Research Expo
2017

HERRICK LABORATORIES
PURDUE UNIVERSITY™

CHPB-A

Station B4 Speaker of the Group: Iason Konstantzos

Station B5 Speaker of the Group: Tianren Wu

Station B6 Speaker of the Group: Stephen Caskey

ACOUSTICS, VIBRATIONS, CONTROLS & DYNAMICS - C

Station C1 -PBE Speaker of the Group: Daniel McArthur

Demo- PBE
Daniel McArthur, Ph.D. Student
Interactive Mobile Robotics

Station C2 -Small Vibs Lab   Speaker of the Group: Janav Udani

Station C3 -High Bay   Speaker of the Group: Nikhil Bajaj

Demo- High Bay Area
#Allison Murray, Trevor Fleck, Ph.D. Students
Ignition of Selectively Deposited Energetic Materials

Station C4 -High Bay   Speaker of the Group: Ankit Agarwal

Station D4 - Engine Test Cell Speaker of the Group: Ali Lenjani

Automated Test Methodology for Refrigerant Charge Optimization

Research Assistant: Akash Patil, MSME Student

Principal Investigator: Professors James E. Braun and W. Travis Horton

Abstract

Amount of refrigerant charge has a significant impact on the performance of a vapor compression system. Conventional control strategies cannot optimize the performance of a system by varying the charge at different operating conditions. Traditionally, extensive psychrometric chamber testing has been done at different charge levels and ambient conditions to obtain sufficient information on optimal charge for a system. This testing is difficult for equipment manufacturers and it can be difficult to find available test facilities. Based on previously developed automated virtual charge sensor tuning methodology, a testing methodology is developed that aims to optimize the charge level inside a system by adding or removing the refrigerant charge from the system while it is in operation. A refrigerant tank is connected to the system with solenoid valves at suction and liquid line. Charge is automatically added to or removed from the system by opening the suction or liquid line solenoid valve respectively. A digital weighing scale continuously monitors the amount of refrigerant inside the system. The entire charging/discharging process is automated and thus reduces the need for human involvement to a great extent. This test architecture has been set up on a roof top unit (RTU) inside the psychrometric chamber. Performance of the RTU will be monitored by automatically changing the ambient conditions and charge levels to determine the optimal charge. An online optimization algorithm will be employed to determine the optimal charge in lesser time. This would result in significant reduction in testing times as well as the costs associated with determination of optimal refrigerant charge.

Areas at Laboratories: Thermal Systems
Key words: Refrigerant charge optimization

Load-Based testing to Characterize the Performance of Variable Speed Equipment

Research Assistants: Akash Patil, MSME Student and Andrew Hjortland, David Halbrooks, Li Cheng, Ph.D. Students

Principal Investigators: Professors James E. Braun and W. Travis Horton

Sponsor: Northwest Energy Efficiency Alliance, Portland, OR

Abstract

Existing equipment performance rating approaches are based on steady state tests and hence do not consider the interaction of controls with the equipment. To adequately assess the performance of alternative control approaches under realistic and reasonable conditions, a new testing methodology is developed that is applicable for both variable and fixed-speed DX (Direct Expansion) equipment. The method is applied in evaluating integrated equipment performance for two variable speed split air conditioning units and one rooftop air conditioning unit (RTU). The units are controlled in response to dynamically varying loads and ambient conditions. Equipment sensible and latent loads are simulated using a virtual building model that is appropriately sized for the equipment under test. Using this virtual building model, units can be tested at different part load conditions and different building sensible heat ratios. The load-based testing procedure followed a draft standard being developed by the Canadian Standards Association (CSA) aimed towards evaluating the performance of variable speed equipment. 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 obtain seasonal energy efficiency for an equipment and also to build a performance model that can be used in an energy simulation program.

