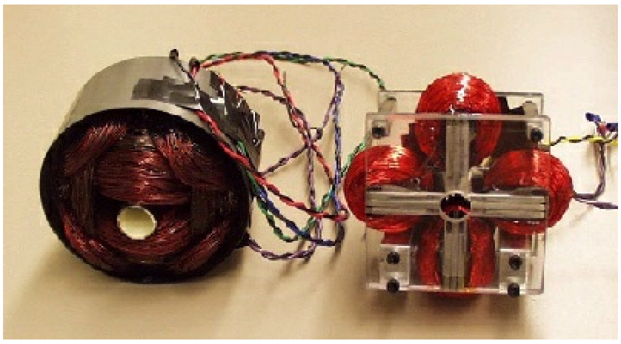
Actuator Design

Description

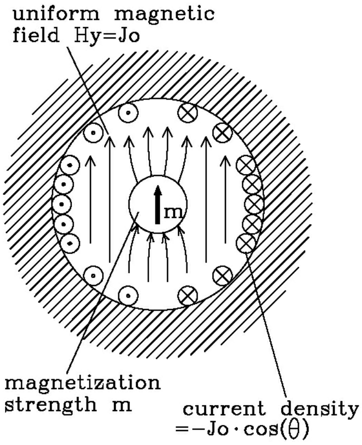
We designed two different actuators and tested their performance. The following picture shows the Dipole-Quadrapole Actuator (left) and the Quad-U-Core Actuator (right). They are both designed to suspend tubes with diameters within 0.5in.

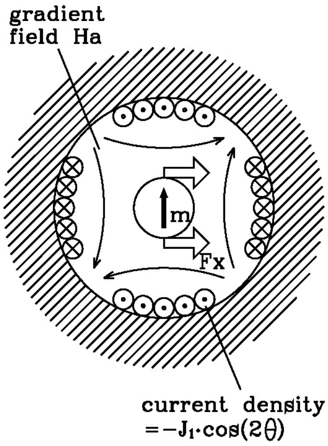


Theory

Dipole-Quadrapole Actuator

The dipole-quadrapole actuator uses a bias field to impose a dipole on the steel tube. A quadrapole field is then added to exert a force on the tube (now a magnetic dipole) which is linear with current and decoupled with the perpindicular direction of motion.



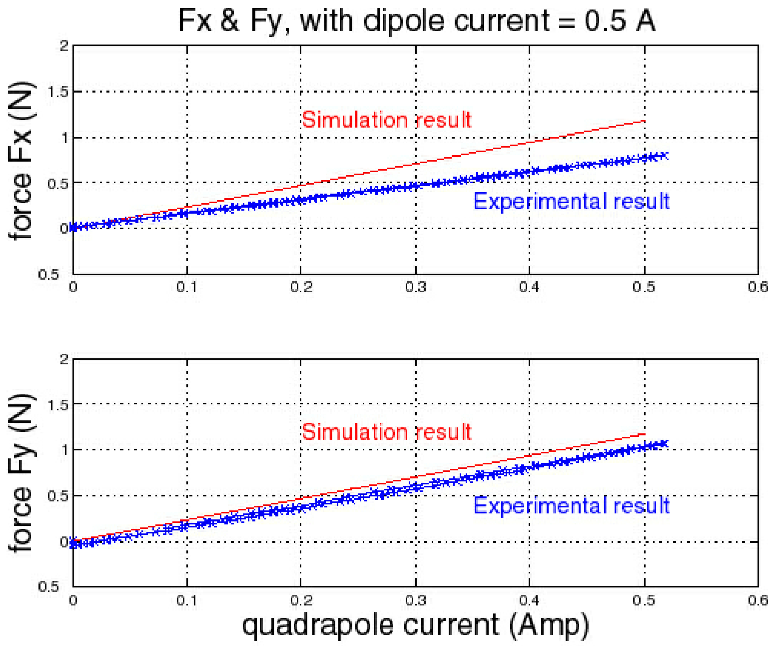


Quad-U-Core Actuator

The quad-U-core actuator consists of 4 U shaped electromagnets, performing a pull-push action on the tube in both X and Y directions. The testing result shows this actuator has a higher power efficiency than the dipole-quadrapole actuator, and it is easier to build. This actuator is chosen to be the 8 actuators used in the final experiment.

