testing in July 1998. A magnetically levitated impeller minimizes blood damages and extends pump life.

Lean into the wind. Streamliner's magnetic suspension uses passive PM control for radial-bearing suspension, and an active control circuit supports the bearing in the axial direction. In contrast to rolling-element bearings, PM bearings have relatively low stiffness and so the Streamliner rotor must operate at supercritical speeds (above the first rotor resonance). However, Paden says, the pump is capable of withstanding 10g accelerations without bearing touchdown.

The control system is a variation of a proportional-integral-derivative (PID) controller that acts to minimize the dc current in the coils rather than minimizing the dc position error. "Consequently," explains Paden, "the rotor moves slightly with pressure variations and uses the axial negative stiffness to counterbalance pumping forces." Such a control methodology is referred to as a virtual-zero power control (VZP) and is unique to magnetic bearing control. "People unconsciously use the same algorithm to balance when they lean into a heavy wind," Paden asserts.



Two permanent-magnet bearings provide radial supprot for the streamliner's rotor, and a feed-back-controlled voice-coil thrust bearing positions the rotor in the axial direction.

This all gets back to the original question, says Antaki, of what's the biggest challenge. "Blood damage is. It's a very evasive, moving target because we don't fully understand thrombosis. If we did we wouldn't have patients with strokes, and we wouldn't have this ongoing heart disease. But we take advantage of everything we have learned to date. And that body of knowledge is growing every day."

A centrifugal flow approach

A magnetic bearing LVAD based on centrifugal flow is the brainchild of Vic Poirier, president of Thermo Cardiosystems Inc. (Woburn, MA) and former Design News Engineer of the Year. His newest design is actually a third generation product, the HeartMate III, which is an improvement upon the original LVAD he developed in the early 1990s. Major design goal? Increase the life expectancy of the device from a maximum of three years to well beyond a decade.

"Our goal of a very long life, low-cost, miniature blood pump is now within our reach," says Poirier. "The new pump will provide cardiac assistance from childhood through old age."

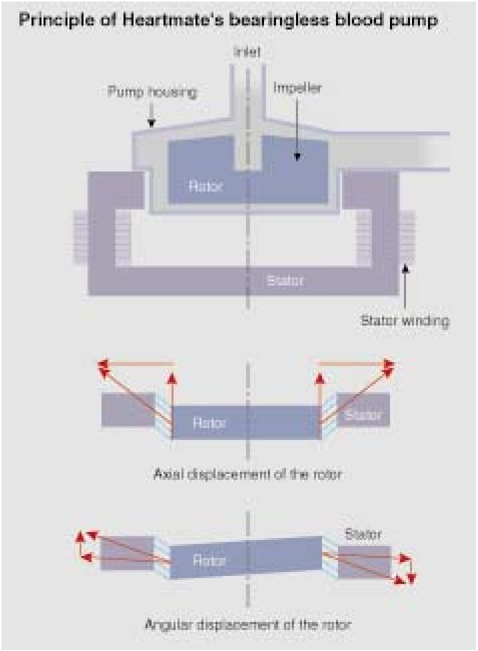
Unlike the reciprocating (pusher-plate) design of Poirier's original HeartMate I, the HeartMate III contains a continuous-flow, centrifugal rotary pump with no valve to wear out. Blood enters the device through a tube on the side, travels into an impeller where it is centrifically forced outward, collects in a volute, and exits from a discharge tube.

But the major reason for the extended operating life of the device is the substitution of magnetic levitation for rotor bearings. The impeller, which is the only moving part, floats in a magnetic field without the contact or friction that can lead to premature wear and shortened device life.

The challenge in using a magnetic bearing is to maintain stable levitation, since any suspended object can move in six possible directions-three translational and three rotational. Some alternative designs use separate magnetic structures for motor action and levitation, some passive and some actively controlled. But design engineers here opted for a relatively simple scheme involving a bearingless slice magnetic technology (Levitronics, Zurich, Switzerland) that combines the bearing and motor in a way that allows them to share the same magnetic field. "The assembly resembles a disk dropped into the hole of a washer-shaped iron structure," says Dave Gernes, director of research at Thermo Cardiosystems Inc. Gernes explains that in this configuration, the magnet will "stick" to the iron sides of the hole. "Even if you could center it with your fingers, you would find that the magnet still prefers to remain within the iron structure," he says. "Since the magnet is passively suspended in axial translation, no external force is required to keep it there.

