Research Expo 2016

HERRICK LABORATORIES
PURDUE UNIVERSITY™

CHPB-A

CHPB-B

Station B1 Speaker of the Group: Nelson James

Station B2 Speaker of the Group: Jaewan Joe

Station B3 Speaker of the Group: Sugi Ramaraj

Station B4 Speaker of the Group: Amir Sadeghi

Station B5 Speaker of the Group: Iason Konstantzos

ACOUSTICS, VIBRATIONS, CONTROLS & DYNAMICS - C

Demo- High Bay Area Presented by: Allison Murray, MSME Student and Whitney Novotny, Ph.D. Student
Nanothermite Deposited Using Piezoelectric Inkjet Printing

Station C3-High Bay Speaker of the Group: Daniel Woods

Station C4 - Semperlotti 's Lab-Original Herrick Bldg
Speaker of the Group: Christian Silva and Hongfei Zhu

Demo: Semperlotti's Lab Presented by: Hongfei Zhu, Ph.D. Student
Anomalous Refraction of Lamb Waves in Thin-Waves in Thin-Wall Structures with Geometrically Tapered Metasurfaces

Station C5 - Acoustic Labs-Original Herrick Bldg
Speaker of the Group: Yutong (Tony) Xue

Station C6 - Acoustic Labs-Original Herrick Bldg
Speaker of the Group: Rui Cao

Station C7 - Acoustic Labs-Original Herrick Bldg
Speaker of the Group: Yiming Wang

Station C8 - Acoustic Labs-Original Herrick Bldg
Speaker of the Group: Weonchan Sung

ACOUSTICS, VIBRATIONS, CONTROLS & DYNAMICS -D

Station D1 – Engine Test Cell Speaker of the Group: Alex Taylor

Laboratory Evaluation of Load Based Testing Approaches and its Effect on Variable Speed Direct Expansion HVAC&R Equipment Rating Standards

Research Assistants: David N. Halbrooks, Andrew L. Hjortland
Principal Investigators: Professors James E. Braun, W. Travis Horton
Sponsor: Northwest Energy Efficiency Aliance

Abstract

Existing HVAC&R rating methods have been incrementally updated throughout the years and abopted by various government bodies to provide industry standards to characterize overall system performance with respect to fixed-speed heating and cooling equipment. However, efficiency requirements continue to increase and the need for variable-speed equipment to modulate delivered system capacity continues to grow to meet those needs. That said, current rating methods that were designed for fixed-speed equipment are unable to capture dynamic system performance benefits that variable speed equipment has the potential to deliver. Fixed-speed and true variable-speed system direct comparisons with respect to performance, efficiency, and overall cost-benefits analyses are nearly impossible when applying fixed-speed rating standards such as CSA C656 and AHRI 210/240 due to the steady-state nature of the testing methodology used. To address the presented issues, a novel load-based testing methodology is presented and tested in a laboratory setting to dynamically vary the load conditions in which the HVAC&R system experiences. This will allow the development of a dynamic net-system performance metric to accurately show the benefits of variable speed HVAC&R equipment as compared to traditional fixed-speed equipment rated under current rating systems. Implications of this research can be used as a basis to enhance system understanding to improve and update current rating methodologies to allow equipment manufactures to better understand system performance, efficiency, and cost implications with respect to component selction, control, and delivered product effectiveness.

RTU Maintenance Optimization and Simulation Platform

Research Assistant: Andrew Hjortland
Principal Investigator: Professor James E. Braun

Abstract

Conditioned-based maintenance and service policies for direct expansion air conditioning equipment has the potential to reduce energy and operating costs in commercial buildings by scheduling service only when needed. In order to quantify these potential benefits, a simulation has been developed integrating an equipment fault impact model and a simple commercial building load model that can be used to estimate the life-cycle operating cost impacts of different faults. Using the simulation, maintenance schedules that minimize the sum of utility costs, equipment costs, and service can be determined using dynamic programming. These optimal solutions have been compared with annual service schedules typically used for commercial equipment. Because *a-priori* optimal schedules determined with dynamic programming are unrealistic for actual commercial buildings, an online scheduling algorithm has been developed that isolates the impacts of individual faults allowing for improved service decision when multiple faults are present.

Control Development and Laboratory Assessment of Next-Generation Heat Pump

Research Assistant: Andrew Hjortland
Principal Investigators: Professors W. Travis Horton and James E. Braun
Sponsor: Electric Power Research Institute (EPRI)

Abstract

In this project, a residential-style heat pump system that is compliant with the Level-2 Next-Generation Heat Pump requirements established by Electric Power Research Institute (EPRI) will be developed. In collaboration with United Technologies Carrier Residential Products, an existing, commercially available 2-ton heat pump system will be used with a heating efficiency of HSPF = 13.0 and a cooling efficiency of SEER ≥ 20.5, EER ≥ 16.0. The primary focus of this work is to develop and demonstrate control improvements, including a load-based auxiliary heat control scheme, ability to scale cooling capacity while maintaining humidity control and sensible heat ratio, automated demand response, and automated fault detection and diagnosis. A final goal is to develop a methodology using low-cost virtual sensors to detect frost formation to enable more efficient defrost operation. The improved controls will be developed for the residential system and laboratory evaluation and demonstration will be performed to benchmark the potential energy savings potential. This will include both heating and cooling mode tests while the system is subject to different fault conditions including low refrigerant charge levels, outdoor heat exchanger fouling, and indoor heat exchanger fouling.

Oil Management in Tandem Compressors of Transport Refrigeration Units

Research Assistant: Vatsal M. Shah
Principal Investigators: Professors Eckhard Groll, James Braun, and W. Travis Horton
Sponsor: United Technologies Carrier Corporation

Abstract

Oil plays an important role in compressors used in HVAC systems. Apart from the function of lubricating moving components of the compressor it acts as a sealant to reduce leakage losses from the chamber. It also helps to absorb some of the excess heat generated during the compression of the refrigerant. However, some of the oil is discharged from the compressor along with the refrigerant and as it travels through the various components of the refrigeration cycle and some oil may be retained in these components due to various factors. As a result of oil retention, the efficiency of heat exchangers (evaporators and condensers) decreases. In addition, the oil level in the compressor reduces, which may ultimately affect its efficiency and life span. Significantly higher oil throws from the compressor can occur during transients due to on/off cycling or significant changes in speed. In addition, oil return can be compromised at lower refrigerant flows associated with part-load operation. Due to these effects, the problems of oil throw and oil return are expected to escalate when using tandem compressors due to repeated cycling of compressors and a wider range of refrigerant flows. The primary objective of this project is to develop tools and test capabilities for studying tandem compressor oil management system designs. The tools should be flexible for a variety of HVAC&R products with validated results for future design work. Additionally, a suitable solution for oil management of tandem compressors in transport refrigeration systems should be designed and developed for system implementation. System testing will include performance and system vibration testing to ensure a proper, robust design. Proposed guidelines for future system oil management design will also be proposed. The initial objective is to develop an experimental set-up to study the amount of oil being discharged from tandem scroll compressors and returned from a system at different operating conditions that simulate driving conditions of long haul transportation vehicles carrying refrigeration units.

Automated Virtual Charge Sensor Tuning using Open Laboratory Testing

Research Assistant: Akash Patil, Andrew Hjortland, Orkan Kurtulus
Principal Investigators: Professors James E. Braun and W. Travis Horton
Sponsors: Johnson Controls

Abstract

Virtual sensors have previously been developed and demonstrated that can provide a low cost and relatively accurate estimation of the refrigerant charge contained in packaged (rooftop) air conditioners. One particular virtual refrigerant charge sensor approach uses four surface-mounted temperature measurements to determine suction superheat, liquid-line subcooling and evaporator inlet quality that are inputs to an empirical model for charge. The empirical parameters of the model are determined using linear regression applied to laboratory data collected from the system. In previous studies, extensive psychrometric chamber testing was required at different refrigerant charge levels and ambient conditions to obtain sufficient data for the regression. This testing is expensive for equipment manufacturers and it can be difficult to find available test facilities. The current work describes the development of an automated open lab training kit for calibrating a virtual refrigerant charge level sensor in an open laboratory space. The developed automated training kit algorithm has the ability to modulate the condenser and evaporator fans to simulate the effects of different ambient conditions and automatically add different amounts of refrigerant. The charge level is automatically adjusted and monitored using solenoid valves and a digital weighing scale. This approach reduces the human involvement to a great extent and eliminates the need for psychrometric chambers. An optimal set of test conditions has been determined using optimal experimental design techniques and implemented as a Python application. An Arduino microcontroller is used to continuously send data from the sensors to a personal computer which is used to supervise the process, including determining when the system has reached steady-state. The training kit has been applied to several different rooftop units in an open lab space. A comparison of the virtual refrigerant charge sensor accuracy and time/cost for calibration determined using the automated system and using psychrometric chamber test facilities has been presented.

Application of Interleaved Circuitry to Improve Evaporator Effectiveness in a Packaged AC System

Research Assistant: Ammar Bahman
Principal Investigator: Professor Eckhard Groll
Sponsors: Adams Communication & Engineering Technology (ACET)

Abstract

Highly constraint air flow pathways as experienced in tightly packaged air conditioning systems, such as Environmental Control Units (ECU) as used by the U.S. Military, result in air flow maldistribution problems in the evaporators. The interleaved circuitry method, where the refrigerant from a circuit with high air flow is routed to a circuit with low air flow and vice-versa, has been used to significantly reduce the effects of the air flow maldistribution. Relative little information is available in the literature with respect to air velocity profile measurements across the evaporator of ECU systems, which is a key input for a simulation model predicting the evaporator performance. In addition, the improvement of using interleaved circuitry has not been experimentally tested in an actual system. This research presents both the measured air velocity profile and system performance tests. Furthermore, the predicted evaporator performance is validated with experimental results. The air velocity measurements have been conducted in Psychrometric Chambers and the measurement locations have been defined by the log-Tchebycheff rule. The velocity profile was obtained by Lagrange Interpolation method as percentage values. The performance of the interleaved circuitry method was compared to the original circuitry for different testing conditions. The results show that the interleaved circuitry method uniforms the superheat of the individual circuits and that it improves the cooling capacity and system performance by up to 12%.

Development and Demonstration of an Automated Method of Test for Rooftop Unit Performance with Integrated Controls

Research Assistants: Akash Patil, Andrew Hjortland, Donghun Kim, and Jie Cai,
Principal Investigator: Professor James E. Braun
Sponsors: Consortium for Building Energy Innovation (CBEI)

Abstract

Existing equipment performance rating approaches are based on steady state tests and hence do not consider the interaction of controls with the equipment. In order to adequately assess the performance of alternative control approaches under realistic and reasonable conditions, a new testing methodology is being developed that is applicable for both variable and fixed-speed DX (Direct Expansion) equipment. The method will be applied in evaluating integrated equipment performance for a rooftop air conditioning unit (RTU) that is controlled in response to dynamically varying loads and ambient conditions. The equipment loads are simulated using a virtual building model that is appropriately sized for the equipment under test. Example results of the test methodology will be presented for an RTU having two stages of control. The overall testing methodology is automated so that performance can be fully evaluated using short-term tests (e.g., 1 day) ultimately leading to the ability to automatically obtain an equipment performance model that can be used in an energy simulation program.

Separate Sensible and Latent Cooling System

Research Assistant: Jie Ma

Principal Investigator: Professor W. Travis Horton

Abstract

Separate sensible and latent cooling (SSLC) systems offer an opportunity for substantial reductions in cooling energy required to maintain comfort conditions in commercial and residential buildings. The proposed project differs from other attempts to achieve separate sensible and latent cooling that typically rely on operating two systems in parallel, one for the sensible portion and a separate system for the latent portion of the heat load. This project will develop an SSLC system that handles the two loads sequentially rather than in parallel, which can be accomplished using a single vapor compression system with variable speed compressor and fan technology. Preliminary theoretical results at Purdue University indicate an energy savings potential of around 25%. And amount of experiments certified the system and energy model. Through further simulation, the energy saving potential for a real system is proposed. The focus of the project will be to develop and optimize the system and its controls, and ultimately to implement the system in a Living Laboratory environment to assess the comfort impacts on the space in a real world scenario. It is anticipated that the proposed SSLC system will easily achieve deep penetration in both the new and existing building markets due to its simplicity and cost effectiveness.

Performance Testing of a 'Level 1' Unitary Split-System Heat Pump

Principal Investigator: Eckhard A. Groll
Research Assistants: Forrest Son and Nick Salts
Sponsor: EPRI

Abstract

This research focuses on extensive performance tests of a highly efficient unitary split-system heat pump with variable speed drives. Variable speed drives increase system efficiency by reducing temperature fluctuations and offering low speed operating options. The performance tests were conducted following the AHRI Standards for testing heat pumps with variable speed compressors. In addition to the performance tests, the second stage auxiliary heat control algorithm and demand response operation is demonstrated as part of this project. The purposes of these additional tests are to determine if second-stage heat is prevented from engaging due to set-point change or user interaction, and to better understand demand response. The heat pump was also tested in single speed mode for a direct comparison of efficiency. Temperature and humidity controlled Psychrometric chambers were used to satisfy the standard Seasonal Energy Efficiency Ratio and Heating Seasonal Performance Factor rating operating conditions. These chambers were designed following ASHRAE standards. The results obtained in this study provide a verification of the improvement in efficiency provided by variable speed heat-pumps, and an increased understanding of variable speed heat-pump's second stage heating control, and demand response capabilities.

Hybrid Drive Control for Unitary Split-System Heat Pumps

Principal Investigator: Eckhard A. Groll
Research Assistant: Nicholas Salts
Research Sponsor: Regal Beloit Corp.

Abstract

Heat pumps utilizing variable-speed compressors and other capacity control techniques offer significant seasonal efficiency improvements over traditional single-speed systems by reducing system cycling and consequent system inefficiencies. Yet, the majority of residential heat pumps operated in the United States utilize single-speed compressors and offer few capacity control options. This situation presents an opportunity for existing single-speed units to be retrofitted with variable-speed technology. The main focus of this research is to optimize the seasonal cooling performance of a 5 ton residential split-system single-speed heat pump that has been modified with a hybrid drive. The hybrid drive is a product being developed for OEM equipment that consists of an inverter drive coupled with a controller that allows control of the compressor and fan motor speeds. The seasonal performance of the modified system can be optimized with respect to compressor speed, outdoor fan speed, and indoor airflow rate. The effectiveness of the hybrid drive is then determined by the increase in SEER rating of the modified heat pump. While research into the seasonal optimization is still ongoing, initial testing has achieved significant SEER improvements compared to the baseline heat pump.

Modeling Human Heat Transfer in Outdoor Environments

Research Assistant: Dayi Lai
Principal Investigator: Professor Qingyan (Yan) Chen

Abstract

Human heat transfer model is an essential tool in the studies of outdoor thermal comfort. Because meteorological conditions, human body clothing, posture, and activity change frequently in outdoors, when studying the heat transfer of a human body in outdoor environments, a dynamic approach is appropriate. This study developed a model that accounted thermal environment transients, as well as alternations in human body clothing, posture, and activity. This model considered the non-uniform outdoor thermal environment by calculating two-dimensional heat transfer in 12 segments of the human body. Direct solar radiation absorbed at different body parts was estimated according to the solar azimuth and altitude angle. The portions of received long wave radiation from sky and from solid surfaces were separated based on the Sky View Factor (SVF). Skin temperature measurements of subjects were conducted outdoors to validate the model. Results showed good agreements between measured and modeled mean skin temperature. Over 90% of the modeled mean skin temperature were within 1 K difference of the measured value and 75% within 0.5 K difference.

Development of a Fast Fluid Dynamics-Based Adjoint Method for the Inverse Design of Indoor Environments

Research Assistant: Wei Liu
Principal Investigator: Professor Qingyan (Yan) Chen
Sponsors: U.S. Dept. of Homeland Security, Science and Technology Directorate, Office of University Programs, under Grant Award 2013-ST-061-ED0001

Abstract

The CFD-based adjoint method may be appropriate for the inverse design of indoor environments, considering both accuracy and efficiency, but a single design of an indoor space still requires tens of hours with the use of a personal computer. To speed up the inverse design process, this study evaluated four FFD models in terms of solving the Navier-Stokes equations, integration with turbulence models, and solving the adjoint equations. This study developed the FFD solvers in OpenFOAM and validated them for predicting steady-state and transient flow in indoor environments. The effect of the time step size was also investigated. This study then validated the FFD solvers for solving the adjoint equations and the FFD-based adjoint method for inverse identification problems and inverse designs in indoor environments. The results showed that FFD was 20 times faster than CFD in predicting transient indoor airflow, and similar computational accuracy could be maintained; the FFD-based adjoint method was 4-16 times faster than the CFD-based adjoint method in the inverse design process.