Experimental Results

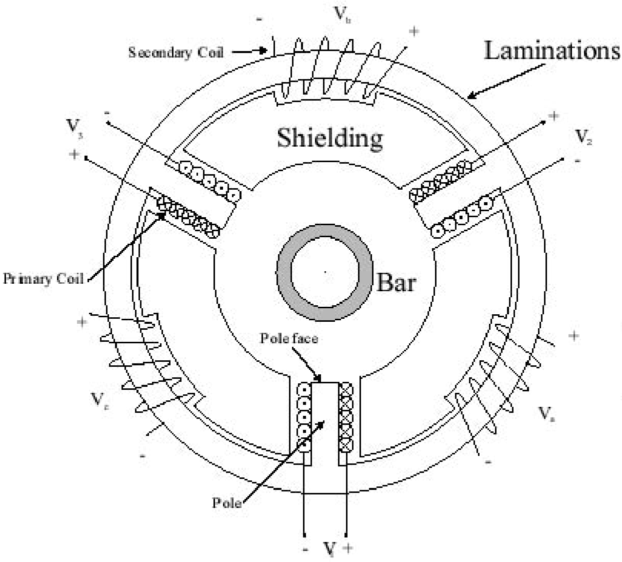
The following figure shows the testing result of the dipole-quadrapole actuator. The force is linear with input current, and decoupled in x and y directions. This means that the control system can command a force directly by commanding a current, rather than computing a square root as required by standard electromagnets (which takes valuable time). Also, the fact that the x- and y-forces are decoupled means that the control system can be much simpler; a single-input single-output system rather than a multi-input, multi-output system. The quad-U-core actuator also shows similar results, and with even larger force output. The testing result is to be attached later.

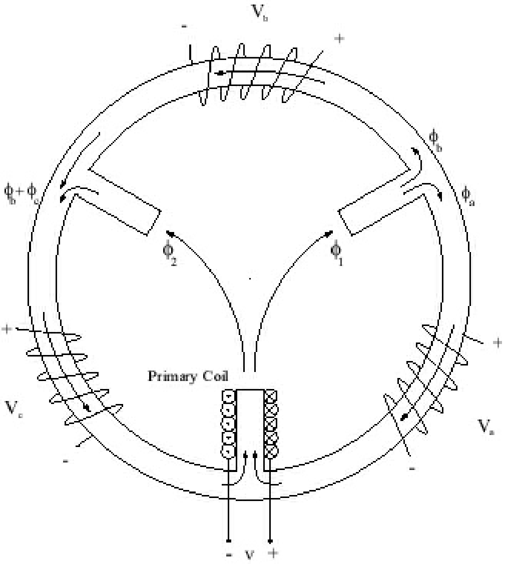

Fx & Fy, with dipole current = 0.5 A
force Fx (N)
2
1.5
1
0.5
0
0.5
Simulation result
Experimental result
0
0.1
0.2
0.3
0.4
0.5
0.6
force Fy (N)
2
1.5
1
0.5
0
0.5
Simulation result
Experimental result
0
0.1
0.2
0.3
0.4
0.5
0.6
quadrapole current (Amp)