Areas at Laboratories: Thermal Systems
Key words: Load-based testing, variable speed equipment

Two-Phase Injected and Vapor-Injected Compression: Experimental Results and Mapping Correlation

Research Assistant: Domenique R. Lumpkin, Ph.D. Student

Principal Investigator: Professor Eckhard A.Groll

Abstract

Vapor compression systems in hot climates tend to operate at higher pressure ratios, leading to increased discharge temperatures, higher irreversibilities during compression, lower specific enthalpies differences across the evaporator, and possibly a reduction in the compressor life due to the breakdown of the oil. To counter these effects, the use of economized, vapor injection compressors is proposed for vapor compression systems in high temperature climates. Such compressors are commercially available however an accurate method for mapping single-port injection compressors is unclear. This paper establishes compressor maps for a single-speed R-407C scroll compressor with two-phase injection and vapor-injected compression. A dimensionless-π correlation for mapping the injection ratio, refrigerant discharge temperature, compressor power consumption, overall isentropic and volumetric efficiencies, and the heat loss ratio for these compressor maps and a variable speed R-410A compressor with vapor injection is presented. The mapping results are compared to the AHRI 10-coefficient polynomial and another proposed correlation.

Areas at Laboratories: Thermal Systems

Key words (4 or 5): Liquid-vapor injected compression, vapor-injected compression, air conditioning, compressor mapping, liquid-vapor injection

Oil Management in Tandem Compressors of Transport Refrigeration Units

Research Assistant: Vatsal M. Shah
Principal Investigator(s): Dr. Eckhard Groll, Dr. James Braun, Dr. 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 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. A transport refrigeration unit was donated by the sponsor on which modifications were made to include appropriate instrumentation. Baseline testing has been conducted at various test conditions to verify the performance of the refrigeration unit. An oil measurement loop was installed on the unit, which can measure the amount of oil that is discharged from the compressor into the system and the amount of oil that is returned to the compressor from the system through the suction line. Testing of oil discharge from the compressor at various test conditions is currently in progress. After the testing of oil in the suction line has been completed, the refrigeration unit will be modified to tandem compressors for capacity control from the current fixed speed compressor and similar oil measurement tests will be carried out to compare the results.

Areas at Laboratories: Thermal Science
Keywords: Oil Management, Tandem Compressors, Transport Refrigeration

Oil Return and Retention in Unitary Split System Gas Lines with HFC and HFO Refrigerants

Research Assistant: Vatsal M. Shah
Principal Investigator(s): Dr. James Braun, Dr. Eckhard Groll

Sponsor: American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)

Abstract

Most air conditioning and refrigeration systems that employ the vapor compression cycle rely on oil circulating with refrigerant to lubricate the bearings and other rubbing surfaces in the compressor. The lubricant acts as a sealant to reduce leakage losses during compression process and it also helps to absorb some of the excess heat that is generated in the compression chamber. However, this oil circulation results in oil retention in various other components outside the compressor depending on the physical interaction between lubricant and refrigerant based on its transport properties. Other factors such as geometry and orientation of connecting lines and system operating conditions such as refrigerant flow rate also lead to oil retention. 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. The current line sizing rules reported in the ASHRAE Refrigeration Handbook have only limited consideration of the effects of oil in the system. With the increasing development of variable speed systems as well as future use of newer HFO refrigerants, there is a need in the industry for upgrading the line sizing recommendations, especially the connecting gas lines of unitary split systems. To develop these rules, measuring oil retention for different test conditions is important in understanding its impact on heat transfer, especially under situations where oil gets trapped and inadequate oil is returned to the compressor. Measuring oil retention within a vapor compression cycle is challenging due to various factors such as phase change of different fluids, miscibility between the oil and refrigerant, and varying flow regimes. ASHRAE Standard 41.1-1996 requires taking a sample and measuring the quantity of oil after boiling off the refrigerant from the sample. However, to measure a wide range of testing parameters, a quicker method of measurement is required. Recently, Canière (2009) developed a capacitive sensor to measure void fraction of two-phase evaporating refrigerant flow that could be applied for in-situ measurement of oil concentration when flowing with refrigerant gas. Due to the difference between the dielectric constants of liquid oil and vapor refrigerant, the measured capacitance between the electrodes correlates with the void fraction. The void fraction can then be used to estimate the oil fraction in a section of the pipe.