Investigating the Impact of Gaspers on Cabin Air Quality in Commercial Airliners with a Hybrid Turbulence Model

Research Assistants: Ruoyu You, Jun Chen, Chao-Hsin Lin, Daniel Wei
Principal Investigator: Qingyan (Yan) Chen
Sponsor: Boeing Company

Abstract

It is not clear whether turning on the gaspers in the cabins of commercial airliners actually improves the air quality. To answer this question, this study first developed a hybrid turbulence model which was suitable for predicting the air distribution in an aircraft cabin with gaspers turned on. Next, the investigation validated the model using two sets of experimental data from a cabin mockup and an actual airplane. This study then used the validated model to systematically investigate the impact of gaspers on cabin air quality in a seven-row section of the fully-occupied, economy-class cabin of Boeing 767 and 737 airplanes. The CFD calculations formed a database consisting of 9660 data points that provide information about SARS infection risk. It was found that the distribution of opened gaspers can influence the infection risk for passengers. Even though the gasper supplies clean air, it is possible for it to have a negative impact on the passengers' health. Statistically speaking, the overall effect of turning on the gaspers on the mean infection risk for the general population was neutral.

A Mathematical Framework for Increasing Trust in Human Machine Interactions

Research Assistant: Kumar Akash
Principal Investigator: Professor Neera Jain
Sponsor: National Science Foundation, Grant #1548616

Abstract

The objective of the proposed research is to mathematically characterize the dynamic relationship between machine user interfaces (UIs) and human trust in autonomous systems. With increasing automation in all aspects of society, humans are increasingly being displaced as the primary decision-maker in roles such as aircraft pilots and plant operators. However, humans still have the ability to override automated decisions, and a significant problem arises when humans override an automated decision due to a fundamental lack of trust in the machine. Two specific aims guide this research. The first aim is to conduct a dynamical characterization of real-time measurements of trust. Such measurements do not currently exist and are necessary in order to allow machines to sense the trust level of the humans that they are interacting with. We have identified a static classifier-based model of trust that relies on real-time psychophysiological measurements including galvanic skin response (GSR) and electroencephalography (EEG). Furthermore, we have established a dynamic human trust model based on data collected from a human subject study with 581 participants. The second aim is to define a mathematical framework for modelling human trust response to machines. Machines communicate with humans through various design features in their user interface (UI). We propose to conduct a human subject study to mathematically characterize how specific machine UI features can be used by a machine to dynamically change human trust in the machine. Through the proposed research, we will enable the design of a closed-loop trust management system that achieves the overarching goal of improving the relationship between human and machine, thereby leading to more reliable and efficient operation of a range of automated systems.

Advanced Caster Roll Gap Control

Research Assistant: Rian Browne
Principal Investigator: Professor Neera Jain

Abstract

We consider the problem of dynamic coupling between the rapid thermal solidification and mechanical compression of steel in twin-roll strip casting. In traditional steel casting, molten steel is first solidified into thick slabs and then compressed via a series of rollers to create thin sheets of steel. In twin-roll casting, these two processes are combined, making the system nine times more energy efficient. Combining the processes, however, makes control of the overall system significantly more challenging. Therefore, a simple and accurate model that characterizes these coupled dynamics is needed for model-based control of the system. We model the solidification process with explicit consideration for the mushy (semi-solid) region of steel by using a lumped parameter moving boundary approach. The moving boundaries are also used to estimate the size and composition of the region of steel that must be compressed to maintain a uniform strip thickness. A stiffening spring model is then used to estimate the forces needed to maintain a uniform strip thickness. These two models will assist in designing a control methodology that maintains consistent strip characteristics across the length of the strip. The development of a control methodology for highly-coupled and high frequency thermal and mechanical dynamics will not only improve the quality of the steel produced by the twin roll casting process but will also translate to other materials processing and manufacturing applications.

Right Fidelity Dynamic Engine Modeling and Validation

Research Assistant: Yeshaswi Menghmalani
Principal Investigator: Professor Neera Jain
Sponsor: Cummins Inc.

Abstract

A fundamental challenge with any modeling effort is characterizing the "right" amount of model fidelity needed for a particular engineering task. Across the spectrum of modeling approaches, ranging from purely physics-based to purely data-based, there are variations in computational complexity, development time, and accuracy, just to name a few. Moreover, if integrating multiple models, consideration of integration across diverse modeling platforms and software packages must be considered. The intent of this project is to develop and validate a low-order dynamic engine modeling platform that balances the tradeoff between model complexity and model fidelity. A key aspect of this project is to quantify the desired fidelity for the engine model in a power generation application. This requires identifying the best modeling approach along with desired fidelity in each of the sub-components of an engine. Modeling of the engine using this approach will be followed by identifying quantitative metrics to verify whether or not the desired fidelity is achieved.

Dynamic Modeling, Control, and Optimization of micro-CHP Systems

Research Assistant: Austin Nash

Principal Investigator: Professor Neera Jain

Abstract

In U.S. industrial processes alone, it has been estimated that 20-50% of energy input is ultimately lost as waste heat. Furthermore, 61% of energy across all sectors was wasted in 2015. Until methods of capturing and utilizing waste heat are further developed, an increase in the amount of energy needed to meet demands is unavoidable. Most efforts to recover waste heat are aimed at large-scale applications such as cogeneration plants or industrial processes. In such instances, dynamics are slow enough that simple control policies are amenable to governing system operation. Conversely, in smaller-scale applications such as domestic homes or small businesses, the dynamics are much faster with transients playing a more critical role. Furthermore, in small-scale waste heat recovery applications, there is often a delay between when the waste heat is recovered and when it needs to be utilized. As such, there exists a critical need to 1) decouple waste heat recovery from utilization via thermal energy storage (TES) systems and 2) actively control transient thermal processes to maximize performance and efficiency.

One approach to addressing these needs is through combined plant and control design, or co-design. The merits of co-design are rooted in the fact that there are fundamental limitations in what can be achieved with feedback control for a given plant design. Through co-design, a controls engineer can simultaneously optimize both the control policy governing the operation of a TES system and plant design variables of the overall waste heat recovery system. This research aims at using co-design to (1) model and control transient TES systems in order to optimally charge and discharge a system with respect to second-law efficiency and (2) to develop a toolset by which a TES system can be integrated with a waste-heat recovery application to realize the full potential of closed-loop performance.

In this work, we are tackling these objectives in the context of a micro-CHP system. We develop a control-oriented dynamic model of a TES system in the form of a domestic hot water storage tank with an immersed heat coil. Additionally, we derive a set of transient second-law based performance metrics for online evaluation of system performance. The metrics will guide future research aimed at simultaneously designing optimal control algorithms and optimizing the plant design of the micro-CHP unit itself.

Characterizing Real-Time Bioaerosol Dynamics in Buildings Using Laser-Induced Fluorescence (LIF)

Research Assistant: Tianren Wu
Principle Investigator: Professor Brandon Boor

Abstract

Bioaerosols are important for the health and comfort of occupants in the indoor environment. The sources of bioaerosols include the transport of outdoor bioaerosols into the indoor environment via ventilation pathways, shedding from human skin, hair, and clothes, and resuspension from flooring and carpet. Traditional measurement techniques of bioaerosols based on cultivation are time-consuming and labor-intensive, and they lack of real-time information. Laser-induced fluorescence (LIF) techniques based on the autofluorescence of bioaerosols allow us to investigate the dynamic features of the fluorescent biological aerosol particles (FBAPs) in real-time, further better understanding its relationship to transient human activities and ventilation conditions taking placing in buildings. Two LIF techniques were utilized to characterize the size distribution and concentration of FBAPs in a resuspension chamber study and a field measurement campaign. A BioScout (Environics Oy) was employed to monitor the crawling-induced and walking-induced resuspension of total particles and FBAPs from carpeted flooring at infant and adult breathing zone heights in an 81.4 m^3 chamber operated at a ventilation rate of 0.66 h^{-1} and supplied with HEPA-filtered air. The BioScout uses a 405 nm excitation source and measures an emission band > 442 nm. A robotic infant simulated the crawling of infant on the carpet and an adult wearing a full clean suit outfit with booties walked on the carpet in the walking experiment. The carpets were collected from local homes in Helsinki, Finland. The field measurements were conducted in the Purple Room at the Ben and Maxine Miller Child Development Laboratory School at Purdue University. Infants in the Purple Room are 6 weeks to 2 years in age and are supervised by two teachers and a child care aid. The room is mechanically ventilated and the flooring materials consist of carpet and hard tile, which are cleaned daily. The Wideband Integrated Bioaerosol Sensor (WIBS-NEO, Droplet Measurement Technology Inc.) sampled at infant breathing zone height with copper tubing in an air-cooled, foam-lined plastic box designed to muffle the noise of the pump and maintain security of the infants. The WIBS-NEO uses dual excitation sources at 280 nm and 370 nm and measures emission bands from 310-400 nm and 420-650 nm. Total particle and FBAP size distributions were monitored continuously during occupied and unoccupied periods for two weeks. The mean number concentration of FBAPs per event, such as free play, group time, lunch, clean-up, and quiet/nap time, was obtained to better understand the dynamic nature of infant bioaerosol

exposures in childcare facilities. The transient behavior of FBAPs in the infant breathing zone was related to the spatial proximity of infants and teachers to the WIBS, as monitored via an observation room. The results of these two studies indicate that the activities of occupants have a significant impact on the bioaerosol concentration in buildings, and that LIF techniques allow us to investigate the relationship between the dynamic features of bioaerosols and transient activities of infants and adults in the indoor environment.

Concentrations and Size Distributions of Sub-3 nm Particles in Indoor Environments

Research Assistant: Wenxin Wang
Principal Investigator: Professor Brandon E. Boor

Abstract

Airborne particles and molecular clusters smaller than 3 nm are widely spread in the atmosphere and may represent a significant fraction of total particle number concentrations. However, they have been seldom measured outdoors, and have yet to be measured in buildings. Sub-3 nm particles form during nucleation processes associated with the rapid cooling of diesel exhaust in ambient air, ozonolysis of terpenes (e.g. limonene and α-pinene), indoor combustion, and emissions of semi-volatile organic compounds during heated processes (e.g. 3D printing). Sub-3 nm particles can grow through condensation and coagulation and can deposit to surfaces via Brownian diffusion. Nearly all aerosol instruments used for airborne nanoparticle measurements have poor particle detection efficiency and/or size resolving capability in the sub-3 nm range. This is due in part to limitations of the particular working fluid used, low particle charging efficiencies, and design features of differential mobility analyzers (DMAs). A recently developed instrument for atmospheric new particle formation studies, the particle size magnifier (PSM), is able to activate and size particles down to approximately 1 nm. The PSM activates particles in diethylene glycol (DEG) vapor and grows them to ~90 nm, after which they are further grown in a condensation particle counter (CPC) and counted optically. DEG is used as a working fluid due to its high surface tension and low enough saturation vapor pressure such that high supersaturations can be achieved without considerable homogeneous nucleation that can bias CPC counts. Recent outdoor field measurement campaigns have employed the PSM to better understand new particle formation events in both pristine environments and polluted megacities, such as Shanghai and Nanjing, China. By measuring sub-3 nm particles, such studies can accurately determine particle nucleation and growth rates. The objective of this investigation is to use the PSM to study particle nucleation processes in the indoor environment, as well as to assess the contribution of sub-3 nm particles to total particle number concentrations indoors. Preliminary data collected in a flower shop will be presented, as well as future plans for an intensive measurement campaign in an occupied residential building.

Biological Particle Adhesion to Indoor Surfaces: A Literature Review

Visiting Researcher: Jin Pan, Tsinghua University
Principal Investigator: Professor Brandon E. Boor

Abstract

Airborne particles of biological origin represent very diverse groups, including bacterial cells and bacterial spores, fungal spores, yeast cells, pollen grains, fragments, and other biological particles. Resuspension of settled dust due to human activities is a major source of biological particles indoors, and clarifying the adhesion of particles to indoor surfaces and other particles is a prerequisite for a comprehensive understanding of resuspension. This study reviews the current knowledge discussing adhesion between biological particles and surfaces. The adhesion force is primarily composed of Van der Waals forces, capillary forces, and electrostatic forces. For different types of biological particles, the three forces play a different role in the adhesion process, which can be described by certain simplified models to make approximate calculations. An overview of experimental measurements of adhesion of biological particles via atomic force microscopy (AFM) is presented, along with a detailed comparison between modeled and experimental results from the literature. The review concludes with an outline of further research that is needed to bridge the knowledge gap on adhesion of biological particles to indoor surfaces.

Nandi Clean Kitchen Study: Mitigating Indoor Air Pollution in Western Kenya

Research Assistant: Danielle Wagner
Principal Investigator: Brandon E. Boor
Sponsor: Purdue Seed Grant #12D

Abstract

It is estimated that about half of the people in the world perform their daily routines without electricity, and thus burn biomass for heating homes and cooking. Biomass combustion releases respirable toxins, including particulate matter ($PM_{2.5}$, soot nanoparticles), CO, and $CO_{2.}$ Women and children, who spend the most time around the cookstoves, are especially prone to developing respiratory diseases resulting from inhalation exposure to these toxins. Previous cookstove interventions across the world have had varying rates of success, but generally do not yield successful indoor air pollution mitigation; cleaner, more efficient cookstoves are not always adapted, and behavioral studies are often not thorough. In response to receiving a large number of patients with respiratory problems, AMPATH Kenya, a healthcare organization rooted Eldoret, Kenya, has begun encouraging groups of women to remodel their kitchens in an effort to reduce their pollutant exposure. This study focuses on the indoor air quality aspect of health in Nandi County in western Kenya, and is motivated by AMAPTH's overall goal to improve the health of Nandi community members. Emission measurements in renovated and non-renovated kitchens will be taken over several months to determine if remodeled, clean kitchens improved the indoor air quality. Fine particle levels will be measured with a portable, battery-powered Pegasor soot sensor, and CO and $PM_{2.5}$ will be measured with solar-powered low-cost air quality sensors (AlphaSense CO and OPC-N2). The outlook of the study also includes educational ideal kitchen demonstrations, and assessing their impacts with further air quality measurements.

Transcritical Carbon Dioxide Cycle Component Test Stand

Principle Investigator: Eckhard A. Groll
Research Assistant: Riley Barta
Sponsors: Regal Beloit and Air Squared

Abstract

In light of recent trends towards energy efficiency and environmental consciousness, the heating, ventilation, air conditioning and refrigeration (HVAC&R) industry has been pushing for technological developments to meet both of these needs. Additionally, the implementation of refrigerants naturally occurring in the biosphere with reduced Global Warming Potential (GWP) has become increasingly important since HFC refrigerants are linked to climate change. As such, solutions to increase overall cycle efficiency while utilizing natural refrigerants have been proposed to help meet these goals, and these solutions need to be experimentally validated before they can be viable for commercialization.

This research focuses on the natural refrigerant Carbon Dioxide (CO_2) due to its GWP being 1, its significant potential for energy recovery during the expansion process, and growing interest in CO_2 being used as a replacement for traditional refrigerants. The goal is to investigate the potential performance of two components in a transcritical CO_2 cycle.

The first component is an energy recovery expansion device, known as the Viper Expander. The Viper Expander was developed by Regal Beloit Corporation and operates by using a nozzle to accelerate the high pressure CO_2 into a high velocity jet of fluid impinging on a micro-turbine impeller. The impeller is coupled with a generator which harvests the kinetic energy of the CO_2 by converting it into electrical energy that can be fed back into one of the system components, such as a fan or compressor motor.

The second component is a scroll compressor developed by Air Squared, Inc. The compressor is being tested in the hot gas bypass stand to utilize the stand's unique capabilities of controlling the suction pressure, discharge pressure, and suction superheat of the compressor independently. This allows for conducting compressor performance tests at rated operating conditions. Both of these components will be installed in the same test stand, highlighting the stands versatility and ability to test multiple components with only adjustment of valves being necessary to switch configurations.

Future work will focus on maximizing the performance of these components and also validating models used to predict their performance.