Sensor Design

Theory

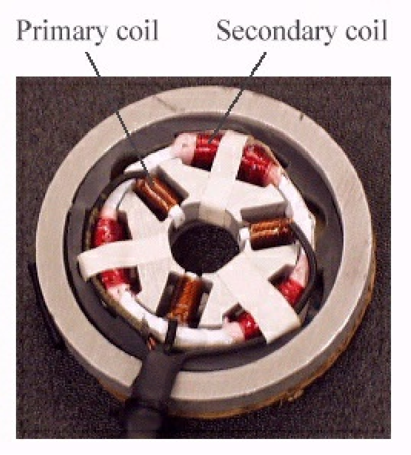
The sensor uses an alternating magnetic field to detect the position of the tube, which passes through the center of the sensor. Three primary poles excite a three phase field in the center of the sensor, which changes as the position changes. The permeability of the tube is much higher than that of air, so the magnetic field would rather travel through the beam than through air. When the beam is off center, more flux travels through one return pole than the other, causing a differential voltage to occur across the output coils. An analysis of the magnetic field gives an expression for the output voltages across the secondary coils in terms of the tube position. Inverting this relationship gives the tube position in terms of the output voltages; this inversion is performed in real time by an analog circuit which outputs x- and y-position dependent voltages. These voltages are then fed into the control computer as feedback for the actuator.



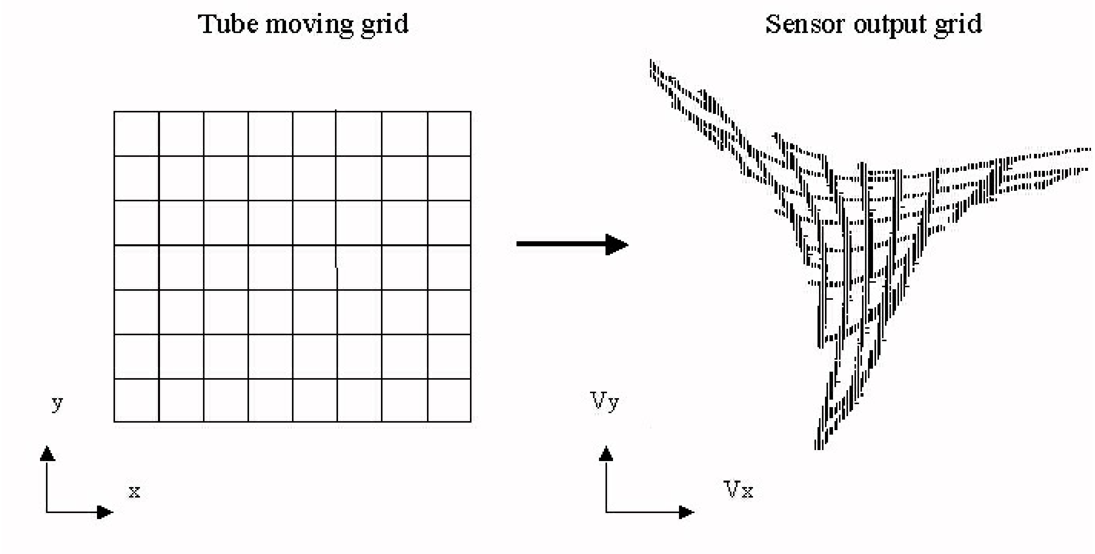


Experimental Results

The sensor works well enough to levitate the tube as desired. The x- and y-output voltages are mostly linear within a 1 millimeter circle in the center of the sensor, but become more non-linear as the outer edge of the sensor is reached. The output is unique and repeatable with the tube position. With a fourth order filter on the output (to convert the sinusoidal 10kHz voltage to a constant voltage) the bandwidth is 1kHz. Sensitivity is adjustable, currently set at 2 Volts per millimeter, with a total useful range of 1cm diameter circle. At this setting, the noise is plus/minus 100 millivolts, and most of that is from the sinusoidal variation of the voltage before filtering. A higher order filter would give a sharper cutoff and reduce the noise in the output voltage.



