Research Topics – Spring 2008

1. Six DOF Positioning Stage with Sub-micron accuracy by Magnetic Servo- Levitation.

The long term goal of this project is the design and construction of a 6-DOF positioning stage with submicron resolution to be used in semiconductor and optics manufacturing. The target workspace is 200x200x1 mm travel with controlled rotations in yaw, pitch and roll. The system is actively controlled in 6-DOF by novel hybrid electromagnetic actuators designed and developed at FIT with NSF support. The proposed design addresses three limitations of state-of-the-art technology:

- A range of motion substantially larger can be achieved (x6), compared to micro positioning stages based on linear piezoelectric or voice-coil actuators.
- Submicron resolution has already been demonstrated in a 1-DOF device
- Future systems will avoid the use of air bearings since electron beam lithography requires operation in vacuum - hence the importance of full magnetic suspension.

Dynamic characterization, modeling and control of the 1-DOF hybrid electromagnetic actuator

Practical magnetic suspension systems require efficient ways to provide a nominal lift force while generating minimal heat. Conventional high-precision machines use air bearings for that purpose, but they have near zero range of motion in the direction perpendicular to the axis of travel. A multi-DOF magnetic suspension must address this issue by a mechatronic design that integrates active electromagnets with permanent magnet suspension within the same machine or actuator. A novel hybrid electromagnetic actuator is currently under development. The actuator uses NdFeB permanent magnets to provide passive suspension action, and a feedback-controlled coil to accurately control the 1-DOF motion of the free end of the actuator.

This effort is dedicated to the development of compact, accurate parametric models of the novel hybrid actuator based on analytical solutions of the field equations and experimental input/output measurements. The goal is to develop models that are compact enough to be executed in real-time, yet accurate enough to allow robust operation with sub-micron accuracy in a multi-DOF workspace. The models will describe the static and dynamic relationship of force, current and air gap, both in the time and frequency domain. The analytical models will be tested both experimentally and with finite-element electromagnetic software (Maxwell-Ansoft 3D). The models will also be used to develop and demonstrate robust tracking control with submicron accuracy in 1-DOF.

Modeling and Control of a 6-DOF magnetic suspension based on Hybrid Electromagnetic Actuator

The actuator described above has been incorporated in a 6-DOF magnetic suspension platform. Three orthogonal displacements and three rotations can be controlled within a workspace of several hundred cubic microns. Current work on the 6-DOF platform has the following objectives: (i) To develop the kinematic relationships that relate the 1-DOF motion of individual actuators to the 6 DOF motion of the platform. (ii) To develop a nonlinear MIMO control algorithm of the 6-DOF platform, including the decoupling matrices and the corresponding simulations. (iii) Implementation of the 6-DOF controller in real-time, including signal interfacing and system integration (capacitance probes, power electronics, and DSP control computer).

6-DOF Design for High-throughput High-stiffness and submicron accuracy

The integration of the 6-DOF platform into a multi-DOF positioning system with 200 mm travel in X and Y, 1 mm vertical travel range, 3 controlled rotations, short settling times and sub-micron accuracy remains a challenging design problem since rapid response, low power consumption and high stiffness in all six directions are necessary. Two separate control computers are used: a DSP board to control small displacements in all 6 DOFs, and a CNC motion control board to control the long range motion (XY) via linear motors and laser interferometer feedback. Both systems need to be integrated via DLLs in the host computer.

The objectives of this sub-task are: (i) Optimization of the 6-DOF platform controller to provide short settling times and zero steady-state error to base motion disturbances (i.e., XY motion), (ii) Integration of the platform controller and the linear motor controller by host computer DLLs, (iii) Design modifications are sought that could lead to having at least 2 DOFs of the platform measured and controlled by laser, relative to a coordinate system fixed to ground. If some of the target mirrors were attached to the 6-DOF platform, it would be possible to control some DOFs relative to ground with the resolution and accuracy of the laser interferometer.

2. Control of the 3-DOF Dynamics of an Electrodynamic Maglev System for Launching

Multi-DOF control of the launch vehicle dynamics in a EDS maglev system is currently being investigated with support from NASA and the Office of Naval Research. The long term goal is the use of electrodynamic suspension for future space and military launch applications. A sub-scale electrodynamic launch system currently located at our facilities.

Although the NASA test track has been designed for speeds up to 90 km/hr with accelerations up to 10 g, the controller currently developed has only been tested under semi-static conditions. Design and system integration work is necessary to enable track operation at full speed while controlling all 3 DOFs of the launch vehicle (heave, pitch and roll) in real time. This implies:

(i) Incorporation of the more accurate model of the flux-current-force track-magnet interactions mentioned above.