Performance Measurements of a R-407C Vapor Injection Scroll Compressor

Research Assistant: Domenique R. Lumpkin
Principal Investigator: Eckhard A. Groll

Abstract

Environmental conditions significantly define the performance of HVAC&R systems. Vapor compression systems in hot climates tend to operate at higher pressure ratios, leading to increased discharge temperatures. Higher discharge temperatures can lead to higher irreversibilities in the compression process, lower specific enthalpies differences across the evaporator, and possibly a reduction in the compressor life due to the breakdown of the oil used for lubrication. To counter these effects, the use of an economized, single-port vapor injection compressors is proposed for vapor compression systems in high temperature climates. Such compressors are commercially available for refrigeration applications, in particular, for supermarket refrigeration systems. However, compressor maps for vapor injection compressors are limited and none exist for R-407C. Through calorimeter testing, a compressor map for a single-port vapor injection compressor using R-407C was developed. The effect of the operating conditions on the vapor injection state, compressor efficiencies and compressor heat loss were also analyzed. A standard correlation for mapping single-port vapor injection compressor is proposed. The system and compressor performance with and without vapor injection was considered. As expected, with vapor injection there was a reduction in compressor discharge temperatures and an increase in the system coefficient of performance.

Modeling of an Oil-Free Carbon Dioxide Compressor Using Sanderson-RockerArm Motion (S-RAM) Mechanism

Research Assistants: Bin Yang, Orkan Kurtulus
Principal Investigator: Eckhard A. Groll
Sponsor: S-RAM Dynamics

Abstract

A comprehensive simulation model to predict the performance of a prototype CO_2 compressor is presented. This prototype compressor employs the Sanderson-Rocker Arm Motion (S-RAM) mechanism, which converts the rotary motion of the shaft into a linear reciprocating motion of the pistons. Additionally, this drive mechanism can vary the piston stroke while keeping the constant dead space volume above the piston top by changing the incline angle between the connecting rod and compressor main shaft centerline. The compressor model is mainly composed of three main sub-models simulating the kinematics and dynamics of the drive mechanism and the compression process. A discharge line gas pulsation sub-model is coupled with the compression process model. The frictional power loss sub-model is built together with the dynamics model of the drive mechanism. The predicted results of the comprehensive model are validated using external compressor performance measurements including the mass flow rate and input power. Future work will be focused on the parametric studies investigating the effects of structural parameters including the stroke-to-bore ratio on the compressor performance.

Organic Rankine Cycle as Bottoming Cycle for Waste Energy Recovery from an Internal Combustion Engine

Research Assistant: Alejandro Lavernia
Principal Investigator: Eckhard A. Groll
Sponsor: Air Squared (ARPA-E SBIR)

Abstract

The objective of this project is to create an efficient electricity generation system that can provide the energy necessary for light residential use at high thermal efficiency and low user cost. In order to achieve the goal of 40% thermal efficiency for a small-scale energy/heat production unit, an Organic Rankine Cycle (ORC) has been implemented as a bottoming cycle in order to recover heat from the exhaust of a small internal combustion engine. The ORC has been optimized for the working conditions of the bottoming cycle by working fluid evaluation and selection along with cycle design and the design of a novel two-stage scroll expander. By utilizing the relatively novel working fluid R1233zd(E), the ORC can operate at higher temperatures, of roughly 300 ^{o}C, which are necessary for use with the integrated catalytic converter evaporator proposed for the system. Operating at roughly 15% thermal efficiency, the ORC feeds the mechanical energy recovered by the scroll expander into the generator to help the system achieve the goal of 1 kW electrical production at 40% overall thermal efficiency. .

Updraft Tower Dry Cooling and Waste Heat Utilization for Power Plants

Research Assistant: Haotian Liu
Principal Investigators: Professors Eckhard A. Groll, Justin A. Weibel, Suresh V. Garimella
Research Sponsor: Duke Energy

Abstract

A study is proposed to investigate an updraft tower, which has the potential to eliminate water use during heat rejection in a power plant. The study includes development of engineering models for the updraft tower system. An updraft tower (Figure 1) involves a heat exchanger distributed around an entrance at the base. The tower is coupled with a secondary loop that is used to transfer the heat from the power plant condenser to the base. Air is drawn through the updraft heat exchanger due to the air density difference between the base of the tower and the top. This eliminates the need for a mechanical fan found in conventional dry-cooling applications. The tower includes a recuperative turbine to generate power by harnessing the energy available in the waste heat stream, which in turn can drive the secondary cooling cycle and increase overall efficiency. The system is evaluated by the power plant water use (if any), thermal efficiency, and potential economic benefits. A detailed simulation model of the power plant, secondary loop and updraft tower system has been developed using the Engineering Equation Solver (EES) software. Parametric studies involving changes in geometric and environmental parameters as well as the operating conditions will be conducted to optimize the system performance.

Affordable Rankine Cycle: Expander Modeling and Dynamic Control Strategies

Research Assistants: Davide Ziviani and Donghun Kim

Principal Investigators: Eckhard A. Groll and James E. Braun

Sponsor: Eaton Corporation

Abstract

To improve energy efficiency and fuel economy of heavy-duty trucks, waste heat recovery (WHR) by means of an Organic Rankine Cycle (ORC) is proposed as a valuable solution. This project includes two main tasks: 1) design, analysis and optimization of different expander technologies, and 2) development of an integrated system model and control algorithm for the ORC-engine coupling. A comprehensive deterministic (physics-based) expander model has been developed to accurately predict its performance as well as to serve as a tool for the geometry optimization. The main expander types considered are roots and screw. The model will be validated using external expander performance measurements, which will be obtained using an available ORC expander load stand at the Ray W. Herrick Laboratories as well as Roots expander performance measurements provided by Eaton. The validated model will be used to supplement CFD-based analysis and, in particular, to provide an effective platform to conduct sensitivity studies to assess impacts of various design and operating variables on expander performance. In addition, a dynamic simulation model for the entire ORC system will be developed to evaluate its transient performance over a drive cycle and under various heat load conditions. The system model will be validated using data obtained through a testing program initiated by Eaton and other partners in this program. Ultimately, the model will be used to develop and assess a model-based control strategy to track power demand for the ORC system and to optimize the performance of the integrated WHR-ICE system. This project also includes demonstration of the control algorithm on test rigs.

Characterization and Performance Testing of Natural Gas Compressors for Residential and Commercial Applications

Research Assistants: Xinye Zhang, Bin Yang, Orkan Kurtulus
Principal Investigators: Eckhard A. Groll
Sponsors: BlackPak Inc.

Abstract

This project focuses on characterization and performance testing of natural gas compressors for residential and commercial applications. The aim of the project is to evaluate the efficiency, performance, and safety characteristics. A three-step sequence of testing will be conducted as part of the project. Initially, the compressors will be tested while dynamically charging a tank with air as the working fluid. In the second step, steady-state tests will be conducted using the hot-gas compressor load stand with carbon dioxide (CO_2) as an appropriate substitute for pipeline natural gas. In the third step, the performance and safety characteristics will be reported during the dynamic charging of a tank using pipeline natural gas as the working fluid. The first and third step compressor performance testing of the proposed project will be conducted during the dynamic charging of a tank. The new test stand will be set up for these compressor performance tests. 300 dynamically charging tests were conducted to simulate the compressor working condition for one year and try to find the critical condition when it breaks. For the second step, a new hot-gas compressor load stand will be designed, built, and commissioned. This test stand will then be used to conduct the compressor performance tests. During the tests, the following compressor measurements will be recorded: compressor mass flow rate, suction and discharge temperatures, suction and discharge pressures, and compressor power consumption. The theoretical performance of the compressor will be evaluated experimentally during this phase of the project. Also, a simulation model to predict the compressor dynamic performance will be developed. In this model, the initial clearance factor for the compressor will be calculated based on available compressor maps and used as the input for the dynamic model. The entire process will be simulated to provide the compressor performance data, as the function of time. Finally, the predicted performance will be validated using the test data.

Development of a General Purpose Simulation Tool for Positive Displacement Compressors

Research Assistants: Davide Ziviani and Xinye Zhang
Principal Investigators: Eckhard A. Groll and James E. Braun
Sponsor: Center for High Performance Buildings (CHPB)

Abstract

The principal investigators (PIs) have been working on the modeling and testing of positive displacement compressors for more than twenty years. Detailed and comprehensive simulation models of hermetic, semi-hermetic and open-drive positive displacement compressors, including scroll, reciprocating, spool, Bowie, Z-compressor, S-RAM among others, have been developed throughout the years and validated against experimental compressor measurements. These models were also used to perform parametric studies where the influences of compressor geometry, leakage gaps, heat transfer coefficients and frictional coefficients on performance were investigated. The objective of the project is to develop a comprehensive compressor simulation platform based on the previous compressor modeling efforts to predict the performance of hermetic positive displacement compressors. The platform will include all the main aspects of compressors such as the geometry (a library of multiple positive displacement compressor geometries will be programmed), the thermodynamic governing equations, i.e., energy and mass balances for the compression process, internal leakage paths, suction and discharge valve dynamics, internal heat transfer, friction and mechanical losses as well as electric motor losses. The generic model platform will be validated using external compressor performance measurements, which are readily available from the previous testing efforts with various compressors and refrigerants using a hot gas-bypass compressor load stand.The comprehensive simulation program developed herein will be available open-source through the CHPB for future use by member’s engineers for design optimizations.

Chemical Looping for High Efficiency Heat Pumping

Research Assistant: Nelson James
Principal Investigators: Professors James E. Braun, Eckhard A. Groll
Research Sponsor: Center for High Performance Buildings

Abstract

A significant amount of energy is used to maintain thermal comfort in buildings via heating and cooling. As demand for heat pumping systems increases, alternative technologies may be needed in order to greatly improve system efficiency. A chemical looping cycle is being investigated for its application as an efficient heat pumping system. Driven by an electrochemical cell, initial thermodynamic modeling has shown that the system can potentially improve on standard vapor compression technology. Multiple possible working fluids have been identified with an isopropanol-acetone being one of the most promising. A test stand has been constructed to evaluate the performance of an electrochemical cell working in the presence of isopropanol and acetone. The test stand was designed to measure flow rates and temperatures entering the cell, the voltage and current consumption required to drive reactions, as well as the extent to which the reaction goes to completion. Preliminary data collected from the setup has shown that it is possible to drive the isopropanol-acetone reaction at the low voltages required for efficient CLHP operation. Future work will be done on examining more membrane types and cell architectures to improve the efficiency of the desired reactions.

A Multi-Agent Control Approach for Optimization of Central Cooling Systems

Research Assistant: Rita C. Jaramillo, Ph.D. Student
Principal Investigators: Dr. James E. Braun and Dr. W. Travis Horton
Sponsor: National Science Foundation under Grant No. 1329875.

ABSTRACT

This research focuses on supervisory control of large central cooling systems. A large central cooling plant consists of several chillers, cooling towers and pumps that supply chilled water to satisfy the cooling requirements of one or more buildings. Optimal supervisory control of such systems involves the determination of the mode of operation and set points that minimize the cost of operation while satisfying cooling and comfort requirements. The optimization problem is complicated because of the presence of both discrete and continuous control variables. Most of the research related to supervisory control of central cooling systems has focused on centralized control approaches. Although these studies have demonstrated the effectiveness of optimal control in reducing operational costs, the results have not been widely implemented. Some of the issues that might prevent a greater penetration of these technologies in the market are the need to have detailed information on the performance profiles of the cooling plant equipment in order to build a model for the optimization process, and the high initial costs associated with site-specific controller design and implementation. Further, once implemented, the plant model and control sequences will need to be updated by experts every time a modification is made to the plant. A promising approach that addresses some of these limitations is distributed multi-agent-based optimal control. The use of intelligent agents makes it possible to solve the optimization problem in a distributed manner by breaking a big complex problem into smaller, more manageable pieces that can be solved independently and in parallel by individual agents. The individual solutions can then be handled by a coordination agent that achieves some consensus. Since intelligent agents can solve individual problems to optimize performance without having total knowledge of the system, they would also add adaptive capability to the control system.

This work consists of the application of a multi-agent control approach for supervisory control of large central cooling systems. The starting point for this work was a multi-agent control simulation framework developed by Cai (2015). To adapt the framework to this problem, agents representing the performance of the different devices of the plant were developed and an optimization method capable of handling non-convex functions and discontinuous design spaces was developed and incorporated in the framework. A case study of an existing cooling plant (The Northwest Chiller Plant at Purdue Campus) was utilized to evaluate the approach in terms of optimality and computational resources. Simulations were carried out for different performance conditions to predict the performance of the plant under three different control strategies: 1) multi-agent control, 2) centralized optimization based on mathematical programming techniques and 3) a heuristic control strategy. The results showed that significant savings can be achieved through the implementation of multi-agent control. It is expected that, if each hardware component of the plant comes with an integrated agent that represents its behavior, then the proposed multi-agent framework could automatically generate the multi-agent structure and control algorithm after some relatively simple pre-configuration steps. This will reduce the site-specific engineering and will provide a more economic and easy to configure solution for central cooling systems.

Agent-based Model Predictive Control for Comfort Delivery in Open-Plan Offices

Research Assistant: Jaewan Joe
Principal Investigator: Professor Panagiota Karava
Sponsors: National Science Foundation, Grant #1329875

Abstract

Advanced supervisory control strategies, such as Model Predictive Control (MPC) have shown good performance for building applications. However, this sophisticated control method requires heavy computations when the system is large and complex while in some cases the solution becomes easily intractable. Also, selecting and implementing an MPC algorithm for each building application requires high engineering cost due to the custom design of buildings. Plug-and play concepts that improve computational efficiency and scalability can be realized with agent-based methods, that is, a special class of distributed approaches. At the same time, this process would become more efficient and smart building features would be widely adopted if intelligence is embedded into physical devices. However, defining and designing the role of each agent and facilitating their communication to obtain a global optimal solution is challenging, and remains an unsolved issue. Towards this goal, this study presents a general agent-based MPC framework, that is demonstrated using a radiant comfort delivery system as a case study. In the estimation part of the framework, estimate parameters of each agent are found individually with information locally known from sensors as well as information communicated from adjacent agents; the latter includes a measured temperature trajectory acting as a fixed boundary temperature for each agent. Then, building models are assembled based on different integration methods. In the distributed MPC part, the optimal control problems in each agent are solved locally in parallel with quadratic programming while exchanging the control input and temperature trajectories. The objective function consists of three terms; price of the HVAC energy consumption, stop criteria, and peak load reduction term. Based on this methodology, case studies are conducted for a single zone with a radiant floor and air system for comfort delivery, and multiple zones with a radiant floor system. A distributed MPC algorithm is simulated assuming an occupancy schedule and an air-cooled chiller as a source. The distributed MPC shows equivalent performance compared to centralized MPC, and also outperforms the baseline case which is a conventional feedback control.

Site Performance of a Model Predictive Control for Coordinating Multiple Rooftop Units

Principal Investigators: Professors Jim Braun and Donghun Kim
Sponsors: CHPB and U.S. Department of Energy

Abstract

Small and medium sized commercial buildings, such as retail stores, restaurants and factories, often utilize multiple roof top units (RTUs) to provide cooling and heating for open spaces. A conventional control approach for these buildings relies on local feedback control, where each unit is cycled on and off using its own thermostat. Because a thermostat operates regardless of overall building's behavior, the conventional control approach could result in unnecessary energy use and high electrical peak demand via poor coordination among the units. Previously, a model based control algorithm (MPC) coordinating an open space building served by multiple RTUs was developed. The control solution is not site-specific and provides reduced energy consumption and peak demand with low sensor requirements. In this project, we provide recent results of long-term performance of the RTU Coordinator at field sites for small/medium commercial buildings.

Sustainable Community Development

Research Assistant: Li Cheng

Principal Investigator: Professor Travis Horton

Sponsor: Center for High Performance Buildings

Abstract:

This focus of this research is on developing and demonstrating an integrated systems-level approach to the design and construction of cost effective and energy efficient housing communities in Indiana. At the same time, we are creating a sustainable community development process, which can be applied throughout this country in different climate zones and locations. We are working with the Indiana Housing and Community Development Authority (IHCDA) and two major property development companies on this project.