A Three-Phase Sensor, opened to show three primary coils on the poles, and three secondary coils on the ring

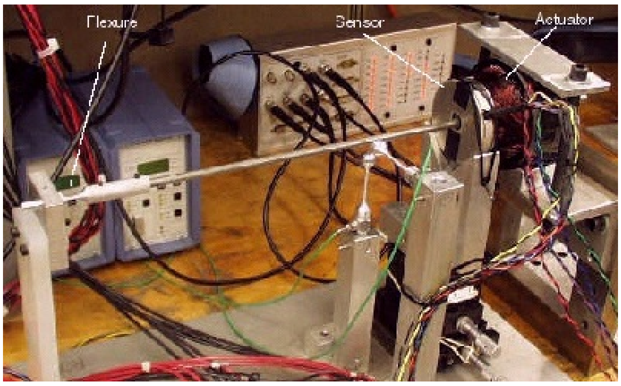


Experimental output of sensor: when the tube is moved at 1mm grid (left), the sensor output of Vx vs. Vy is shown (right)

Magnetic Suspension Experiment I: 2 foot long beam

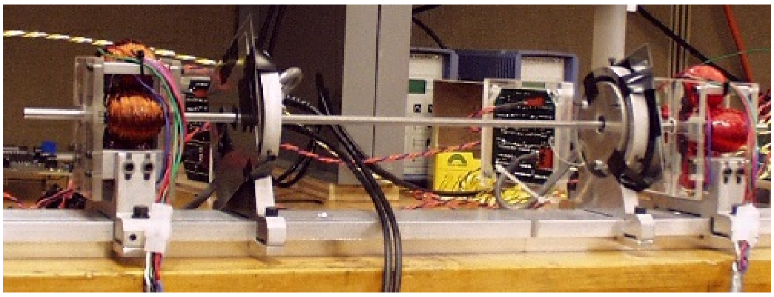
Hinged-Free Ends Suspension

The first magnetic suspension experiment uses 1 sensor and 1 actuator to suspend a tube on one end, while the other end of the tube is simply supported. The suspension control is implemented by using a lead compensator on X axis, and another lead compensator on Y axis; X and Y direction dynamics are assumed uncoupled and are controlled independently. The closed loop bandwidth is below the first vibration frequency.



Free-free Ends Suspension

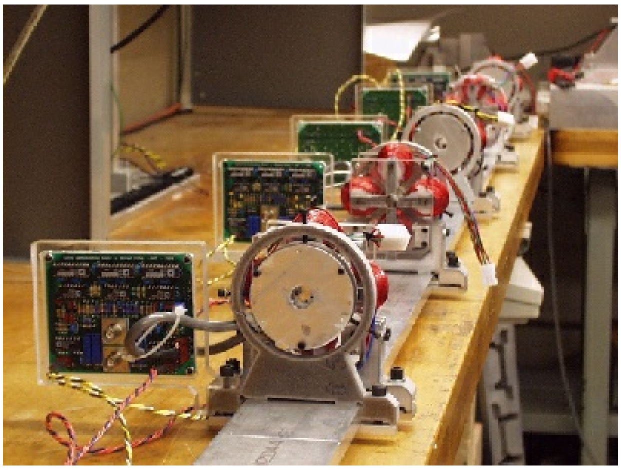
The second magnetic suspension experiment uses 2 sensors and 2 actuators to suspend a tube one both ends, the tube is only supported by the magnetic force; it floats in the air without any contact. The suspension control is implemented by local control; each sensor/actuator pair is controlled independently. X and Y direction dynamics are controlled independently. The closed loop bandwidth is below the first vibration frequency.