Areas at Laboratories: Thermal Science
Keywords: Oil Return, Oil Retention, Unitary Split System, Gas Lines

Vapor Injected Compression with Economizing in Packaged Air Conditioning Systems for High Temperature Climate

Research Assistant: Ammar M .Bahman, Ph.D. Student

Principal Investigator: Professor Eckhard A. Groll

Sponsors: Adams Communication & Engineering Technology (ACET)
Emerson Climate Technologies (Emerson/Copeland)

Abstract

The use of packaged air conditioning (AC) units has been increasingly growing in U.S. military applications, where they are called Environmental Control Units (or ECUs). An ECU has distinctive features when compared to commercialized packaged AC unit. It is designed to sustain harsh and extreme weather conditions, and it is used to cool people and equipment in enclosed spaces such as shelters, vehicles, and containers. However, in desert or very hot regions, both the cooling capacity and the (COP) of packaged units drop significantly with an increase in outdoor temperature. One possible method to increase system performance is to inject economized refrigerant liquid or cool vapor into the compression process to reduce the heat generated and reduce the discharge temperature. With the addition of an economizer, additional subcooling helps with increasing the cooling capacity.

To the best of the researchers' knowledge, the vapor injection (VI) with economizing technology has not been experimentally investigated in a packaged AC unit for hot climates. In this work, a detail simulation model of vapor injected compression with economization has been developed and its predictions have been experimentally validated. The results showed that despite a relative small COP improvement, the cooling capacity of the VI system was increased by 14%. The VI system predictions matched the experimental results with overall mean absolute error (MAE) of less than 5%. It is recommended to optimize the single injection port compressor for AC application. Future work will be on optimizing the VI system components, mainly the economizer, to maximize system COP.

Areas at Laboratories: Thermal Systems Research Area
Key words (4 or 5): ECU, vapor injection, modeling, validation

Evaluating Adhesive Bonding of Aluminum and Copper in HVAC&R Applications

Research Assistant: Haotian Liu, Ph.D. Student

Principal Investigators: Professors Eckhard A. Groll and Justin A. Weibel

Collaborators: Patrick J. Geoghegan and Adrian S. Sabau

Sponsor: Oak Ridge National Laboratory

Abstract

Using adhesive bonding to manufacture air-to-refrigerant heat exchangers would remove the need for energy consuming brazing furnaces. Adhesive bonding between aluminum and copper can significantly simplify the joining process and avoid the galvanic corrosion that typically occurs in aluminum microchannel heat exchangers. Furthermore, manufacturing of the heat exchanger would be more cost effective with increase design freedom. This enabling technology reduces the payback time for future high-efficiency HVAC&R equipment. The research team will conduct rigorous thermal performance and mechanical reliability testing of adhesively joined heat exchangers in HVAC&R systems in close cooperation with Oak Ridge National Laboratory (ORNL). Surface preparation techniques will be characterized using x-ray photoelectron spectroscopy (XPS) to assess the extent of contaminant removal and the cleanliness of the surfaces. Other imaging techniques, such as extended focal imaging (EFI) optical micrographs, interferometric topography mapping, or SEM imaging, will be used to study the effect of the laser processing on surface morphology. Identification of the joint strength and adhesive failure mechanisms of the adhesive bonds will be done through experiments, such as double cantilever beam (DCB), tensile/shear, and notch testing as well as simulation analysis using an Abaqus model. After joints strength testing and model validation, an adhesively joined heat exchanger will be built for testing in a real system to validate the system performance using different refrigerants. The adhesively joined heat exchanger will be tested based on relevant ASHRAE and AHRI standards for a range of operating conditions. The results will be documented and reported, which will provide a deeper understanding of adhesive bonding and potentially transform the manufacturing of heat exchangers in industry.