The first stage is to develop a "baseline" energy model for representative buildings based on available prototypical buildings as well as actual geometry information provided by the developers. The 1st baseline model is of an urban in-fill community located in Bloomington, IN, and the 2nd baseline model is of a green-field community located in Fort Wayne, IN. The energy models are developed consistent with ASHRAE standard 90.1. The Energy Use Intensity (EUI) results of the baseline simulations have been compared with target values provided by the developers and found to be acceptable. In addition, the energy end uses are consistent with data from the Residential Energy Consumption Survey (RECS).

In the second stage of this project, various alternative technologies are chosen to create different building design packages. These packages upgrade the baseline models into different building design scenarios. With complete models of these scenarios, annual energy performance and building construction cost are analyzed to give rise to design suggestions for the development of sustainable communities in Indiana.

In the following stages, baseline models will be modified and simulated according to building design requirements in different climate zones around United States. A similar process will be replicated and result in applicable design strategies in different locations. Finally, this systems-level approach of designing sustainable communities along with a database of different building scenarios will be conducted in this research

National Benefit Assessment of Variable-Speed Retrofits for Packaged Rooftop Units (RTUs)

Research Assistant: Jie Cai, Post Doc
Principal Investigator: Professor James E. Braun
Sponsor: Ray W. Herrick Laboratories, Purdue University, USA

Abstract

Packaged rooftop units (RTUs) are widely used in small commercial buildings in the U.S. and over 90% of these unit's employ fixed-speed fans for air supply to the indoor space. The electrical energy usage associated with constant volumetric air delivery fan systems is on the order of half the total RTU electrical energy usage because the fan-motor efficiencies tend to be low and they operate continuously during the occupied period in commercial buildings. In addition, compressors within RTUs typically feature single- or two-stage capacity controls leading to frequent unit cycling and thus, deteriorated performance in energy efficiency. In this study, two types of variable-speed retrofits will be considered: 1) variable-speed retrofits of the air delivery (indoor) fans for existing RTUs and 2) retrofits of RTUs with new RTUs that incorporate variable-speed compressors and fans (indoor and outdoor). The energy and economic benefits of these technology improvements will be evaluated in comparison to single- and two-stage baseline systems for a range small commercial building types and locations across the U.S. using a simulation study. In addition to HVAC energy and cost savings, effects on indoor comfort delivery in terms of relative humidity regulation will be considered. The generated results could provide guidance to equipment manufacturers, policy makers, and building managers regarding the most significant and economically feasible situations for application of this technology.

Econometric Modeling and Optimal Operation of a Combined Cooling, Heating and Power Plant System

Research Assistant: Sugirdhalakshmi Ramaraj
Principal Investigators: Professors Jim Braun and Travis Horton
Collaborated with: Wade Power Plant, Purdue University

ABSTRACT

Combined Cooling, Heat and Power (CCHP), also known as trigeneration, has great potential to minimize primary energy consumption in distributed energy generation systems due to its ability to recover low- grade thermal energy resulting in higher energy efficiencies, reduced emission rates and lower operating costs. Trigeneration also offers a higher level of energy security and control by removing the reliance on centralized power grids. The Wade power plant at Purdue University produces chilled water, steam and electricity using CCHP (Combined Cooling, Heating and Power) systems to meet the campus cooling, heating and electricity demands. Steam generated from utility boilers is not only used to meet campus heating demand but also used for power generation, chilled water production and in-plant auxiliary usage. Chilled water is generated using both steam driven chillers and electric chillers and is used to meet the time-varying cooling demand. The electricity generated using two steam turbine driven generators provide 30-50% of the campus electricity requirements while the remainder of the electricity is purchased from the local electric utility at a real-time pricing. Plant primary energy use and costs can be significantly reduced through an optimal operation strategy that responds to time varying factors such as costs of fuel and electricity, environmental conditions, building loads, component design, operational limitations, availability of resources and site operational changes. Optimal control should minimize costs while ensuring that the systems meet campus electricity, heating, and cooling demands. This work presents an approach for optimizing the operation of the CCHP system using a multimodal genetic algorithm based on hourly load forecasts and fuel pricing with a joint characteristic for the energy components to minimize the total operating cost of the plant. The tool is used to evaluate the benefits of optimal control for the Purdue CCHP plant as a function of different (possibly future) utility rate incentives.

A Bayesian Modeling Approach for Learning Occupant Thermal Preferences in Office Buildings

Research Assistant: Seungjae Lee
Principal Investigator: Professor Thanos Tzempelikos
Sponsor: CHPB, National Science Foundation, Grant #1539527

Abstract

Typical thermal control systems automated based on the use of "widely acceptable" thermal comfort metrics cannot achieve high levels of occupant satisfaction and productivity since individual occupants prefer different thermal conditions. The objective of this study is to develop environmental control systems that provide personalized indoor environments by learning their occupants and being self- tuned. Towards this goal, we develop a new methodology, based on Bayesian formalism, to learn and predict individual occupant's thermal preference without developing different models for each occupant. We develop a generalized thermal preference model in which our key assumption, "Different people prefer different thermal conditions" is explicitly encoded. The concept of clustering people based on a hidden variable which represents each individual's thermal preference characteristic is introduced. Also, we exploit equations in the Predicted Mean Vote (PMV) model as physical knowledge in order to facilitate modeling combined effects of various factors on thermal preference. Parameters in the equations are re-estimated based on the field data. With the generalized thermal preference model, individual occupants' thermal preference profiles were inferred to validate our method. The results show that the method is more effective in terms of learning individual occupants compared to developing different models for each occupant.

A Bayesian Modeling Approach of Human Interactions with Shading and Electric Lighting Systems in Private Offices

Research Assistant: Seyed Amir Sadeghi
Principal Investigator: Professors Panagiota Karava and Professor Thanos Tzempelikos
Sponsor: Lutron, National Science Foundation, Grant #1539527

Abstract

Human-building interactions provide information on the energy impact of different control behaviors and are also used to infer occupant preferences and individual differences in experiencing thermal and visual environments; they reveal stimulus-response relationships for the integration of humans in sensing, control, and simulation frameworks. In this study, we present a hierarchical Bayesian approach to model human interactions with motorized roller shades and dimmable electric lights. At the top level of hierarchy, Bayesian multivariate binary-choice logit models predict the probability of shade raising/lowering actions as well as the actions to increase the level of electric light. At the bottom level, Bayesian regression models with built-in physical constraints estimate the magnitude of actions, and hence the corresponding operating states of shading and electric lighting systems. The models are based on a dataset from a field study conducted in private offices designed to facilitate a large number of participants and to collect data on environmental parameters as well as individual characteristics and human attributes governing human-shading and –electric lighting interactions. Our study demonstrates the advantages of the Bayesian approach that captures the epistemic uncertainty in model parameters, which is important when dealing with small-sized datasets, an ubiquitous issue in human data collection in actual buildings; it also enables the incorporation of prior beliefs about the systems; and offers a systematic way to select amongst different models using the Bayes factor and the evidence calculated for each model. The findings reveal that besides environmental variables, human attributes are significant predictors of human interactions, and improve the predictive performance when incorporated as features in shading action models.

Real-Time Characterization of Nanoparticle Exposures by Welders: Impact of Base Metal and Weld-Type

Research Assistants: Kelsey M. Hall, Alexander J. Hughes, Mahmoud Nour, Spencer Thomas, Eric J. Ward
Principal Investigators: Professors Brandon E. Boor and Ellen M. Wells

Abstract

There is a growing body of evidence in the literature that suggest welders and adjacent workers are exposed to high levels of welding fume particles and experience neurological health effects. The chemistry and particle size distribution of the welding fume are important in predicting the toxicity and hazards associated with exposure. The goal of this study is to (1) examine the particle number size distribution and elemental characterization of the fumes of three common welding types (MIG, TIG, and Stick); (2) investigate the particle number size distribution and elemental characterization of welding fume for four different steel types (Steel, High Strength Steel, Stainless Steel, Galvanized Steel); (3) investigate how the particle number size distribution changes with distance from the welding arc (outside vs. inside welding helmet), including both the welder's breathing zone (near-field) and far-field (three foot distance) to represent second-hand exposure of other workers. A high resolution electrical low pressure impactor (HR-ELPI+, Dekati Ltd.) was used to monitor particle size distributions from 6 nm to 10 μm over two phases in a local welding facility. Phase I: Real-time sampling (1 Hz, greased foil substrates) of the total particle size distribution to capture the dynamic nature of exposures during the welding process; and Phase II: Elemental characterization of the particle size distribution (time-integrated, greased polycarbonate substrates) via off-line analysis of collected particles with inductively coupled plasma mass spectrometry (ICP-MS). Preliminary data suggests that particle number size distributions during welding were different at the three positions from the welding arc. The total particle number concentrations measured in the breathing zone of a welder inside and outside the welding helmet (near-field) were very similar but greater than those measured at three feet distance from the welding arc (far-field). Total particle number concentrations for the active welding arc period ranged from approximately 1 to 20 million #/cm^3. Data collection and analysis for this project is presently ongoing.

Daylight Glare Evaluation with the Sun in the Field of View Through Window Shades

Research Assistant: Iason Konstantzos
Principal Investigator: Professor Thanos Tzempelikos

Abstract

This study provides new insights on daylight glare evaluation for cases with the sun in the field of view through window shades. 41 human subjects ($n = 41$) were tested while performing specific office activities, with 14 shade products of different openness factors and visible transmittance values (direct and total light transmission characteristics) installed on the windows. The measured variables and survey results were used to: (i) associate discomfort glare with measured and modeled parameters (ii) evaluate the robustness of existing glare indices for these cases (iii) examine alternate illuminance-based criteria for glare assessment through fabrics, extract discomfort thresholds and suggest a new related index and (iv) propose corrections in the DGP equation coefficients when the sun is visible through the shades. The modified DGP equation resulted in the best fit; the findings show that the general form of the DGP equation is reasonable and can be adjusted to account for different cases, by clustering different sets of coefficients for different environmental conditions or fenestration systems. The new alternate glare discomfort index developed in this study, based on direct and total-to-direct vertical illuminance on the eye, captures the impact of sunlight as well as the interdependence between the fabric color, overall brightness, and the apparent intensity of the visible sun. It can simplify annual simulations, eliminating the need for detailed luminance mapping of the interior, and can be directly associated with fabric optical properties for development of design guidelines and glare-based shading controls.

Personalized Shading Control Strategy to Maximize Occupant Satisfaction while Minimizing Lighting Energy Use by Multi-Objective Optimization

Research Assistants: Jie Xiong and Seungjae Lee
Principal Investigators: Professors Panagiota Karava and Thanos Tzempelikos
Sponsor: Lutron Electronics Co Inc. and National Science Foundation, Grant #1539527

Abstract

In this study, a personalized shading control framework is developed to maximize occupant satisfaction while minimizing lighting energy use using a multi-objective optimization scheme. A personalized satisfaction model was developed based on specially-designed experiments in private offices, to quantify the occupant satisfaction level with motorized roller shades by predicting the override probability of occupants considering different variables. Then, a multi-objective optimization algorithm was constructed, considering the shading override probability and predicted lighting energy use as objectives, where the occupants are the decision makers in the final balancing between their personalized comfort limits and energy use considerations. The developed method serves as a prototype study on adaptive shading controls with learned personalized comfort profiles and parallel energy use considerations.

Integrated Design Tool of Building System Optimization for Building Life Cycle Cost

Research Assistant: Yeonjin Bae
Principal Investigator: Professor W. Travis Horton

Abstract

The optimization of energy efficient buildings is a highly complex problem, which requires a long computational process due to the many options that exist at the time a building is being designed. Although this is the time when critical decisions can be made that have the largest impact on building life-cycle cost (LCC), such large-scale optimization problems are often prohibitive within the building industry because of the excessive computational time. Therefore, this research aims to develop an accurate and efficient integrated design tool for performing building life cycle cost optimization. The developed methodology includes follow objectives. 1.) Develop a detailed building life cycle cost analysis. To predict energy consumption accurately, detailed modeling is done with energy simulation software. To evaluate construction cost, realistic data is taken from actual construction and equipment cost database. 2.) Using the variable selection process, significant variables that demonstrate the most significant contribution in the optimization study are identified. By identifying these variables, the design space is reduced significantly. 3.) To overcome the long computational time required to generate sufficient data that can be used during the variable selection process, a simplified energy consumption model is developed to replace the full annual energy simulation. 4.) With an appropriately reduced number of input design variables the optimization methodology is applied to building life cycle cost using energy simulation software and available cost data. With optimized result of the significant variables, the design space is explored near the optimum to identify the best value of the insignificant variables to get closer to the true optimum. The developed methodology has been applied to residential building types. The case study results show that the developed methodology effectively and accurately finds the optimum point compared to the full optimization process with all design variables.

An Emulation Framework for Optimal Solar Energy Utilization in Building Operation Under Weather Uncertainty

Research Assistant: Xiaoqi Liu
Principal Investigator: Professor Panagiota Karava
Sponsor: ASHRAE

Abstract

This study presents an emulation framework that incorporates a novel stochastic solar forecast model for the optimization of solar energy utilization in building operation under weather uncertainty. An open plan office space is used as test-bed, in which the energy system includes a building-integrated photovoltaic-thermal (BIPV/T) system connected to an air-to-water heat pump, thermal energy storage (TES) and radiant floor heating (RFH). The emulator built in TRNSYS incorporates a predictive control module developed in MATLAB as one of its components through TRNSYS Type 155, thus the building system is emulated together with the predictive controller. The control model receives weather forecast information, and returns to the building the control decision on the minimized heating power, considering the prediction uncertainty through a solar forecast model with hidden autoregressive factors. The solar forecast model takes only sky cover forecast as input and the samples generated are capable of approximating the true irradiance values. The results show that the stochastic controller with weather uncertainty achieves energy savings that are close to those obtained with the deterministic control strategy, assuming perfectly known weather conditions, and maintains a comfortable thermal environment.

HVAC Solutions for Existing Small- and Medium-sized Commercial Buildings Retrofit Opportunities

Research Assistants: Bonggil Jeon, Janghyun Kim, Yeon Jin Bae
Principal Investigator: Professor W. Travis Horton
Sponsor: DOE – Consortium for Building Energy Innovation (CBEI)

Abstract

According to the Commercial Building Energy Consumption Survey 2003 (CBECS 2003) conducted by the U.S. Energy Information Administration, over 70% of existing commercial buildings across the United States are more than twenty years old, with many of these buildings soon in need of renovation. Also, the CBECS 2003 shows that existing small- and medium-sized commercial buildings (smaller than 200,000 square feet) consume about 75% of the energy used in commercial buildings, which means there is a great potential for energy savings with integrated technologies and building retrofit solutions, such as HVAC and envelope integration, and window and lighting integration. The primary focus of this study is to compare the annual performance of different types of HVAC equipment in existing small- and medium-sized commercial buildings, and to identify appropriate HVAC systems that could be effectively retrofit into different commercial building types. Prototypical building types and characteristics for baseline models are proposed based upon the CBECS 2003 microdata and annual energy simulation results from the EnergyPlus are being utilized to analyze the different HVAC retrofit technology options.

Recovery of Waste Thermal Energy in U.S. Residential Appliances

Research Assistant: Stephen L. Caskey
Principal Investigator: Professor Eckhard A. Groll
Sponsor: Sustainability Group, Whirlpool Corporation, Eric J. Bowler

Abstract

With the United States being the world's second largest consumer of primary energy, research into areas of significant consumption can provide large impacts in terms of the global energy consumption. Buildings account for 41% of US total energy consumption with the residential sector making up a majority. Household appliances account for the second largest site energy consumption at 27%, after the HVAC system for the U.S. residential sector. By quantifying the expected energy available in the waste stream for five major appliances; household refrigerator, clothes dryer and washer, dishwasher, and cooking oven, a potential energy source is presented. A cold water cooling stream is applied to the waste stream of each appliance and an estimated amount of energy can be recovered. The household refrigerator is modeled having an increase in cooling capacity of about 12% and a reduction on compressor power consumption of about 26%. A sample operation of the clothes dryer has the exhaust air stream being cooled down to 30.5°C (86.9°F) or on the other side, is able to heat 19 liters (5 gal) of water up to about 54.5°C (130.1°F). Large volumes of water are available by the clothes washer, but due to typical operation characteristics, low wash and rinse temperatures, the waste stream was not high in temperature. While the dishwasher provided higher heat source temperatures, 40°C (104°F), than the clothes washer, 36°C (97°F), the opposite was true. The volume of waste water drained is very low compared to the clothes washer 11.7 liter (3.1 gal) to 155 liters (41 gal). Thus water temperatures in the storage tank did not reach above 30°C (86°F) even with low storage volumes. The cooking oven can generate very high water temperatures depending how small of a storage tank is connected. Further work in this area is recommended due to the potential of high water temperatures generated from residential waste energy streams not currently being captured, and thus can offset some site-energy usage.

