Control of a Magnetically Levitated Blood Pump

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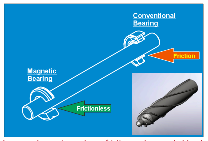
1. Introduction

Advantages and Challenges

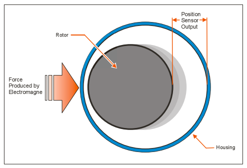
A magnetically levitated axial-flow blood pump is a very promising option for an implantable ventricular assist device because it reduces problems associated with friction. Magnetic suspension has several advantages over traditional methods:

- *Eliminates need for lubrication*
- *Reduces*
  - *-Red cell damage due to high shear stresses*
  - *-Blood clot formation in zones of stagnant flow*
- *Increases device lifetime*



Increased gap size reduces friction and prevents blood damage. Insert: 3D rendition of pump's impeller.

The gap distances and impeller orientation of this pump design set it apart for currently available technologies. The device's control is, therefore, a new application of magnetic bearing technology.

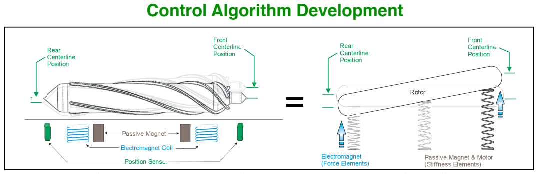


Hall Effect sensors output a voltage proportional to the magnetic field of the rotor. Though the field varies effectively with position, it may not be radially uniform adding error when rotation occurs..

The pump's magnetic levitation system is similar to most magnetic bearing applications in that its goal is to center a rotational component with respect to its housing. Hall Effect sensors are used to measure shaft position because they offer a non-invasive measurement through the specified medium (blood). However, these sensors are susceptible to interference-type noise as well as sensor runout, thus making magnetic suspension a difficult control problem especially at high speeds.

2. Methods

Control Algorithm Development



The main components of the pump can be expressed in terms of idealized elements whose dynamics are defined by differential equations.

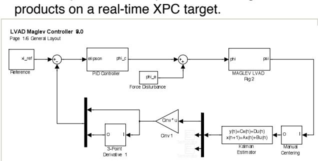
A system model was derived using Energy and Momentum conservation methods. Adequate modeling can provide essential information about the system, such as:

- *System Stability*
- *System Resonant Frequencies*
- *Controllability & Observability*
- *Control Gains*

A Proportional-Integral-Derivative (PID) algorithm was developed using simulations and previous experimental data. A Kalman state observer and a runout compensator were incorporated to add robustness.

Experimental Setup

Control system was implemented using Matlab's Simulink and Real-Time Workshop products on a real-time XPC target.



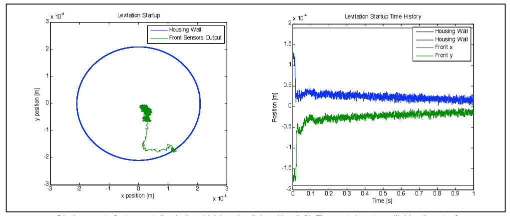
SIMULINK block diagram of magnetic suspension control system.

Impeller and magnetic bearing stator assembly.

3. Results

Model Validaton

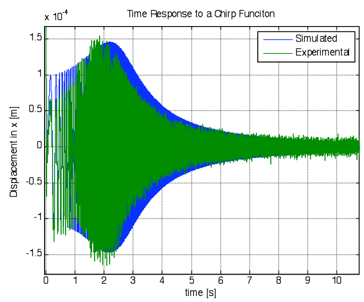
An initial set of gains were obtained by solving the Linear Quadratic Regulator problem for the system. These gains were also confirmed by simulation. In addition to experimental tuning, the PID control scheme was sufficient to achieve rotor levitation.



Displacement of rotor centerline in time (right) and radial position (left). The control system will drive the rotor from its initial position (resting against the housing) to its operating position.

Performance

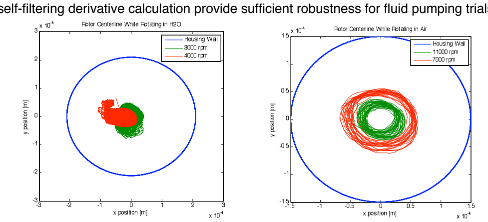
In order to validate the accuracy of the derived system model, identical inputs were feed to the model (simulation) as well as in the actual system (experiment). Tracking a path of fixed amplitude but increasing frequency, also known as a chirp input, is a way to compare computational and experimental data.



Comparison between simulated and measured response to a 1-1250 Hz chirp: Response is similar in the time and frequency domains.

Performance

A model-based Kalman state observer, a variable-frequency runout compensator, and self-filtering derivative calculation provide sufficient robustness for fluid pumping trials.



Rotor centerline position while levitating and rotating at various speeds and in different media

At 6200 rpm, the device pumps 6L/min of blood at 120mmHg

4. Conclusion

Device Effectiveness

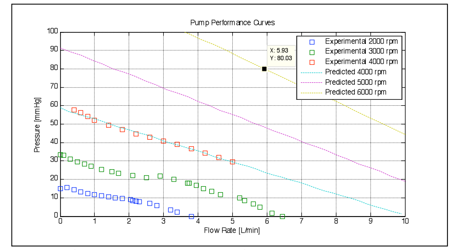
- The current control system proved effective in air
- The pump works in water at speeds up to 4000 rpm
- The system dynamics are accurately represented by the mathematical model

Need for Control at Higher Speeds

The pump design calls for a flow rate of 6.0 Liters/min at 80 mmHg (48 inches of water). Scaling of current empirical data indicates that this can be achieved when the rotor spins at 6000 rpm.

Thus far, the maximum stable rotor speed of the system in water is 4000 rpm. Instability at higher rotational speeds is related to:

- System Noise - lowers ability to increase gains
- Unbalanced forces - require more control effort



The pump's performance curves indicate that the design specification, 6 L./min at 80mmHg, may be met when the rotor spins at 6000 rpm.

This research provided a first demonstration of a working large-clearance, axial-flow blood pump.

5. Future Work

The current strategy for increasing controller performance is a combination of the following:

PID Tuning
- Fine-tune Kalman Observer
- Tune derivative filters

New Control Scheme
- Sliding Mode Control – A proactive, robust control method designed to withstand unmodeled dynamics and model inaccuracies

Hardware Improvements
- Analog anti-aliasing filter improvement
- Amplifiers with more electrical current (and thus force) capacity.

Acknowledgements

National Heart, Lung, and Blood Institute
Grant 1RO1 HL 077085-01A1

Special Thanks to:
Matthew N. Giarra, Rochester Institute of Technology