Magnetic Suspension Experiment II: 10 foot long beam

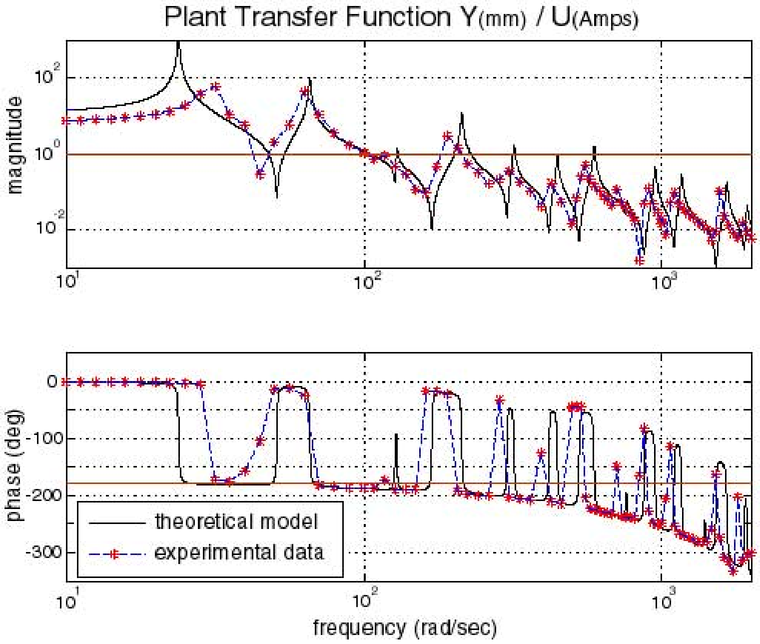
Final Experimental Setup

The final experimental setup for the magnetic suspension consists of 8 sensors and 8 actuators. The hardware and electronics are completed. The experimental setup can be used to study the sensor/actuator positioning, and controller design.



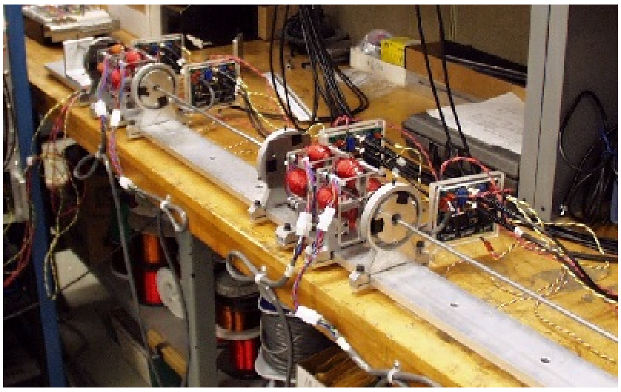
Beam Dynamics

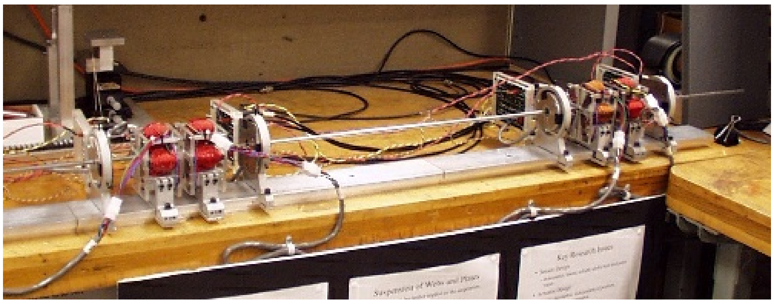
Magnetic suspension of an elongated beam is difficult because of its lightly-damped vibration modes. The Bode plots of the system plant is shown in the following graph, it includs the dynamics of the beam, sensor, actuator and time delay.



Clamped-Free Ends Suspension

This magnetic suspension experiment uses 8 sensor and 8 actuator to suspend the 10 foot long tube, while one end is free and the other end is clamped. The suspension control is implemented by using a multiple-lead compensator on X axis, and another multiple-lead compensator on Y axis; X and Y direction dynamics are assumed uncoupled and are controlled independently. The closed loop bandwidth covers about 8 to 10 vibration modes.