Evaluation of Passive Chilled Beam System Based on Experiment, Modeling and its Application to Building Simulation with Energy Efficiency and Thermal Comfort Assessment

Research Assistant: Janghyun Kim
Principal Investigators: Professors James E. Braun & Thanos Tzempelikos

Abstract

Existing modeling approaches for passive chilled beams are not adequate for assessing overall energy usage and occupant comfort within building simulation programs. In addition, design guidelines for passive chilled beam systems are needed for identifying appropriate applications and optimal configurations. This work will develop improved passive chilled beam testing approaches and semi-empirical modeling that will allow performance measurements from tests on a single chilled beam in a laboratory setting to be used in modeling multiple chilled beams in a building application within a building simulation tool. The research includes characterizing the performance of passive chilled beams by experimental investigations and development of models, and integration of these models into building simulation models for overall assessments of passive chilled beam systems. The integrated simulation tool will be used to perform comprehensive comparisons of passive chilled beam and conventional systems in order to provide guidelines for appropriate applications. A single passive chilled beam is being tested under controlled conditions to acquire measurements that can be further used to develop a semi-empirical model. Comprehensive measurement parameters are considered to capture both convection and radiation cooling capabilities of the passive chilled beam. The performance of passive chilled beams is relatively more affected by the indoor conditions compared to conventional cooling systems due to the naturally convective cooling nature. For this reason, field measurements from a real occupied office space installed with multiple passive chilled beams are also taken to verify the validity of using the model developed from laboratory tests on a single passive chilled beam in a system simulation for spaces with multiple chilled beams. The most cost-effective and precise method of estimating the annual performance of radiant heating and cooling systems (including passive chilled beam system) in terms of energy efficiency and thermal comfort is to use a dynamic building simulation tool due to the mix of convective and radiative heat transfer characteristics. Thus, an integrated building simulation model is chosen and is being developed in this study to assess and optimize the passive chilled beam at a system level and to compare it with conventional cooling systems. The computationally efficient semi-empirical passive chilled beam model that will be developed based on experiments will be implemented in the integrated building simulation model. This integrated building simulation model will be used to evaluate overall energy usage of chilled beam systems compared to conventional cooling systems and other passive ceiling cooling

systems under different simulated weather conditions. Optimizing design and operation of the passive chilled beam system will also be performed with this integrated model in terms of sizing, control and installation layout, which will help for the penetration into the market.

A Computationally Efficient Modeling Approach for a Finned-Tube Evaporator for Design and Evaluation of Defrost Controls

Principal Investigators: Professors Jim Braun and Donghun Kim
Research Assistant: Sugirdhalakshmi Ramaraj
Sponsor: Department of Energy through the Consortium for Building Energy Innovation

Abstract

Growth of a frost layer on an evaporator surface due to low evaporator temperature as well as moisture contained in surrounding air deteriorates performance of a refrigeration system significantly and requires significant energy for defrost. Many studies have been performed to model the heat and mass transfer phenomena in an attempt to have insight and accurate prediction. However, many models form nonlinear algebraic differential equations and thereby it is computationally demanding to include them into a typical building energy simulation environment for a cooler or freezer consisting of an enclosure, refrigeration equipment, defrost elements, and controls. Computationally efficient but reasonably accurate models are needed in order to evaluate overall system performance. The objective of this project is to develop a modeling approach to overcome the problem. A numerical solution strategy based on an enthalpy-based reformulation and linearization method will be presented. Results of the simplified model are compared with measurements and results from a more detailed reference model.

A Single-Bit Binary Estimator for Use in Control Systems Featuring Serial Communication Channels

Research Assistant: Josiah Thomas
Principal Investigator: Professor George T.C. Chiu
Sponsor: Purdue Research Foundation

Abstract

This presentation deals with digital control systems where serial communication channels are used to transmit data from the plant to the controller. Recently, a group of researchers explored the tradeoff between quantization error and transmission delay in such systems. They sought to find the optimum number of bits to use in the quantizer, since more bits reduce the quantization error, but take longer to transmit. The conclusion of their work was that one bit is the optimum number to use, implying that it is better to act on less precise information as fast as possible, rather than wait longer for higher precision. Other researchers have also shown interest in one-bit quantizers, practically implemented as delta-sigma modulators, from the standpoint of simplicity, hardware minimization, and cost reduction. These results have inspired the current researchers to analyze the same system, but from a slightly different perspective. We study the situation where multiple bits are used in the quantizer, but the information is acted on one bit at a time. The rationale behind this is that each bit contains information about the value represented. Thus, while the information about the value is incomplete mid-transmission, some information is received with each bit. An algorithm is proposed that estimates the value mid-transmission, and updates this estimate as each bit is received. Also, some initial analysis is done to determine whether such a method merits further pursuit. Our method is compared to the standard sample and hold method, and also a model-based method of intersample estimation that updates at the same rate. Simulations are then conducted to determine in what scenarios the new method would be most useful. It is found that there is significant benefit when the maximum frequency content of the transmitted signal is fast relative to the transmission rate of the channel. However, the benefit deteriorates if the channel rate allows the signal to be sampled much faster than the Nyquist rate. Conclusions and directions for future research are also presented.

A Real-Time Machine Vision Inspection System for Gravure Coating of Cellulose Nanocrystal Thin Films

Research Assistants: W. Chen, R. Chowdhury
Principal Investigators: Professor G. Chiu, Professor J. Youngblood
Sponsor: National Science Foundation

Abstract

Gravure coating is a widely used technique, which is able to fast processing material ink to large areas of thin films. Cellulose nanocrystal is an attractive material for its environmental friendly and multifunctional properties. Gravure coating combined with roll-to-roll processing is a promising method to transfer cellulose nanocrystal from small-scale research in laboratory to large-scale industrial production. However, undesired surface patterns related to process parameters and defects, such as dust and gel, could happen during processing. Therefore, a surface pattern and defect inspection system is needed to ensure quality of thin film production. In this research, a real-time machine vision inspection system for gravure coating is demonstrated. Near real-time pattern and defect detection is achieved with semi-supervised classification algorithms. A laboratory roller setup is built to demonstrate the feasibility of the proposed machine vision inspection system and evaluate its detection and classification performance.

Aero-Structural Optimization of Distributed Piezoelectric Actuation in Smart Morphing Wing

Research Assistant:	Ashwin Clement Henry
Principal Investigators:	Professor Andres F. Arrieta, Purdue University and Dr. Giulio Molinari, Laboratory of Composite Materials and Adaptive Structures, ETH Zurich, Switzerland

Abstracts

Morphing structures for aerospace applications have attracted great attention in the past decades, resulting in a significant body of literature. Despite many published examples very few morphing designs introduce compliance to, and exploit the structural efficiency of, lightweight aeronautical structures. Furthermore, the consideration of distributed actuators capable of contributing to load-carrying function of the structures, thereby providing multi-functionality, remains rare. In particular, concurrent optimization of the load-carrying and actuation characteristics of distributed actuators for 3-D compliance based morphing wings still requires further studies to assess their promise for allowing mass reduction and higher performance.

This research investigates the optimal geometrical parameters for maximizing deflection of distributed piezoelectric actuators on a compliant based morphing wing subject to aero-elastic loads. A previous design obtained following a multi-disciplinary optimization, for which the aero- structural response has been numerically simulated and experimental, yielding the ideal structural parameters maximizing roll controllability is utilized as a baseline individual. The global design, however, did not consider in detail the local thickness of underlying skin. This investigation therefore focuses on exploring the design space by conducting a parameter search of the ideal thickness ratio between the piezoelectric actuators and the morphing skin, with the objective of maximizing deflection while minimizing mass, subjected to aerodynamic loads. This is achieved by implementing concurrent aero-structural loop in which the load redistributeion effects with change in geometrical parameters are evaluated until convergence is reached. The algorithm progresses until the optimal geometrical distribution for the piezoelectric distributed actuators producing maximum deflection, while fulfilling the load-carrying constraints, are reached. The preliminary results show that the baseline design was significantly close to obtaining maximum deflection as only an increase of 4.9% was found in our parameter search. Therefore, pointing out that further gains can be obtained by including positioning of the distributed actuators in the optimization.

Extreme Wave Propagation in Nonlinear Metamaterials with Bi-stable Unit Cell

Research Assistant: Myungwon Hwang
Principal Investigator: Professor Andres Arrieta

Abstract

Metamaterials are artificially engineered materials that have unique properties that are not readily found in conventional materials. For the last decades, the behaviors of mechanical metamaterials in the linear regime have been widely studied and relatively well understood. However, introducing nonlinearity into the system can lead to achieve even richer dynamics. One example is extreme anisotropy in dynamic stiffness, through which classes of solitary waves can be generated. A bi-stable element features a quartic strain energy potential so that it allows adopting two different stable configurations and achieving negative effective stiffness. It is possible to tailor the element to have asymmetry in its potential so that one state has a higher potential than the other does. Cascading such asymmetric bi-stable elements to form a lattice can lead to a mechanical diode concept, allowing energy propagation only in a desired direction. This concept can find interesting applications in wave guiding, protective materials and energy harvesting, as experimentally illustrated in the current investigation.

Optimal Excitation Strategy for Escape from a Potential Well in Duffing-like Oscillators

Research Assistant: Janav Parag Udani
Principal Investigator: Dr. Andres F. Arrieta

Abstract

Compliant structures have received significant attention owing to the unique functionalities and performance advantages they offer over conventional, mechanism-based systems for load-carrying applications in aeronautical engineering and robotics. To fully exploit the potential advantages of compliant systems, structures capable of showing large shape adaptability with reduced energy requirements need to be developed. An interesting class of compliant systems showing such often conflicting features are multi-stable structures due to their ability to exhibit two or more statically stable shapes, with energy only required to switch between stable configurations via a snap- through. Furthermore, the inherent tendency to settle into the available stable equilibria simplifies the control to access several configurations. This study focuses on establishing optimal actuation strategies for inducing escape and controlled settling to the desired configuration for the symmetric twin-well Duffing oscillator system exploiting its inherent non-linear dynamics. The transient and steady state response is analyzed by varying the forcing frequency and amplitude to find the optimal excitation leading to a snap-through between the stable states. State feedback techniques are implemented to control the response of the system after snap-through is triggered to achieve low amplitude oscillatory behavior about the desired stable state, thus avoiding cross-well oscillations. The proposed actuation scheme establishes analytically the optimal actuation frequency for inducing minimum amplitude escape, demonstrating that it differs from the linearized natural frequency associated with each stable state of the system. Furthermore, the utilization of the dynamic response allows for obtaining large displacements as a result of the snap- through from a stable state to another with a small strain, effectively using the structure as a mechanical amplifier which finds applications in energy harvesting, shape adaptable systems, soft robotics and micro-electro-mechanical systems.

Trace Energetic Vapor Detection via Nonlinear Resonant Sensors

Research Assistant: Nikhil Bajaj
Principal Investigators: Professors George T.-C. Chiu and Jeffrey F. Rhoads

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Abstract

The detection of energetic materials is a significant safety and security challenge. To date, the various methods of detecting energetic materials have been highly setting-dependent, and tend to rely on expensive equipment that is not portable or practical. In many instances, the systems in place to detect energetic material vapors are not sensitive enough to do so, largely stemming from the fact that many dangerous materials have low vapor pressures at ambient conditions. The present work has developed a low-cost, highly-sensitive sensor platform referred to as PIMS (Portable, Integrated, Microscale Sensors). These PIMS devices are comprised of electronics for sensing and driving a microscale resonator into a nonlinear response regime, to leverage sensitive bifurcations that can detect small changes in mass and indicate this with a large change in response amplitude. Nonlinear feedback (with adjustable gains) allows the system to take a low cost device with a highly-linear response and cause it to exhibit a response similar to that of a Duffing resonator. Improvements have been made to the devices to allow high frequency (MHz range) and improved sensitivity (limit of mass detection as low as the 100s of picogram range) in operation. The sensor has been tested with water vapor to confirm its functionality, and an experimental method has been developed for sensitivity characterization. Current work is focusing on exploring various detection chemistries for energetic materials and further improving sensitivity.

SecureMEMS: Microscale Nanothermite Deposition Processes

Research Assistant: Allison K. Murray, Whitney A. Novotny, Trevor J. Fleck, Raghav Ramachandran
Principal Investigators: Professors I. Emre Gunduz, Steven F. Son, George T.-C. Chiu and Jeffrey F. Rhoads
Sponsor: Department of Defense-Defense Threat Reduction Agency

Abstract

This work investigates the use of piezoelectric inkjet printing for the small-scale deposition of energetic material. It works towards the goal of seamless integration of energetic and electronic components. Three inkjet printer systems have been tested to explore their feasibility within the context of this effort. Aluminum Copper (II) Oxide samples of varying geometries have been successfully printed. A dual nozzle system that allows for ink mixing directly on non-porous substrates has also been investigated. Collectively, these results demonstrate the ability to effectively deposit energetic material utilizing inkjet printing technologies, which can allow for energetic integration with electronic components for various applications including anti-tamper protection and micropropulsion.

Secure MEMS: Utilizing Inkjet Printing to Integrate Metal Initiators and Energetic

Research Assistants: Whitney A. Novotny, Allison K. Murray, Trevor J. Fleck, Raghav Ramachandran

Principal Investigators: Professors I. Emre Gunduz, Steven F. Son, George T.-C. Chiu and Jeffrey F. Rhoads

Sponsors: Department of Defense, Defense Threat Reduction Agency

Abstract

This work demonstrates printed metallic bridge wires with the ability to ignite a nano-energetic material. The bridge wires were printed on a mesoporous printing media using a piezoelectric inkjet system and required no thermal curing. The effect of various excitation voltages, ranging from 7.5 V to 13.75 V, on bridge wire failure was investigated using bridge wires 1 mm in length. The bridge wires were able to ignite nano-aluminum and nano-bismuth (III) oxide mixed at stoichiometric values in dimethylformamide (DMF) using a resonant mixer. These results demonstrate the ability to print an effective bridge wire, without thermal curing, that can be integrated with selectively-deposited energetic materials to form an initiator.

Analysis of the Dynamics of Very Large Systems of Coupled Resonators

Research Assistant: Conor Pyles, Purdue University and Chaitanya Borra, University of Akron
Principal Investigator: Professor Jeffrey Rhoads, Purdue University and Professor Dane Quinn, University of Akron

Abstract

The study of systems incorporating nonlinear resonators has been an active area of research interest due to the wide range of dynamic effects that may be observed and utilized in practical application. This is particularly apparent in the field of resonant micro- and nanosystems, where improvements in manufacturing processes are allowing for the fabrication of highly-reliable small scale devices at production volumes. To date, a majority of this research has been focused on either single uncoupled resonators or relatively small systems of coupled resonators. In this project, a methodology is proposed to facilitate the analysis of systems including a very large number of resonators coupled through both reactive and dissipative effects. The primary feature of the proposed method is the reduction of the equations of motion for the individual resonators (modeled as canonical Duffing systems) to a single integro-differential equation by recasting the system into continuum form. The resulting equation may then be solved through conventional perturbation methods. The resulting dynamics of the continuum model are then explored, primarily focusing on the effects of different types of coupling on the response of the spectrum of resonators.

Detection of Traumatic Brain Injury Protein Biomarkers with Resonant Microsystems

Research Assistants: Michael J. Wadas, Nikhil Bajaj
Principal Investigators: Professor George T.-C. Chiu and Jeffrey F. Rhoads

Abstract

Microelectromechanical resonators have the potential to enable a sensitive and inexpensive detection method for biological proteins. The current focus of this research is on the detection of the S100b protein, a protein that is secreted in high concentrations in patients who have experienced traumatic brain injuries, such as concussions. Sensor functionalization via polymer/antibody coatings is explored as a method to allow for the adsorption of the S100b protein onto the surface of the resonator. Frequency domain analysis of the sensor reveals a shift in the resonant peak caused by an increase in mass presumably owing to adsorption of the S100b protein. Benchtop experiments using tuning fork style resonators have confirmed the presence of the S100b protein with a probability value of 0.06. The present work specifically focuses on improving the detection concentration threshold using improved functionalization techniques and higher sensitivity resonators.