(ii) Development of a systematic test procedure for all subsystems and signal interfaces, including the propulsion section - power and distribution electronics.

(iii) Design of a robust nonlinear MIMO control scheme that operates properly at all speeds over the entire length of the track - the look-up and inverse mapping interpolation method described in Section 2.1 will be implemented and tested on the real-time DSP platform.

3. Seismic Hazard Mitigation of Structures by Semiactive Magneto-Rheological Mass-Dampers

The last two decades have seen the development of important new technologies for the control of structures subject to dynamic loading. Effective passive devices such as base isolation systems are sometimes impractical to implement and, in spite of their advantages, not always suitable to retrofit in existing structures. Passive tuned mass-dampers provide limited improvement, and their performance is hampered by several factors such as de-tuning or nonlinear behavior of the structure. Active devices (direct force actuators) provide significant improvement of the structure's response, but require massive and expensive actuators directly incorporated as part of the structure. In a hazardous event such as an earthquake, electric power failure may render these actuators useless.

Semi-active devices such as magneto-rheological (MR) dampers are a very attractive alternative since they are adjustable in real time and their power requirements are relatively small. The potential advantages of MR dampers have generated substantial interest - MR damper models have become increasingly sophisticated, and the most accurate models available to date are indeed very complex. For a given set of structural dynamic specifications, there is no straight forward method to design a system that includes a MR damper, which has greatly limited their use. Due to the complexity of the MR models, most algorithms used to control MR dampers use some sort of on-off control, based on some variation of a Lyapunov stability condition. This has limited the closed-loop system's performance - the advantage gained by the use of MR dampers has been in many cases marginal. Successful work in vibration control of structures using MR dampers has used them as direct force actuators, making the size of the damper comparable with the size of the structure (20 Ton MR dampers have been described). Significant advances in modeling and control of MR actuators and MR-based systems are necessary to fully exploit their potential, and to make the technology readily available to structural designers.

This project proposes a novel approach to structural hazard mitigation based on MR mass-dampers. The MR-MD uses an MR damper not as a direct force actuator but as a semi-active connection device between the mass of the structure and a free-moving mass. The MR-MD provides real-time adjustability combined with smaller size and low power consumption. By itself or in combinations with other methods such as base isolation, it has the potential to provide a reliable and economical answer to the challenge of substantially improving the comfort and safety of many existing and future structures.

Testing the proposed MR-MD concept using complete full-scale test structures would be prohibitively complex and expensive. Real-time hybrid simulation offers a viable alternative to conduct full-scale experiments, and the Real-time Multidirectional Facility for Seismic Performance Simulation of Large-Scale Structural Systems (RTMD) at Lehigh University is ideally suited for the proposed research.

Intellectual Merit -The size and cost issues associated to the use of MR dampers in large structures are addressed by a design that uses the MR damper not as a direct force actuator but as a semi-active connection device between the mass of the structure and a free-moving mass, that could be part of the structure itself, controlled in real time.

- A novel modeling approach of the MR damper that facilitates its use in structural design is presented (the piece-wise input-invertible MR damper model), including a simple and straightforward method to extract the MR model parameters.
- A robust model-based control method that takes advantage of the model's algebraic input invertibility is presented. The proposed controller includes both a switching term for robustness, and a model-based continuous term for enhanced performance (modified non-affine sliding control).
- The effectiveness of the MR-MD, as a low-power, low-cost alternative to hazard mitigation of structures will be demonstrated by full-scale hybrid simulations performed at the Lehigh NEES site
- Practitioners will be directly involved on the outcome of this research through an advisory panel. The resulting guidelines for the design of structures with MR-MDs will take into account real-time implementation issues, and case studies of real structures.

Broader Impacts - The proposed approach to model hysteretic behavior by fitting input-output data to a piece-wise invertible structure could possibly have applications in a wider range of scientific and engineering fields. Real-time hybrid simulation techniques will be used to conduct large-scale testing to evaluate the proposed approach. Through the use of a NEES Center, researchers across the nation will be able to directly share the results of this research and further the state of the art in an incremental manner. The long-term outcome of this effort will be the confident adoption of MR technology by the structural design community. A better understanding of the behavior of MR-MDs would also lead to the combination of this technology with passive control methods such as base isolation.