"Because of the low height-to-diameter ratio of the washer shape, you would also find that it is very difficult even to tilt the magnet in the hole, leaving only the two axes of radial translation to control-back and forth and horizontal side to side," continues Gernes.

To center the magnet, design engineers mounted an array of Hall Effect sensors along the periphery of the stator. Eddy current sensors detect any radial shifting of the rotor, then add or subtract current in the motor windings to create magnetic fields that offset the instability.

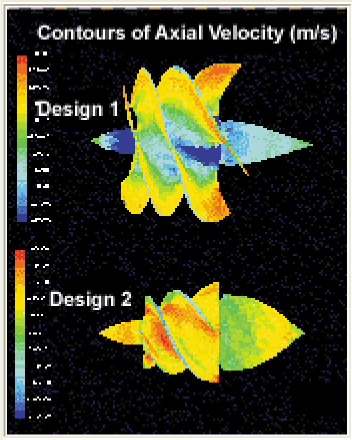


The challenge in using a magnetic bearing is to maintain stable levitation. By opting for a relatively simple scheme in which a circular magnet resides within a washer-shaped structure, engineers achieved passive stabilization in the axial directions. An array of Hall Effect sensors mounted on teh periphery of the stator maintain stabilization in the radial directions.

Streamliner and HeartMate III at a glance

	Streamliner	HeartMate III
Maximum diameter:	2.0 inches	2.7 inches, excluding the screwring
Length, stem to stern:	4.2 inches	1.2 inches, excluding inlet and outlet ports
Pump flow capability:	up to 10 lpm	2–10 LPM
Rpm:	up to 8,000	2,500 to 6,500
Weight:	200g	320g
Displaced Volume:	approx. 75 cc	–
Priming Volume:	6 cc	–
Volume:	–	10.7 in3 (175 cc)
Power Requirements at operating point:	10W = 9W pump + 1W bearing	10W @7 LPM and 135 mmHg
Efficiency at operating point:	pump efficiency = 24%; motor = 85%	overall efficiency = 19.5%

From aerospace to biotech



The McGowan Center used extensive CFD analyses for flow visualization, modification of the fluid flow paths, blood-damage analysis, and to optimize impeller design.

Using a combination of custom-written software, plus Fluent CFD code from Fluent Inc. (Lebanon, NH), and unstructured grid generation software called AFLR3-a product from Mississippi State University that breaks models into analysis elements—Greg Burgreen, research assistant professor with the University of Pittsburgh's Department of Surgery, extended the biotech industry's state of the art in CFD-based design optimization. "If the mesh was poor and we morphed the design to test a new geometry," Burgreen says, "we ran into problems with creating inverted elements of negative volumes. The AFLR3 software gave us a high enough quality mesh so that whenever I deformed it, we retained high quality elements."

The primary challenge was learning how to use blood as a working fluid because Burgreen's background was in aerospace engineering designing aircraft wings where he was used to working with compressible fluids. "Here I'm working with blood, which has formed elements such as red blood cells and platelets that tend to become damaged whenever they are subjected to high shear stresses or stagnation regions in the flow. So I had to change my design philosophy from one of seeking optimum efficiency to one that was minimizing blood damage."

That meant coming up with objective functions that mitigate regions of flow separation and minimize shear stress, and also developing numerical models for blood damage. That is, models that predict blood hemolysis, which is the tearing apart of red blood cells due to shear stresses, and also blood thrombosis (blood clotting.) Mechanical blood hemolysis depends on fluid shear stresses and time exposures to that shear stress. So the Pitt team derived a non-linear blood damage function that correlated quite well with experimental data, according to Burgreen.

"The thrombosis model minimizes any regions of flow separation where we believe thrombosis would occur. Also, we have a function that relates to increasing the average velocity near the blood contacting surfaces to increase the surface washing capabilities of the device."

A second and the more rigorous approach to the thrombosis model requires solving a series of convection-diffusion-reaction equations that describe the chemical reaction processes and the coagulation cascade. "So we are solving about eight different chemical species equations," says Burgreen. "So far we've correlated the model against experimental data that consisted of blood flow through a collagen-coated parallel plate flow chamber observing platelet coverage over the surface, with extremely good results. Although analyses are ongoing with still more work to be done, both models show promise and could serve as objective functions for future Streamliner optimization."

Engineering challenges

- Maintain magnetic bearing stability
- Reduce electromagnetic interference
- Moderate power consumption
- Minimize shear stresses in the blood
- Eliminate stagnation regions in the flow

Other applications for magnetic bearings

- Machine tool spindles
- Turbomolecular pumps
- Compressors
- Turbomachinery