Characterization and Identification of Low Frequency Dynamic Behavior of Surrogate Explosive Materials

Research Assistant: Jelena Paripovic
Principal Investigator: Professor Patricia Davies
Sponsor: Air Force Research Lab

Abstract

The mechanical response of energetic materials, especially those used in improvised explosive devices, is of great interest in the defense community. It is believed that by understanding the dynamic behavior of the energetic material a remote acoustic or electromagnetic excitation may be tuned to produce signatures that are indicative of the presence of explosives. The goal of this work is to observe and characterize the mechanical material behavior of the energetic materials by developing robust models of low frequency uniaxial behavior. This is achieved by conducting low frequency vibration tests on a mass-material systems at various levels of excitation, and then using a two-stage system identification methodology developed in this research to determine system model structure and to estimate system parameters from which energetic material parameters (stiffness, damping and viscoelastic properties) can be extracted. Focus is on mock energetic materials comprised of binder with varying solids loading levels and different geometries. Various linear, nonlinear and viscoelastic models with different order hereditary kernels and different forcing functions have been considered. It has been found that including high order viscoelastic kernels is critical when developing models that can predict the responses of mass-material systems at different excitation levels. The inclusion of a hysteretic damping term alongside a viscoelastic term improved the prediction of the response only in the region of the mass-material resonance. Future work includes exploring more complex hysteretic damping terms, higher order viscoelastic models, sample size effects, and automated model order selection within the system identification algorithm. One outcome of this work will be the development of a comprehensive material properties database for these types of mock energetic materials, including how these properties change as the materials age. The models developed and estimated material properties are already being shared with other researchers within the energetic materials group. The system identification approach that has been developed can also be applied to other viscoelastic materials such as foams and rubber-like materials using in many isolation applications.

The Influence of Thermal Boundary Conditions on the Thermomechanics of Particulate-Composite, Mock Explosive Samples under Near-Resonant Excitation

Research Assistant: Allison R. Range
Principal Investigator: Professor Jeffrey F. Rhoads

Abstract

The systematic exploration of the near-resonant thermomechanics of energetic and inert particulate composite materials is of pronounced interest in the defense community. This work seeks to further characterize the macroscale, thermal and mechanical response of these materials under various mechanical excitations for a range of ambient temperatures. As part of this work we are creating new mock energetic materials to complement the existing samples made in previous years. New samples are fabricated based on the PBXN-109 formulation, comprised of hydroxyl-terminated polybutadiene (HTPB) binder with varying solids loading (0%, 50%, and 85%) and additive content (0%, 15%, and 30%). The solids loading provides the ratio of solid crystals to binder, either sucrose (chosen to mock RDX) or spherical aluminum crystals to understand how metal content will affect the mechanical and thermal characteristics. Experiments were performed on rectangular plate samples (7 in x 10 in 0.5 in) comprised of ammonium chloride crystals (chosen to mock ammonium perchlorate) held within a HTPB binder. Samples were mechanically excited using an electrodynamic shaker, with the thermal and mechanical responses recorded using a thermal camera and laser Doppler vibrometer, respectively. These harmonic-base excitation tests were performed at 2g near the first resonant frequency of each respective plate for 60 minutes at both ambient and insulated boundary conditions. Resulting measurements exhibited increased heating for the insulated boundary condition in all of the trials as expected. Experiments performed at ambient conditions exhibited good correlation to similar experiments performed in previous years. As a point of comparison, heat generation simulations were conducted to provide an upper bound of temperature increase under perfectly insulated conditions.

Acoustic Wave Profiles for Enhanced Energy Transmission into Solid Materials

Research Assistant: Daniel C. Woods
Principal Investigator: Professor J. Stuart Bolton and Jeffrey F. Rhoads
Sponsor: Office of Naval Research (ONR)

Abstract

Energy transmission into solid media by acoustic or ultrasonic waves is of interest in a wide range of applications including, for instance, nondestructive testing and ultrasound imaging. However, the transmission is generally limited by the large impedance-differences between air and typical solids. The present work is focused on tuning the spatial pressure profiles of incident acoustic waves to maximize the transmission into representative solid materials, including both idealized (i.e., lossless) and dissipative solids. Inhomogeneous plane waves are considered and the degree of inhomogeneity is tuned, along with the incidence angle near the Rayleigh angle, to minimize the reflection coefficient and consequently maximize the energy transmission. Bounded waves, which must be used in practice, are also being investigated, and acquired results have revealed that a maximum in the predicted surface wave excitation efficiency can be achieved by varying the beamwidth and the rate of spatial amplitude decay of the incident wave profile.

Acoustics-Based Improvised Explosive Device (IED) Detection and Defeat

Research Assistant: Caleb Heitkamp, Trevor Kyle
Principal Investigators: Professors J. Stuart Bolton and Jeffrey F. Rhoads
Sponsors: Office of Naval Research (ONR)

Abstract

Energetic materials have been shown to be susceptible to weak, external insults, such as mechanical loads, which can induce an increase in the materials' temperature. Given the temperature-vapor pressure relationship for these materials, such excitations can enhance the detectability of hidden explosive threats, and in some cases provide a potential pathway for IED defeat. Based on promising, preliminary experimental results, it has been theorized that tailored acoustic waves could serve as a suitable source of *stand-off* excitation. This notion is guided by the fact that by selectively distributing sound sources in an array form, power levels and source phasing can be adjusted to create any desired acoustic pressure waveform at a given stand-off distance. The present effort is focused on (i) generating appropriately-tailored pressure waveforms using the aforementioned source arrays and (ii) characterizing the acoustic material properties of various energetic and mock energetic materials.

Autonomous Image Localization for Visual Inspection of Civil Infrastructure

Research Assistant: Jongseong (Brad) Choi
Principal Investigator: Professor Shirley Dyke
Sponsor: National Science Foundation

Abstract

Low-cost, high-performance vision sensors in conjunction with aerial sensing platforms are providing new possibilities for achieving autonomous visual inspection in civil engineering structures. A large volume of images focusing on a given structure can readily be collected for use in visual inspection, overcoming spatial and temporal limitations associated with human-based inspection. Although researchers have explored several algorithms and techniques for vision-based inspection in recent decades, a major challenge in past implementations lies in dealing with a high volume of the images while only a small fraction of them are useful for actual inspection. Because processing irrelevant images can generate a significant number of false-positives, automated visual inspection techniques should be used in coordination with methods to localize relevant regions on the images. When combined, automated visual inspection will be able to meet the objectives and quality of human visual inspection. To enable this technology, we develop and validate a novel automated image localization technique to extract regions of interest (ROIs) on each of the images before utilizing vision-based inspection techniques. ROIs are the portions of an image that contain the region of the structure that is targeted for visual interrogation, denoted the targeted region of interest (TRI). ROIs are computed based on the geometric relationship between the collected images and the TRIs. Analysis of such highly relevant and localized images would enable efficient and reliable visual inspection. We successfully demonstrate the capability of the technique to extract the ROIs using a full-scale highway sign structure in the case where weld connections serve as the TRIs.

A Benchmark Problem on Hybrid Simulation of a Multi-Degree-of-Freedom Structure

Research Assistants: Christian E. Silva, Daniel Gómez P.
Principal Investigator: Professor Shirley J. Dyke
Sponsor: SENESCYT and National Science Foundation

Abstract

Real-Time Hybrid Simulation (RTHS) is a novel experimental technique that allows researchers to conduct dynamic testing of specimens of considerable size in rather small labs, through the separation of the real specimen into two substructures: a physical (experimental) and a numerical (computational). Indeed, several investigators have ventured into this field, which has produced a huge deal of literature. However, most of this literature is heavily focused in just a couple of the many fields that constitute a RTHS scheme; whether advanced dynamics, vibrations, feedback control, signal processing, numerical methods or finite element analysis. However, little of this body of literature brings together all these fields into a single procedure to conduct a test from scratch. The objective of this work is to propose a comprehensive, versatile and flexible methodology to conduct RTHS, aimed for researchers with any level of understanding in the topic. Such a methodology is presented in a modular way, with four specific modules: namely design, control, test and validation. Each one of these modules will be interconnected with one another, but leaving the user room to choose which to use. The proposed tool will consist of codes, guides and validation data. To validate this methodology, a 3 story—2 bay structure will be used, a portion of which will be set up as the physical substructure (one story of the whole structure); and the rest, will be the numerical one. For the design module, the substructural equations of motion will be derived, and after choosing a partitioning ratio, stability will be assessed. For the second module, an $H\infty$ tracking controller will be implemented for use with the transfer system; moreover, time delay and noise implications will be compensated accordingly with use of appropriate control strategies. The third module will consist of a step-by-step guide on how to conduct the test with basic lab equipment; and finally, the fourth module will contain the necessary validation data (benchmark) to compare the test experiments in a root mean square error (RMSE) sense.

Automated Collection and Measurement for Construction Pay Items

Research Assistant: Chul Min Yeum
Principal Investigator: Professor Shirley Dyke
Sponsor: National Science Foundation

Abstract

Accurate and safe measurement of actual pay items placed is a critical step in the timely completion of a construction project. Prior to each payment to contractors and suppliers, it is necessary to carefully measure and document the amount of pay items placed on the site. Currently, this is an entirely manual process, with substantial risk for personnel as well as human errors. Thus, inefficiency and unnecessary expense are introduced. In this situation, methods should be established to remove personnel from the dangerous environment and yet achieve rapid measurement. In this study, we develop software that can generate a high-resolution orthophoto for measurement by blending and stitching images collected from the site. Images can be rapidly collected using low-cost with handheld and aerial cameras with the minimum effort. Thus, frequent measurements can be made with higher accuracy and at very low cost. Additionally, promoting the use of more accurate methods to save time while reducing the potential for human errors and inefficiencies, are needed.

Vision Based Vibration Measurement

Research Assistant: Ziyi Zhao
Principal Investigator: Professor Shirley J. Dyke
Sponsor: National Science Foundation

Abstract

Structure health monitoring is always a hard problem due to the restriction of environment and high costs. Thus a computer vision method is introduced which makes the process easier and cost lower. In the study, we developed an algorithm which can track the vibration of a model from a video which records the process. The video consists of pictures taken by a high speed camera. The vibration displacement of points in the model will be acquired and processed. The research is an interstudy between structure vibration and video tracking. Our recent study focuses in working out an algorithm which can real-time track the points and monitor the structure vibration.

Anomalous refraction of Lamb Waves in Thin-Wall Structures with Geometrically Tapered Metasurfaces

Research Assistant: Hongfei Zhu
Principal Investigator: Professor Fabio Semperlotti
Sponsor: Air Force Office of Scientific Research Grant YIP FA9550-15-1-0133

Abstract

The concept of Metasurfaces has recently opened new exciting directions to engineer the refraction properties in both optical and acoustic media. Designed based on arrays of sub-wavelength inhomogeneous scatters, these surfaces are able to mold incoming wavefronts in rather unconventional ways. We investigate the design of acoustic Metasurfaces to control elastic guided waves in thin-walled structural elements. These engineered structural discontinuities enable anomalous refraction of guided wave modes in full agreement with the generalized Snell's law. The Metasurfaces are made out of locally-resonant torus-like tapers enabling accurate control of the phase shift of the incoming wave, ultimately affecting the refraction properties. Results show that anomalous refraction can be achieved on transmitted antisymmetric modes (A_0) when using either symmetric (S_0) or antisymmetric (A_0) incident waves. Experimental results validate the design and show the robustness of the design methodology. The acoustic Metasurfaces concept opens the way to the design of structural elements and devices that offer an unprecedented level of control on the propagation of acoustic energy. These engineered structures can play a fundamental role in the design of passive vibration control systems for the next generation of high-performance structures.

Barrier Mass and Flow Resistance Optimization for Interior Noise Reduction

Research Assistant: Hyunjun Shin
Principal Investigator: Professor J. Stuart Bolton
Sponsor: Ford Motor Company

Abstract

In recent years, minimization of motor vehicle weight while maintaining good acoustic performance has been a subject of interest. In this research, both analytical and Finite Element Analysis approaches are introduced to study the weight minimization of a vehicle dash panel system. Automotive barriers systems, which are typically a combination of closed and open cell materials, yield both absorption and transmission performance, both of which serve to mitigate the noise level of the vehicle interior space. Therefore, balancing between absorption and transmission performance should be considered in the process of weight optimization. An acoustic model has been developed using a transfer matrix method to predict the sound pressure levels in an interior space. A parametric study was performed to identify the relationship between barrier mass and its flow resistance. It has been found that contours of constant interior noise reduction can guide the tradeoff between mass and flow resistance and suggest that mass can indeed be reduced while maintaining acoustic performance. Optimization of a barrier weight corresponding to certain value of flow resistance is done by using MATLAB optimization tool. Validation of an acoustic performance of a barrier with obtained flow resistance and its weight is in process using a commercial FEA software tool.

Spatial Localization of Combustion and Mechanical Noise Sources in a Diesel Engine

Research Assistant: Tongyang Shi
Principal Investigator: Professor J.S. Bolton
Sponsor: Cummins

Abstract

To-date, procedures that allow the transfer functions between cylinder combustion pressures in a diesel engine and radiated noise at 1 m microphone locations to be identified have been developed. Similar procedures have also been developed for estimating the transfer functions between nearfield transducers such as microphones and accelerometers and the 1 m microphone sound pressure levels. This capability, when combined with the mathematical procedure Singular Value Decomposition (SVD), allows the contributions of mechanical and combustion-related noise sources to be separated and individually quantified. The success of that procedure, of course, depends on the nearfield transducer having been placed in the immediate proximity of the source. It would therefore be useful to relax that restriction so that source locations could be identified with greater precision. To satisfy this objective, Nearfield Acoustical Holography (NAH) is being used in this project. NAH allows high resolution images of acoustic source locations to be generated. NAH based on the Equivalent Source Method (ESM) has considerable promise to improve the capability of NAH because of its mathematical and conceptual simplicity. Thus the objective of this project is the application of the ESM to diesel engine source identification. The outcome of this project is to be a stand-alone source identification tool that would offer much better spatial resolution than existing beamforming procedures by combining the transfer function and equivalent source methods. Measurements have been performed on operating engines at the Cummins Noise Lab to demonstrate the application of this procedure and to demonstrate its ability to locate the spatial origin of combustion noise or gear rattle noise. In the end, Purdue will deliver a source identification code that will expand the capabilities of the Cummins Noise Lab.

Transmission Loss of Automotive Door Seals

Research Assistant: Weimin Thor
Principal Investigator: Professor J.S. Bolton
Sponsors: Ford Motor Company

Abstract:

Due the increasing concern with the acoustic environment within an automotive vehicle, there is an interest in measuring the acoustic properties of automotive door seals. These systems play an important role in blocking external noise sources, such as aerodynamic noise and tire noise, from entering the passenger compartment. Thus, it is important to be able to conveniently measure their acoustic performance. Previous methods of measuring the ability of seals to block sound required the use of either a reverberation chambers or a wind tunnel with a special purpose chamber attached to it. That is, these methods required the use of large and expensive facilities. A simpler and more economical desktop procedure is thus needed to allow easy and fast acoustic measurement of automotive door seals. In the present work, a desktop, four-microphone, square cross-section standing wave tube was modified by the addition of a new sample holder to make it possible to measure the transmission loss of door seals under various states of compression. In this new procedure, the sample is clamped between a sliding piston and one wall of the standing wave tube: hence, the piston partially blocks the channel, thus impacting the measured transmission loss. Therefore, an initial set of measurements was performed to identify the correction factor required to adjust the measured transmission loss of the clamped seal to eliminate the contribution of the clamp itself. Once the accuracy of the correction procedure was verified, a number of typical door seals were then tested at various degrees of compression. The transmission losses of the seals were generally in excess of 30 dB, and the transmission loss was found to increase significantly as the seals were compressed. The latter point, in particular, indicates that careful design of the seal mounting arrangemenst in the vehicle is crucial to ensuring their optimal performance.