4. Novel Topology for High-Speed Superconducting Electrical Machines Using Double-Helix Coils

This project proposes the development of enabling technologies for the design and construction of a new generation of superconducting electrical machines with unparalleled power density, quench safety and electrical performance. The proposed concepts are based on the use of a novel coil configuration, the double-helix tilted winding (DH coil), that offers unique advantages over conventional superconducting windings: they are easy to design and fabricate, provide excellent management of both electromagnetic and mechanical forces, have low inductance and low harmonic losses, and provide excellent field uniformity and improved robustness to insulation failure. DH coils also have a larger conductor bending radius, which makes them easy to manufacture without significant degradation of the superconducting properties. The second enabling technology is a novel rotary flux pump transformer, which will enable iron-free low-inductance rotors that operate at very high currents, resulting in a significant increase in reliability (quench safety) and power density with respect to state-of-the-art machines. The development and experimental validation of design, analysis and simulation tools for high-power density, iron-free superconducting electrical machinery is also being proposed, along with the design, construction and testing of a high-current low-inductance fully-superconducting motor with superior electrical performance.

Intellectual merit: Three important contributions to the state-of-the-art are made: (i) A novel topology for high-speed, high energy density generators has been proposed, (ii) A contact-free high-current rotor excitation system based on a novel rotary rectifier flux pump design has been proposed. Since no external connection to the rotor coil is required, very high rotor currents are possible, and excellent flux coupling, power density and efficiency can be reached, (iii) a novel DH coil geometry, which is easy to manufacture and has excellent mechanical stress management while providing very high field uniformity, low inductance, excellent quench safety, and a reduced chance of insulation failure. The proposed research thus represents a breakthrough in superconducting electrical machine technology that will enable the design and construction of next-generation electrical machinery with unparalleled power density, quench safety, reliability and electrical performance.

Broader impacts of the proposed research: High-speed high-power density electrical machines with iron-free rotors have the potential to become the next generation electrical power generation systems for applications where optimal power to mass ratio is critical, and lightweight, reliable and efficient electrical machinery is required. This includes mobile and airborne applications, high power density motors and generators for aerospace applications. The proposed technology can have a broad impact in many other power systems (synchronous condensers, energy storage systems, etc). In a world where reliance on electrical power is becoming increasingly important, the development of high-performance electrical machine technology is of utmost relevance.

5. Electromagnetic Launching by Constant-Flux Synchronous Propulsion

Electromagnetic launching can deliver payloads at speeds in excess of Mach 20 from electrical power. Although several different concepts have been proposed, a number of unresolved technical challenges have prevented it from becoming a reality. The critical limitations of EM launching have been (i) large heat dissipation, leading to potential damage to both payload and launcher when reaching high speeds, (ii) complex wear and contact phenomena resulting from mechanical contact at high speeds, (iii) the lack of an efficient method to generate current in the projectile without excessive heating of the payload.

The constant-flux synchronous motor (CFSM) is a novel concept that addresses most of these critical problems. The CFSM launcher is based on a constant magnetic flux zone that moves with the projectile in a traveling wave - constant-flux operation eliminates inductive heating of the projectile. Superconducting rings operating in persistent mode are used as current source in the projectile, eliminating the need of feeding the launch vehicle through brushes, contact armatures or AC induction. The resulting contact-free, self centering suspension and propulsion dramatically improves survivability (wear and tear) of the launcher since heat dissipation in the track during launch is relatively small and distributed over the length of the launcher. A conical/cylindrical projectile design allows stabilization by spinning, introduced at the home position prior to launch - this stabilizes the projectile both during the acceleration phase and during the coasting flight through the atmosphere.

An integrated simulation that combines the electromagnetic and aerodynamic forces acting on the projectile will be developed to calculate the multi-DOF projectile trajectory during acceleration. The simulation consists of the following sub-modules: (i) Computation of the instantaneous mutual inductance (ii) Computation of the instantaneous electromagnetic forces and torques, (iii) Computation of the instantaneous aerodynamic forces and torques induced in the projectile during launch.

An experimental proof-of-principle experiment is currently under development, to demonstrate the basic electromagnetic interactions and forces in the proposed concept.

6. Comprehensive Framework for Modeling Blast Events and Blast-Related Brain Injury

The effect of a blast on the human body can be insidious; vital organs can be severely damaged with no visible external evidence, and other complex clinical symptoms may occur. Historically, estimating blast effect comes from live animal testing, largely concerned only with lethality estimates, whereas physiological effects are present at much lower levels of blast pressure. In general, blast injury can occur even when no external evidence is visible. Research in traumatic brain injury currently found in the literature is almost exclusively dedicated to blunt head trauma. A systematic approach to study blast-related injury is largely nonexistent. Current models of blast-related injury lack the ability to accurately predict transient phenomena, and do not provide a connection of how such events affect the functionality of vital organs. There are no models that attempt to correlate organ-specific biomarker results with blast wave signatures to assess levels of individual and multi-organ injury.