Areas at Laboratories: Thermal Science
Key words (4 or 5): Adhesive bonding, heat exchanger, joints, performance

A General Open-Source Platform for Evaluating Advanced Vapor Compression Air Conditioners and Heat Pumps

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Research Assistant(s): Davide Ziviani, Ammar M .Bahman
Principal Investigator(s): Prof. James E. Braun, Prof. Eckhard A. Groll,
Sponsor(s): Center for High Performance Buildings (CHPB)

Abstract

The design of high-efficiency HVAC&R systems is of great interest for both industrial and residential applications. Vapor compression system simulations models are very useful tools toward the improvement of existing system design and for evaluating new concepts, i.e. cycle architectures and alternative working fluids, that can meet current and future environmental and energy-efficiency requirements. Publicly accessible tools for modeling vapor compression systems are available but they have limitations in terms of considering new technology concepts and are not open-source. To this end, an open-source model was developed to simulate vapor compression equipment that is called ACHP that considered some different air conditioning and heap pump configurations as well as included a secondary loop with an indoor air-handling unit. The overall objective of this project is to enhance the open-source platform to: (i) include alternative and novel vapor compression cycle technologies and refrigerants (subcritical, supercritical, with vapor-injection, with flooding, etc.), new component models (micro-channel heat exchangers, low-order compressor models, alternative expansion devices) as well as optimization and calibration capabilities; (ii) to improve robustness and computational speed of the steady-state cycle solver for both design and off-design performance predictions and (iii) improve the user interface. The system model is obtained by connecting each component in an object-oriented fashion programmed in Python which allows the simulation tool to be flexible enough to model different cycle configuration. The detailed cycle model account for the geometry and the physical behavior of the components. A charge-based solution scheme along with a charge tuning method have been implemented. The model has been validated with a high temperature air conditioning unit using vapor injected compression. This work will result in a software platform to be used by the engineers of industrial partners as well as for research purposes.

Areas at Laboratories: Thermal Systems Research Area
Key words (4 or 5): Vapor compression cycles, modeling, open-source, validation

Advanced Caster Roll Gap Control

Research Assistant: Rian Browne, Ph.D. Student

Principal Investigators: Professors Neera Jain and George Chiu

Sponsor: Castrip, LLC

Abstract

We consider the problem of periodic disturbances in the thickness profile of a strip produced using the twin-roll casting process. In twin-roll casting, a strip is produced by pouring molten metal on the surface of two casting rolls that simultaneously cool and compress the strip as they rotate. This rotational motion can produce periodic disturbances in the thickness profile due to angular variations in the shape and thermodynamic characteristics of the rolls. Compensating for these disturbances is further complicated by the existence of large measurement delays between the initial casting and the thickness profile measurement. We explore the use of an iterative learning control (ILC) algorithm to reduce the influence of these disturbances on a per-revolution basis. Further consideration is given to managing the measurement delay within the ILC framework. Simulation results show that the proposed controller is able to reduce the effect of the periodic disturbance on the strip thickness profile by a factor of 2 in a 2-norm sense. 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 strip casting process but will also translate to other materials processing and manufacturing applications.