Transfer Matrix Models for Fibrous and Porous Treatments

Research Assistant: Yutong (Tony) Xue
Principal Investigator: Professor J. Stuart Bolton
Sponsor: 3M Company

Abstract

To create better driving and transportation environments, the design of quieter vehicles is pursued by automotive manufacturers all over the world. 3M Thinsulate Acoustic Insulation (TAI) products provide highly efficient acoustical performance particularly in the middle and high frequency ranges [1] for different parts of a vehicle such as engine, doors, wheel wells, instrument panel, the dash panel, etc. The TAI products mainly consist of fibrous materials. The joint study between Purdue and 3M on improving acoustical performance of fibrous, porous, or perforated materials has been carried out for more than twenty years. Previously, with certain input of material structure related parameters, an analytical model (BAL Model) based on the Transfer Matrix Method returned the acoustical properties of a material, such as sound absorption coefficient, for example, or the Transmission Loss (TL), and Noise Reduction Coefficient (NRC) of a specific sound attenuating layered structure. However, since the BAL Model was developed, there have been many fiber model improvements together with the development of perforated film models. Furthermore, 3M has introduced at least three new TAI products including a high-temperature TAI product launched in 2016. Therefore, for this study, an updated, documented, MATLAB-compatible, computational implementations of the best, state-of-the-art, models of fibrous layers and perforated films will be developed. Besides, tests of airflow resistivity, sound absorption, and transmission loss are carried out for validation. [2]

Experimental Investigation of Tire Noise

Research Assistant: Rui Cao
Principal Investigator: Professor J. Stuart Bolton
Sponsor: Ford Motor Company

Abstract

Tire noise is an important issue both in the vehicle interior and to the vehicle exterior, since it affects passenger comfort and pass-by noise levels, respectively. Such noise is increased when a tire encounters discontinuities on the road surface, the discontinuity being either a gap or a bump. The relatively high frequency tire noise generated due to such discontinuities is defined as tire slap noise in this study. An increase in amplitude compared to noise generated on a flat surface is observed generally below 1 kHz and also around 1.2 k -1.5 kHz in the high frequency range (> 1 kHz). In addition, the loading effect on tire noise radiation has also been studied using the same experimental settings. It was found noise is generally proportional to the loads in the investigated 0.2 k – 2 kHz range, except in the frequency range 1.2 k -1.6k Hz where the noise-loading relation is reversed. Our static tire surface mobility measurement provided the dispersion relation in the tire tread, indicating that a high frequency supersonic structural wave is a strong sound radiator and could be the cause for the slap noise high frequency portion. The loading effect could be affecting the excitation mechanism of such a wave and be the cause of the anomalous noise-loading relations.

Squeaking Noise Detector in a Printer

Research Assistants: Nicholas Kim, Yutong (Tony) Xue and Xihui Wang
Principal Investigators: J. Stuart Bolton, Patricia Davies, George Chiu and Jan Allebach
Sponsor: HP Printers

Abstract

A printer, as used in the office or home, is composed of many parts, for example, motors, rollers, gears, etc., that are required to print an image on paper after receiving data. Because there are so many parts, it is often difficult to identify a specific faulty component when a malfunction occurs. Being able to identify faulty components accurately, would, of course, reduce the cost of repair and also reduce environmental impact by replacing specific parts instead of multi-component units. The objective of the present work was thus to develop procedures that would allow defective components to be identified by using on-board acoustic measurements. The particular target of this work was “squeaking”, which can be particularly annoying in office spaces and which can result in multiple service calls. The squeaking noise is generated by stick/slip phenomena acting on rollers and usually appears in 3 to 5 kHz frequency range. The high frequency squeak is observed to be modulated at the rotational frequency of the component that is squeaking. To analyze and solve the squeaking noise problem, first, a noise was recorded at the top and inside the printer. For the recording above the printer, a half-inch B&K microphone was used and for recording inside the printer, a MEMS microphone was used. From the recorded data, any peaks in the 3 to 5 kHz range were isolated by bandpass filtering. After filtering, the modulation frequency of filtered tonal noise was calculated, and finally, the defective roller can be identified by matching the modulation frequency with the known rotational frequencies of the various rollers.

Experimental Investigation on Reduced Order Modeling in Room Acoustics Using Equivalent Source Models

Research Assistant: Yangfan Liu, Post Doc
Principal Investigator: Professor J. Stuart Bolton

ABSTRACT

As an alternative to models based on geometrical acoustics and the computationally intensive Finite Element or Boundary Element methods, the Equivalent Sources Model (ESM) has recently been modified and extended from its original application in acoustical holography to room acoustics simulations. Previous numerical simulation results have demonstrated the advantages of room acoustics ESM's (especially when higher order sources are used as its equivalent sources) as a flexible reduced order modeling procedure in room acoustics. In the present work, an experimental investigation of the room acoustics ESM was conducted in which the sound field generated by a loudspeaker in a small room was measured. The ESM prediction of total sound field in the room is calculated by coupling a free-space ESM (gives the source information) with a room acoustics ESM (for the room effect). The ESM predictions are compared with the measurements to show the validity of the room acoustics ESM in a realistic application.

Noise Source Identification Based on an Inverse Radiation Mode Procedure

Research Assistants: Jiawei Liu, Yangfan Liu, PhD.
Principal Investigator: Professor J. Stuart Bolton
Sponsors: Cummins Inc., Department of Research and Development

Abstract

Nearfield Acoustical Holography (NAH), Statistically Optimized Nearfield Acoustical Holography (SONAH) and the Equivalent Source Method (ESM) are widely used in noise source identification. Fourier transform based NAH requires the sound field to fall to negligible levels at the edges of the measurement aperture, a requirement rarely met in practice. As a result, SONAH and ESM have been developed. In addition, the Inverse Boundary Element Method (IBEM) can be used, given sufficient computational resources. Unfortunately, none of these methods directly guides the changes necessary to unequivocally reduce noise radiation. Radiation mode analysis has previously been primarily associated with forward prediction of radiated sound power and active noise control applications. Since radiation modes contribute independently to sound power radiation, it is only necessary to modify the surface vibration so that it does not strongly couple with those modes in order to ensure sound power reduction. Since the radiation modes can be used as the basis functions through which the surface motion of a source can be described, an inverse method based on radiation modes allows the surface vibration that results in the majority of the radiated sound power to be identified unequivocally, and so will, in turn, guide the design changes needed to reduce radiated sound power.

The Effect of Honeycomb Cavity: Acoustic Performance of a Double-leaf Micro Perforated Panel

Research Assistant: Yuxian Huang
Principal Investigator: Kai Ming Li

Abstract

A micro perforated panel (MPP) is a device consisting of a thin plate and submillimeter perforations for reducing low frequency noise. MPPs have many advantages compared to traditional sound absorption materials, such as durability and designability, and they can be used in a variety of places such as room interior designs, passenger and crew compartments of aircrafts and combustion engines. The models in this study were designed and fabricated with the latest 3-D printing technology. The transmission loss and sound absorption coefficient of the 3-D printed double-leaf MPPs with honeycomb cavities were studied. According to the established theory, MPPs work well with the help of a backing and a cavity. Earlier experimental and theoretical developments have suggested that the acoustic performance of the MPPs can be improved by partitioning the backing cavity. A Brüel & Kjær type 4206 impedance tube was used for the experiments and the one-load method was implemented for calculating the absorption and transmission coefficients of the MPPs. A honeycomb structure was chosen to be placed in the cavity because it can provide the required partitions between perforated panels so that the overall transmission loss was expected to be higher than those without the cavity partitioning. Measured results indicated that use of the honeycomb structure in the cavity have improved the acoustic performance of the MPPs. The sound absorption coefficient of a double-leaf MPP was similar to that of a single-leaf MPP if the cavity was long enough. Future studies should involve an investigation of the acoustic performance of the MPPs at oblique angles of incidence because the current study only provides the pertinent information at normal incidence since the standing wave tubes were used in the experiments.

The Prediction of Enroute Aircraft Noise

Research Assistants: Yiming Wang
Principal Investigators: Professor K. M. Li
Sponsors: FAA

Abstract

This study investigates the noise emitted from enroute aircrafts with high elevations, which produces unneglectable impact to people living in the vicinity of airports. The objectives of the study is to enhance current FAA tools in modeling and predicting aircraft noise, and accurately quantify uncertainties at various stages of propagation. The model combines the influences of atmospheric absorption, ground reflection and Doppler Effect together to predict the sound field due to different aircrafts. Ray tracing method is used to identify the sound ray path where Doppler modified is included into the ray model. The theoretical model is compared with flight noise data measured by Vancouver airports noise monitoring system and Volpe flight tests with Lockheed P-3B Orion aircraft and Beechcraft B-200 Super King Air aircraft. The test measured the noise level at different receiver locations on the ground due to enroute aircrafts with different flying paths. The noise is predicted with the recorded GPS location of the aircrafts and the meteorological data measured at the same time. The preliminary comparison shows good agreement and the follow up study is progress.

Characterization of Next-Generation Car Sounds

Research Assistant: Youyi Bi
Principal Investigators: Professors Tahira Reid and Patricia Davies
Sponsor(s): Ford Motor Company

Abstract

Car designers are interested in understanding what attributes of naturally occurring, generated, and modified sounds make them more or less desirable to end-users. In this research, we investigated millennials' perception of the proposed next-generation car sounds and other product sounds. A subjective test was conducted to determine sound preferences when people were presented with a current sound, a very different sound, and something in between the two. Intentional sounds (e.g., turn signal) and consequential sounds (e.g., car door closing) were considered in six contexts. Because of the focus on next-generation cars, responses from millennials (purchasers of cars over the next 40-50 years) are of particular interest. The very different sounds were inspired by the music preferences of the millennial generation (e.g. music and film). The influence of visual information and perceived functionality on the sound preferences were also examined. Forty university students and staff volunteered to participate in the test. The results showed that millennials preferred traditional sounds in most contexts and their sound preferences aligned with certain sound evaluations and verbal descriptions. Participants' verbal descriptions of the sounds provided interesting insights into the relationship between the sound evaluations and participants' perception of the sounds. In several cases the pictorial and textual cues of context and their presentation order could impact how people perceived the sounds. These results may shed light on how to integrate millennials' preferences into the design of future product sounds.

Sound Quality Investigation of Wind Noise in Cars

Research Assistant: Daniel Carr
Principal Investigator: Professor Patricia Davies
Sponsor: Ford Motor Company

Abstract

To guide automobile design, predictors of human response to wind noise are desired, and these are being developed through laboratory experiments. While it is well known that more recent models of loudness are generally accurate predictors of peoples' responses to steady-state wind noise, there is concern that other sound characteristics may also influence people's responses. A test was conducted where 33 subjects aged 18-53 listened to wind noise recordings and modified recordings presented over earphones, and then either compared them or rated them on an acceptability scale. Original recordings supplied by the sponsor were recorded by using binaural heads in the driver and passenger locations in five vehicles placed in a wind tunnel. The wind speed and the yaw angle of the vehicle to the wind were varied. Some of the recordings were modified by isolating the speech-band energy of the sound with a band-pass filter, amplifying or attenuating that energy within the sound, and then amplifying or attenuating the whole sound. This signal modification process was designed to vary Articulation Index, a measure of whether people will be able to understand speech with the sound as background noise, while controlling loudness, as predicted when using Zwicker's Loudness model. Linear models that included one or more sound quality metrics and predict average acceptability ratings were fitted to the response data. While a model just containing a loudness term produces reasonably accurate predictions of the subjects' responses to the sounds, the addition of a spectral balance term to the model increases the accuracy of the model predictions significantly. A test is now being designed to validate the accuracy of the predictions from this estimated model. It should be noted that subjects' understanding of speech was not measured in this test, and that future work should also include examination of how ease of communication impacts acceptability of interior automobile noise. Automobile manufacturers may use these types of models to benchmark the acoustic performance of their vehicles.

Sound Quality of HVAC&R Equipment

Research Assistant: Weonchan Sung
Principal Investigators: Professors Patricia Davies and J. Stuart Bolton
Sponsor: UTC/Carrier
Collaborator: Asad M. Sardar and Robert Chopko

Abstract

Some HVAC&R (Heating, Ventilating, Air-Conditioning, and Refrigerating) machinery can produce noise that is irritating to people. The goal of this research is to develop better metrics for HVAC&R machinery noise that can be used in HVAC&R system design. Most metrics that are used today to evaluate HVAC&R noise are just functions of a level, but there are several HVAC&R sound characteristics that could contribute to annoyance. HVAC&R noise is complex, it is composed of broadband noise and multiple tonal components related to rotation rates of fans and compressors. A database of sounds has been assembled and additional measurements have been conducted. Existing metrics are being examined to see how well they predict strengths of perceived sound attributes. Modifications to sounds were made to change loudness, roughness and tonality, making sure that the new sounds also sounded realistic. Two subjective tests and some additional follow-up tests were conducted; these are two of three planned subjective tests. Subjects' descriptions of sounds in Test 1 were categorized into 9 groups. The occurrences of the words within a group were compared to values of sound quality metrics, and to the results of a preliminary annoyance rating test. There was a high degree of correlation between the occurrences of the words and the sound metric values. The results of Test 1 were used to design a semantic differential test which was conducted and the results are now being analyzed. The results of this test will be used to construct candidate sound quality models. Test 3 will be conducted to evaluate these models and also to determine whether a unified model or application specific models are more appropriate. By combining sound quality models with physical models of equipment component noise and the transmission paths to persons exposed, the designer can predict the impact of the sound generated by the HVAC&R equipment. This allows the engineer to explore sound design options prior to prototyping and thus equipment sound becomes an integral part of the equipment design process.

Aftertreatment Thermal Management Strategies on a Diesel Engine Equipped with Variable Valve Actuation System

Research Assistants: Aswin Ramesh, Dheeraj Gosala, Cody Allen, Alexander Taylor, Kalen Vos, Matthew Van Voorhis, Mrunal Joshi, Troy Odstrcil
Principal Investigator: Prof. Greg Shaver
Project Sponsors: Cummins Inc. and Eaton Corporation

Abstract

Stringent EPA emission norms require aftertreatment systems to be extremely efficient and effective. Aftertreatment systems in a diesel engine are heavily dependent on temperature for their efficient functioning. Specifically, the selective catalytic reduction system achieves its maximum efficiency only when the catalyst bed temperature reaches a certain temperature range. Diesel particulate filters in the aftertreatment system can only undergo regeneration once sufficiently high exhaust gas temperatures are present. Reducing the time taken by the aftertreatment system to reach the desired temperatures can enable effective emission reduction to begin earlier than usual and can thus enable fuel efficient functioning of the engine later in the drive cycle. The underlying principle of these strategies is to increase temperature downstream of the turbocharger by increasing the amount of heat in the exhaust gas. The ECM is capable of operating the engine in a special aftertreatment thermal management mode when necessary. A variable valve actuation (VVA) system allows us to explore additional methods for thermal management. Extensive studies on a 6.7l camless diesel engine have shown that modifications in valve timing can result in favorable aftertreatment thermal characteristics along with lower NOx emissions as compared to stock thermal management strategies. Moreover, flexible valve actuation allows the use of an optimal thermal management strategy depending on the operating condition of the engine (speed and load). These strategies have been studied first in steady state operating conditions and then implemented for those speed/load conditions in the transient drive cycle. Early opening of the exhaust valve, internal EGR and cylinder deactivation are examples of VVA enabled thermal management methods.

Cummins Power Laboratory at Herrick Labs

Research Assistant: Alexander H. Taylor, Dheeraj Gosala, Cody Allen, Mrunal Joshi, Kalen Vos, Matt Van Voorhis, Aswin Ramesh, Troy Odstrcil

Principal Investigator: Professor Greg Shaver

Sponsors: Cummins, Eaton

Abstract

The Cummins Power Laboratory at the Ray W. Herrick Labs includes a 350 horsepower, 800 ft-lb torque Cummins 6.7L turbodiesel “camless” engine. This engine is equipped with a Variable Valve Actuation (VVA) system, which allows for real-time cycle to cycle control of the intake and exhaust valves. The test cell is outfitted with an AC dynamometer capable of performing drive-cycle testing per the EPA’s Federal Test Procedure (FTP) drive profiles, in particular the HD-FTP and FTP-72. Exhaust emissions such as Soot (particulate matter), NOx (Oxides of Nitrogen), Unburned Hydrocarbon, and CO2 are studied over these drive-cycles. Research in the last year has focused on the trade-off between engine-out emissions and fuel consumption over a drive-cycle as various actuators on the engine (e.g. valve timing, fuel injection) are optimized. Another area of research is studying, via simulation models, the thermal management of exhaust after-treatment hardware which converts emissions such as NOx into harmless byproducts before reaching the tailpipe. This after-treatment hardware has a NOx conversion efficiency based on temperature, which presents its own trade-off of tailpipe emissions versus fuel consumption as added fuel energy is needed to both heat up and maintain temperature of the after-treatment hardware so that it operates efficiently. In the coming weeks, work is underway to install exhaust after-treatment hardware in the test cell which will allow for experimental testing of tailpipe and engine-out emissions over EPA drive-cycles, with the goal of validating after-treatment thermal management hypotheses created from simulation model studies. This testing will commence with the recent additions of both conditioned combustion air (both humidity and temperature controlled intake air) and controlled charge-air-cooler water supply temperature. Both of which will improve test repeatability by means of controlling the engine’s boundary conditions.