Although the physics of blast waves are complex and nonlinear, a wave may be broadly characterized by its peak overpressure (pressure above atmospheric) and the duration of the blast event. The intensity of the blast wave can be assessed from those two, and exposure threshold limits can be determined, although this only applies to a specific scenario. Many published results do not demonstrate a proper characterization of the blast environment. To vary the peak overpressure at the specimen, some researchers vary the distance from the blast tube exit to the specimen, traversing between the near and far-field behavior of the wave. Also, a majority of data sets only report the shock or blast wave static pressure, while the dynamic pressure of the ensuing air blast may have the same or greater magnitude,

The proposed research represents an original and comprehensive approach to characterize the effects of a blast and the associated blast-related brain injury. It is proposed that in the case of a blast, in addition to the four brain exposure factors previously described in head trauma, the restitution coefficient between the head and the oncoming blast wave is a mechanism of traumatic brain injury specific of blast-related insults. This hypothesis will be experimentally tested with animal studies, and a statistical model based on a one-way MANOVA.

Intellectual Merit of the Proposed Research. (i) A novel experimental technique to characterize blast events is proposed. (ii) A novel method to measure restitution coefficient in blast events based on shadowgraphy and high speed imaging is proposed. (iii) Characterization of the aspects of a blast event that contribute to injury, in particular, the effect of restitution coefficient in brain injury. (iv) Model the physics of the restitution coefficient between an oncoming blast wave and a free standing target, as related to blast-induced brain injury, including the analytical and numerical estimation of the restitution coefficient in a simple head model based on wave propagation theory. (v) A blast-related brain injury model. A novel mechanism of blast-related brain injury based on restitution coefficient as brain exposure factor is proposed. The brain injury model consists of the statistical correlation (one-way multivariate analysis of variance, MANOVA) between the proposed brain exposure factor (restitution coefficient), and the corresponding injury metrics as dependent variables. Injury metrics include (a) concentration and type of brain-specific blood-borne biomarkers, (b) morphological brain injury data, including histology and other imaging data (CTSCAN), and (c) clinical metrics of brain injury as measured by established protocols for clinical evaluation of brain damage in rats.

Broader impacts. (i) A novel framework to characterize blast events is proposed (development of blast signature parameters), (ii) A novel method to experimentally measure restitution coefficient in blast events based on retro-reflective shadowgraphy and high speed imaging is proposed. This is a contribution on itself to the field of experimental fluid dynamics. (iii) A method to develop scaling laws for blast experiments based on blast signature parameters is proposed. (iv) A model of blast-related brain injury based on restitution coefficient is proposed. (v) The proposed framework can be the basis of a general methodology to analyze blast-induced trauma. (vi) The experimental and statistical modeling tools developed from this study will also be a direct benefit to human safety, as they can be used to develop modeling tools for design and performance assessment of protective gear, and CAE tools to simulate different blast scenarios to quickly assess injury to military personnel on the field based on blood-borne bio-markers.

Industry- University Collaboration. The most important benefits of this partnership stems from the fact that both animal testing and the proposed biomarker studies for this project will be carried out at Banyan Biomarkers, Inc. Animal testing is expensive, and requires specialized facilities and personnel. If this funding request is granted, both the cost of animal testing and access to Banyan's proprietary state-of-the-art biomarker technology will be contributed by Banyan as cost sharing. This makes the cost of this project low, compared to the potential benefits it can bring.

7. Novel Framework for Characterization of Slosh Dynamics in Low-Gravity

The slosh dynamics in cryogenic fuel tanks under microgravity is a pressing problem that severely affects the reliability of spacecraft launching. In preparation for orbital insertion of the payload, the upper-stage of the rocket undergoes a series of maneuvers which may lead to sloshing motion of the propellants. Liquid propellant reaching the relief and orbital control vents within the tanks may result in a significant increase in expelled mass causing a dynamic instability which may cause mission failure. An additional consideration in launch vehicle design is potential overlap of the slosh resonant frequencies with the control system and structural dynamics frequencies. To date, computational and numerical models of the dynamics of fluid-structure coupling during slosh events have not been benchmarked against low-gravity experimental data. In particular, a direct comparison of fluid damping coefficient with numerical-predicted damping would be of significant interest to the engineering and scientific community.