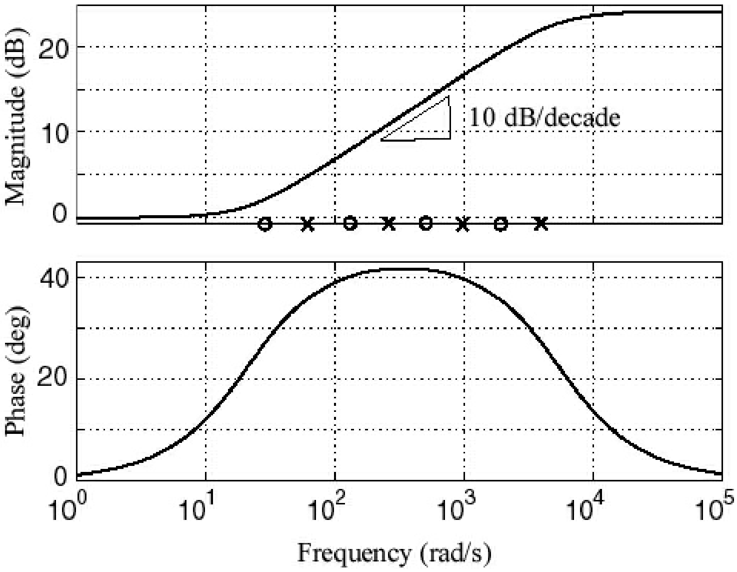



Suspension of Webs and Plates
Key Research Issues

Controller Design

Slow Roll-Up Lead Compensator

The controller we are using is a Single-Input-Single-Output controller. To add damping to vibration modes of the structures, we use lead compensation. To avoid over-amplifying higher frequency modes, we adjust the locations of multiple zero-pole pairs, and have a 10 dB/decade gain slope and 30 degree phase all over the vibration modes that we are controlling. The Bode Plots are shown in the following.

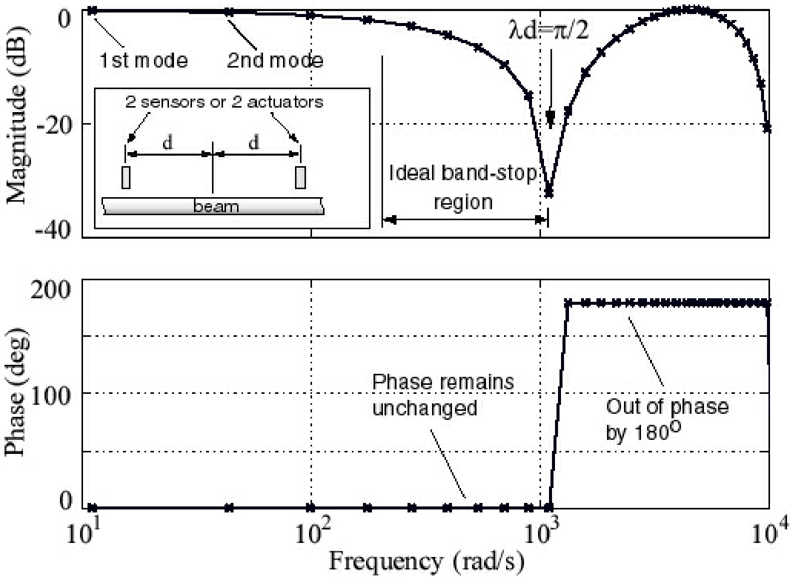


Sensor/Actuator Positioning: Sensor Averaging and Actuator Averaging

Sensor Averaging

We developed a novel sensor positioning method: sensor averaging. By placing 2 sensors apart by 2d, and use the average of the two outputs to control the middle point. The averaged output has less observability on the vibration modes with wavelengths close to 4d. Therefore, we can attenuate the undesired vibration modes robustly. The Bode plots of the resonance modes are shown in the following figure. The broad notch filters undesired resonance modes. The advantage of this averaging methods are:

- It eliminate sensor/actuator noncollocation problem.
- It robustly attenuates undesired resonance modes without adversely affecting phase
- The attenuation is a function of wavelengths, and is independent of structure boundary conditions, structure lengths, and structure positions.



Actuator Averaging

The dual of sensor averaging is actuator averaging. It is not as straight forward as sensor averaging, but the effect is very similar. We place two actuators set apart by 2d, and apply the same force to control the middle point. The resulting force has less controllability on the vibration modes with wavelengths close to 4d. Therefore, we can again attenuate the undesired vibration modes robustly. The bode plots of actuator averaging is the same as the previous figure for sensor averaging.

We can place 2 sensors and 2 actuators, and together we can create a even broader notch to filter the undesired resonance modes. The experiment of 10 ft beam suspension with free-free boundaries were not successful until we use both sensor averaging and actuator averaging. The resulting closed-loop system is robustly stable for varying boundary conditions.