Validating Thermal Management and Fuel Economy Benefits of a Variable Valve Actuation Enabled Diesel Engine through After-treatment System Installation

Research Assistant: Matthew VanVoorhis
Principal Investigators: Professor Gregory Shaver
Sponsor: Cummins, Inc. and Eaton Corporation

Abstract

In order to study the real-world environmental impact of novel diesel engine advancements being researched on an electrohydraulic variable valve actuation (VVA) enabled diesel engine, a production-grade after-treatment system is currently being implemented in Test Cell 1. The after-treatment system is in addition to the 6.7L Cummins ISB diesel engine already present in Test Cell 1. This allows validation of VVA enabled strategies' ability to increase thermal management and/or increase fuel economy. In order to meet increasingly tight emissions regulations, set by the Environmental Protection Agency (EPA) while also increasing fuel efficiency, various strategies are being studied and tested on a 6.7L Cummins ISB diesel engine through utilization of a VVA system. The electrohydraulic VVA system allows for independent control over both the intake and exhaust valve events for each cylinder on a cycle to cycle basis. The main driver for meeting emissions requirements in diesel engines is the use of an after-treatment system that is able to take harmful emissions from the combustion event, particularly unburned hydrocarbons (UHC), particulate matter (PM) and nitrous oxides (NOx), and convert these emissions into less harmful products such as nitrogen and water. This is accomplished through a three-stage after-treatment system composed of a diesel particulate filter (DPF), a diesel oxidation catalyst (DOC), and a selective catalytic reduction (SCR) system. In order for the after-treatment system to work properly, it must reach a certain temperature of around 300 degrees Celsius. Strategies enabled by VVA have been shown to increase exhaust temperatures by up to 200 degrees Celsius over stock valvetrain performance during steady state operation. These strategies include early exhaust valve opening (EEVO), late inlet valve closing (LIVC), and internal exhaust gas recirculation (iEGR), among others. These strategies have been studied on the Cummins engine without a physical after-treatment system. Engine out emissions were measured before being analyzed with a Cummins after-treatment model in order to gain understanding of the effects of these VVA enabled strategies on the after-treatment system and tailpipe emissions. Reductions in tailpipe emissions levels were predicted, therefore physical hardware has been acquired and being installed in order to validate the results from the model over real-world representative drive cycles.

Improving Fuel Economy Through IVC Modulation Using Variable Valve Actuation

Research Assistant: Kalen Vos
Principal Investigator: Gregory Shaver
Sponsors: Cummins Inc., Eaton

Abstract

In effort to meet stringent emissions regulations while continuing to improve upon fuel economy, various strategies are being studied and tested to understand the effects of modulating a 6.7L Cummins ISB diesel engine's valves through the use of a Variable Valve Actuation (VVA) system. The VVA system allows for independent control over both the intake and exhaust valve opening, closing, and lift timings with respect to crank angle on a cycle-to-cycle basis. Intake valve modulation, more specifically intake valve closing (IVC), has shown promise in regards to fuel economy benefits. By advancing or delaying the closing timing of the intake valve in each cylinder, the effective volume of the cylinder as a result will vary, hence directly effecting the volumetric efficiency of the engine. Although volumetric efficiency itself can provide benefits, during these valve modulation studies it functions as the enabler to incorporate other strategies without penalizing our emissions. Using GT-Power guided simulation results as a starting point for engine testing, an optimal IVC timing was found at 30 CAD delayed from the nominal IVC timing. Taking advantage of the volumetric efficiency benefits such as dynamic charging allowed for the EGR valve and start of injection (SOI) timing to be adjusted to obtain a 1.25% fuel economy benefit over stock valve timings. The primary focus of these studies were guided by the understanding that during a Heavy Duty Federal Test Procedure (HDFTP) a large portion of fuel energy is expended at high speed high load conditions. Therefore, the results being concluded from this particular study are at 2200 RPM and 12.7 bar.

HEV Design Optimization: Incorporating Battery Degradation in its Economic Analysis

Research Assistants: Vaidehi Hoshing, Xing Jin, Tridib Saha, Ashish Vora
Principal Investigators: Dr. Gregory M. Shaver, Dr. Oleg Wasynczuk. Dr. Edwin Garcia

Abstract

The average energy consumption of heavy duty vehicles in the transportation sector is predicted to increase by 30% by 2040 and the fuel economy standards for heavy duty vehicles are set to increase by 28% by 2027. This provides the motivation for hybridization of heavy duty vehicles. Given the diversity of heavy duty transportation vehicles available for hybridization, a comparison of their economic analysis provides helpful insights for vehicle integrators and component manufacturers in making more informed decisions on investing in the right application at the right time. This poster demonstrates a methodology for evaluating and comparing the economic viability of different hybrid vehicle applications with different hybrid architectures. A model based framework is designed and used with a set of economic assumptions, to incorporate the effect of battery degradation on the economics of the vehicle, thereby providing the ability to predict fuel consumption, electrical energy consumption, and battery replacements and their effect on the financial benefit obtained for a powertrain configuration. This enables the exploration of a large design space (which spans powertrain design & control variables, noise variables, and economic scenarios) from a total cost-of-ownership perspective to provide better insights to vehicle integrators, component manufacturers, and buyers of heavy-duty hybrid electric vehicles. The methodology is applied to series and parallel plug-in hybrid electric and extended-range electric powertrain architectures for medium duty truck applications. The results show that under the assumptions made, the bus application becomes favorable earlier than the truck and in that bus with the parallel architecture becomes favorable earlier than the series architecture for urban drive cycles.

Physically-based Reduced-Order Capacity Loss Model for Graphite Anodes in Li-Ion Battery Cells

Research Assistants: Xing Jin, Ashish Vora, Vaidehi Hoshing, Tridib Saha
Principal Investigator: Prof. Greg Shaver, Prof. Oleg Wasynczuk, Prof. R. Edwin Garica
Sponsor: DOE, Cummins Inc.

ABSTRACT

Physically-based Li-ion electrochemical cell models have been shown capable of predicting cell performance and degradation, but are computationally expensive for optimization-oriented design applications. Faster empirical models have been developed from experimental data, but are not generalizable to operating conditions outside of the range established by the calibration data. In this effort, a reduced-order capacity-loss model for graphite anodes is derived based upon the salient physical loss mechanisms to improve computational efficiency without sacrificing model fidelity. This model captures the two primary degradation mechanisms that occur in the graphite anode of a typical lithium ion cell: a) capacity loss due to Solid Electrolyte Interface (SEI) layer growth, and b) capacity loss due to isolation of active material. The model is calibrated and validated for a commercial 2.3-Ah cell with a Lithium Iron Phosphate (LFP) cathode and graphite anode. One data set is used for calibration; another four data sets are used for validation. The model matches experimental capacity degradation results within a 10% error. Moreover, the reported model is 2400x faster than currently existing more complex physically- based electrochemical models that are only slightly more accurate (less than 9% error).

Control System Architecture Selection for Natural Gas Engines

Research Assistant: Xu Zhang
Principal Investigator: Professor Gregory M. Shaver
Sponsor: Caterpillar

Abstract

This poster presentation has six parts. First part is the problem statement, including a schematic of the gas engine and two problems the research mainly focuses on. Second part is the approach of the research, talking about RGA analysis, decentralized controller design and decoupling controller design. The third part presents the current result, including RGA analysis, 3 I/O throttle-governed system and the driving cycle simulation of it. The fourth part talks about the next steps. The fifth part is potential impact of this research. The last part is acknowledgement.

Modeling of NH_3 Storage in Vanadia based SCR Catalyst for Urea Dosing Control in a Diesel Electric Hybrid Car

Research Assistant: Kaushal Kamal Jain
Principal Investigator: Professor Peter H. Meckl
Sponsor: Delphi, Faurecia, Argonne National Labs, General Motors, Dept. of Energy, Discovery Park Energy Center, Purdue, Hoosier Heavy Hybrid Center of Excellence

Abstract

In order to meet increasingly stringent NO_X emission regulations, Urea-SCR (Selective Catalytic Reduction) is an essential component of the diesel engine after treatment system. The Urea-SCR system employs ammonia (NH_3) to reduce NO_X into molecular nitrogen (N_2) and water (H_2O) in presence of abundant O_2. Since it is difficult and dangerous to store NH_3, Diesel Exhaust Fluid (DEF or AdBlue, a mixture of 32.2% urea and 67.8% ionized water) is injected into the Urea-SCR system. The water gets evaporated and the urea is converted into NH_3 through thermolysis and hydrolysis. At Purdue, the Urea-SCR system is mounted on EcoCAR2 which is a modified Chevy Malibu 2013 with 1.7 L Opel Turbo Diesel Engine. In order to keep the tailpipe NO_X emissions and NH_3 leakage under permissible limits, a urea dosing control strategy needs to be employed. However, the state of the art of urea dosing control is not capable of meeting near future emission regulations. This calls for increasing the model fidelity and development of NH_3 storage based closed loop control. Hence, the goal of this research is to develop an observer to estimate NH_3 storage for such a control which, in turn, calls for identification of system parameters. Some of the key challenges to system identification are system's non-linearity in parameters and states, NO_X sensor's cross-sensitivity to NH_3 and measurement noise. The poster will present the ideas to tackle these challenges and the progress made thus far.

Control of a Hybrid Diesel Vehicle

Research Assistant: Mingyu Sun
Principal Investigator: Professor Peter H. Meckl
Sponsors: Delphi, Faurecia, Argonne National Labs, GM, DOE, Discovery Park Energy Center Purdue, H3COE

Abstract

The project uses a parallel-through-the-road hybrid architecture vehicle, with the control objective to minimize the fuel consumption and emissions. Different power management strategies are studied. To begin with, a detailed model of the vehicle is developed based on dynamometer testing. The power management algorithms developed are implemented on these models instead of the real vehicle. Dynamic programming has been used to find optimal GHG emissions for the test vehicle. The dynamic programming solution is found to result in a 19% improvement in GHG emissions and is also used as a benchmark for other power management approaches such as equivalent consumption management strategy, proportional state-of-charge algorithm and dynamic-programming-based regression strategy.

Mobile Robotics Research

Research Assistants: Daniel McArthur & Arindam Chowdhury
Principal Investigator: Professor David J. Cappelleri
Sponsors: National Science Foundation
U.S. Army Medical Research and Materiel Command

Abstract

This research is focused on developing individual robots and teams of robots that are capable of advanced physical interactions with the environment. In aerial robotics, we introduce a new vehicle configuration called the Interacting BoomCopter (I-BoomCopter). The I-BoomCopter is based on a standard tricopter frame, with an additional boom extending out of the front of the vehicle which is used for interacting with the environment. A 3D-printed propeller mechanism, which rotates around the front boom, is combined with a reversible speed controller to provide forward and reverse thrusts. This feature allows the vehicle to travel at high speeds without pitching forward, or to apply horizontal forces on an object such as a door or a wall. Recent work has focused on utilizing the Robot Operating System (ROS) to integrate vision sensors and custom end-effectors with the onboard BeagleBone Black computer to automate various aerial manipulation tasks. For example, using image processing techniques, we have enabled the BoomCopter to successfully locate an electrical panel door and open it by pulling on the door handle with a simple, passive end-effector. This task has been performed autonomously on the ground with the BoomCopter mounted on a wheeled chassis, and further work is being done to obtain more robust sensor feedback to enable precise aerial manipulations. The I-BoomCopter shows great promise in advancing the field of aerial manipulation research with applications in industrial maintenance, search and rescue operations, nuclear contamination detection and cleanup, etc. On the ground, TurtleBots (from Clearpath Robotics) along with an original centimeter scale robot: the AgBug, are being combined with custom and open-source hardware and software to enable collaboration among heterogeneous teams of ground and aerial robots. The software developed in the lab makes use of the (ROS) framework, and allows multiple robots to work together in both indoor and outdoor wireless networks.

Topological Synthesis of Resonators for Energy Harvesting Applications

Research Assistant: F. Danzi
Principal Investigator: Professor J. M. Gibert
Sponsor: Grant given by Politecnico di Torino, Department of Mechanical and Aerospace Eng.

Abstract

The objective of this research is to use topology optimization to design resonators with 1:n resonances undergo planar vibrations. The resonators are intended for the use of kinetic energy scavenging in signals that exhibit two dominant frequency components, i.e., a fundamental component with large energy content and secondary component with smaller energy content. This phenomenon is often seen in rotary machines; their frequency spectrum exhibits peaks on multiple harmonics. Several theoretical resonators are known to exhibit 1:2 or 1:3 internal resonances, notably the L-shape beam. However, designing manufacturable resonators is still a daunting task. We formulate the problem in its non-dimensional form. In this way, we can eliminate the constraint on the allowable frequencies' bandwidth. The frequency can be obtained a posteriori by means of linear scaling. Conversely to other researchers, which use the clamped beam as initial guess, we synthesize the final shape starting from a ground structure (or structural universe). We remove of the unnecessary beams from the initial guess by means of a graph-based filtering scheme. The algorithm determines the simplest structure that gives the frequency's ratio sought. Within the optimization, the structural design is accomplished by a linear FE analysis. Regardless of the frequency’s ratio sought, we demonstrate that: if one penalizes the number of beams of the initial structure, one obtains two beams as optimum, i.e. a generalized shape exists. Results highlight how the beam orientation, which had never been considered so far, is a key parameter in the synthesis of resonators. We report the design envelope to show the dependencies of the beam orientation on the frequency ratio sought. Furthermore, we derive a reduced order model that aims to investigate the nonlinear behaviour of the resonator and analyze if, and how, the effect of the beam orientation influences the energy pumping.

Packaging Solutions: From Predictive Modeling Tools to SMART Packaging Development

Research Assistant: Amin Joodaky
Principal Investigator: Professor J. M. Gibert
Sponsor: Purdue Start-Up

Abstract

Our focus is development of innovative packaging design tools and products through a combination of dynamic modeling, numerical simulation and experimental validation. The lab's work is motivated by three trends: 1) the demand for environmentally sustainable packaging, 2) the need to reduce losses in product distribution, and 3) the exponential growth in the burgeoning -field of smart packaging. The work of the lab is concentrated in the three focus areas: I) Shock Absorption: Develop numerical and analytical tools to reduce the time needed to characterize impact by cushion curves, as well as include environmental factors shock absorption, II) Random Multi-Axis Testing And Modeling: Develop metrics for multi-axis vibration quantification, compare time domain and frequency damping quantification, real-time testing and laboratory simulation of transport conditions, and III) Smart Packaging: Develop packaging solutions that concurrently protect a product and scavenge energy from the environment. Uses range from RFID location to humidity sensing.

A Nonlinear Analysis of Acoustic Softening

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Abstract

Ultrasonic additive manufacturing (UAM) or ultrasonic consolidation (UC) is a solid state manufacturing technique for 3-D printing of metals. The current process for UAM is a base plate is fixed to an anvil and a metal foil is placed on top of the base plate. After the foil is placed on the base plate, the foil is ultrasonically vibrated and compressed by a sonotrode to induce plastic deformation and bonding due to dynamic recrystallization of grains across boundaries. Subsequent foils can be added on top of the bonded foil, and the process can be repeated. A benefit of using ultrasonic vibrations is the phenomenon of acoustic softening. Acoustic softening occurs when metals are subjected to ultrasonic vibrations, and as a result the yield stress is decreased. Current understanding of the mechanism behind acoustic softening is that stress superposition of the applied stress and the vibration stress produces a total stress that is greater than the yield stress. From a literature review of the current studies on the mechanisms of acoustic softening, stress superposition is accepted because the other possible mechanisms for acoustic softening are eliminated due to experimental observations. However, experimental observations do not precisely match up with the stress superposition model. A possible reason for why the observations do not match the model is that the model assumes a linear stress-strain relationship when the material is plastically deforming. This study proposes that the stress superposition model is modified to assume a non-linear stress-strain relationship when the material is plastically deforming and compare the non-linear model with experimental observations.