The intellectual merit of the proposed activities is related to the complexity and novelty of the proposed approach. Historically, slosh damping has been difficult to predict analytically, especially for large amplitude, non-linear slosh events, and is not sufficiently accurate for design verification. With few exceptions, previous work in slosh dynamics has been mostly theoretical or treats the mass of fuel as a variable inertia only - models that do not consider the viscosity, surface tension, and other important fluid effects that become magnified at low-gravity conditions. What we propose is to bridge the understanding of slosh dynamics in microgravity by a comprehensive approach that combines computational fluid dynamic tools, dynamic simulation tools, semi-analytical models of the predominant fluid effects, and a novel experimental framework for the characterization of liquid slosh in a multi-DOF maneuver.

The broader impacts of the proposed activities are several: first, a set of numerical, analytical and experimental tools will be developed to produce a comprehensive framework to understand slosh dynamics under microgravity, including a novel framework for the experimental characterization of slosh dynamics. Second, the proposed framework will enable engineers to correctly benchmark computational and modeling tools currently used to predict slosh in spacecraft. The capability of properly predicting dynamic slosh effects will have a broad impact in the development of design tools for cryogenic fuel tanks and control systems for spacecraft, fluid storage aboard future space stations.

Industry- University Collaboration. ARES Corporation, a provider of engineering and technical services to NASA and the aerospace industry would like to partner with the Florida Institute of Technology (FIT) in the development of solutions for the specific challenges mentioned above, in particular the first-ever comprehensive benchmarking of numerical slosh dynamics codes with relevant low-gravity experimental data. FIT has an active collaboration with NASA Kennedy Space Center for the computational and experimental study of slosh dynamics, and plans for experiments in a NASA low-gravity aircraft are currently in place. The project would also involve the participation of two doctoral students and two teams of senior undergraduate students over two years.

The low-gravity slosh dynamics experiment will be a truly unique endeavor resulting in an improved understanding of low-gravity fluid phenomena. This GOALI proposal supports the academic-industry synergy between FIT and ARES Corporation in the context of a challenging scientific problem of great interest to NASA and the scientific community. This GOALI proposal would enable the FIT-ARES Corporation team to leverage existing equipment funding from NASA to further promote an understanding of low-gravity fluid dynamics, and the development of novel instrumentation that can be used in a wide range of low-gravity fluid flow studies.

8. Integrated Environment for the Coupled Simulation of On-Orbit Upper-Stage Launch Vehicle Dynamics

A comprehensive simulation environment of upper-stage launch vehicle dynamics involves the simultaneous solution of aerodynamic and fluid dynamic equations, chemical kinetic equations, and multi-DOF motion equations. Although these effects are obviously coupled, they are usually simulated separately due to the computational complexity involved and the lack of proper computational tools: the aerodynamic and fluid equations are typically solved using finite element methods (CFD), and both the chemical kinetics and the motion equations are handled by time-domain differential equation solvers. This project proposes the development of an integrated environment for the coupled simulation of upper-stage launch vehicle dynamics by integrating currently existing tools during run-time from the Matlab environment.

The proposed method also opens an attractive path for future development: the use of Matlab-based tools for parallelization of the computational tasks in a complex coupled simulation. Computer hardware has made great progress in RAM technology, front bus speed and the use of multi-processor architectures, and to take advantage of these while avoiding the complexity and cost of multi-node computing, scientific computations can be parallelized at the motherboard level. The proposed approach will eventually lead to a simulation environment of the spacecraft dynamics that uses a multi-core multi-processor computer to simultaneously solve the aerodynamic, chemical and motion equations based on scheduling functions for parallel computing recently available as part of Matlab.

9. Liquid Rocket Engine Manifold Fluid Whistle Model

NASA's Project Constellation (next generation of launch vehicles for space exploration) is currently under development, and ensuring that the propulsion systems of these vehicles function properly is of critical importance. This project investigates the fluid-structure interaction within a manifold typical of those used in liquid rocket engine regenerative cooling jacket nozzles, such as will be employed on Constellation.

The basis of this study stems from a recent harmonic issue traced to fluid whistling on a current rocket engine's regenerative cooling manifold. A better understanding of the first principles involved in this phenomenon is necessary to mitigate the whistling from either occurring altogether or from occurring at a resonant frequency of any of the engine's components.

The proposed approach is to first evaluate the open literature associated with both manifold flow and vortex-induced harmonic oscillations. This is followed by derivation of the governing equations as applicable to the situation at hand, development of either a numerical simulation or laboratory scale test of a representative manifold to verify the development and shedding of vortices at the manifold/feedline hole interface. Finally, the study will conclude with an examination of mitigation approaches.

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