Keywords: manufacturing, iterative learning control, steel, control systems

Developing an Innovative Ventilation System for Aircraft Cabins

Research Assistant: Ruoyu You, Ph.D. Student

Principal Investigator: Professor Qingyan Chen

Abstract

In commercial aircraft cabins, mixing ventilation system with gaspers was not efficient in controlling contaminant transport. To enhance the cabin environment, this investigation developed an innovative ventilation system to reduce the contaminant transport and maintain thermal comfort level in aircraft cabins. First, this study obtained suitable parameters of the system by designing cabin environment for a one-row, fully occupied cabin of Boeing-737. This study then manufactured and installed the proposed ventilation system in a seven-row, fully occupied, single-aisle aircraft cabin. Air, temperature, and contaminant distribution in the cabin mockup were obtained by experimental methods. It was found that the developed system could increase the contaminant removal in aircraft cabins by 2.8 times and 1.6 times for mixing ventilation system and displacement ventilation system, respectively. Although the diffusers in the developed system were close to passengers, it could still maintain the thermal comfort level in cabin. In real application, the developed system could provide acceptable air and temperature distributions.

Keywords: Computational fluid dynamics (CFD); Aircraft cabin; Contaminant Transport; Mixing Ventilation; Displacement ventilation.

A Behavior Neutral Network Model for Acceptable Indoor Environment

Research Assistant: Zhipeng Deng, Ph.D. Student

Principal Investigator: Professor Qingyan (Yan) Chen

Sponsor: Center of High Performance Buildings (CHPB)

Abstract

It is important to create comfortable indoor environments for building occupants. However, the majority of existing evaluations on indoor thermal environment use questionnaires to collect subjective thermal sensation data. The answers obtained from questionnaires depend largely on how they are designed, which may not provide objective evaluations. The purpose of this study is to develop an evaluation method for thermal comfort that can objectively reflect occupant's satisfaction. The present study developed a novel behavior neural network model by using occupants' behaviors to evaluate the acceptability of office environment in different seasons. The behaviors in offices included adjusting thermostat set point and adjusting clothes. The environment, thermal sensation and behavior data were collected in 10 HLAB offices from winter to summer in 2017. We used Matlab to build and train the neural network models. After the training, the model could predict the behavior occurrence in different indoor environment with accuracy over 85%. The model results demonstrated that temperature from 69℉ to 77℉in winter and from 70℉ to 77℉ in summer were acceptable for 90% of the occupants in offices, since they have no adjustment behaviors in such environment. The results also showed that the relative humidity had little impact on thermal comfort. Composition between these results with ASHRAE standard 55 showed that the comfortable zone in winter was similar, but the acceptable temperature in summer was 5℉ lower. These findings suggest that the building occupants' behavior is becoming a significant parameter for evaluating indoor thermal comfort.

Areas at Laboratories: Thermal Systems and High Performance Buildings

Key words: indoor environment, thermal comfort, office, occupant's behavior, neural network model

Methods for Improving Indoor Thermal Environment in Residential Kitchen

Research Assistant: Jiankai Dong, Visiting Scholar

Principal Investigators: Professor Qingyan (Yan) Chen

Sponsor: Ministry of Science and Technology, China

Abstract

Residential kitchen is an important place in a family, where a housewife could spend about a quarter of her daily life. Therefore, a comfortable kitchen environment is important for the house to increase productivity and ensure her health. However, the thermal environment in the kitchen is poor in China due to high heat generation, poor ventilation, and airtight conditions without cooling. The previous studies showed that the air temperature in kitchen could reach as high as 50℃, while 89% of housewives complained that they suffered intensive smell of cooking fume. To improve the thermal environment in residential kitchen, opening outdoor windows and installing conventional air-conditioner are two main possible solutions. But both of them may disturb the air distribution so the capture efficiency of the range hood may decrease. As the result, the indoor thermal environment may not be improved. Our study is to develop an integrated cooking unit that supplies make-up air around the range and conditioned air on the side to the lower part of the housewife in summer. The numerical simulations predicted the distributions of air temperature, air velocity, and contaminant concentrations in the kitchen with the integrated cooking unit. The results showed that the air temperature around the housewife could be maintained at 26℃, while the CO_2 concentration could be maintained close to the outdoor air level with the integrated cooking unit when outdoor air temperature was 35℃. Therefore, the integrated cooking unit could effectively improve the kitchen thermal environment.

Areas at Laboratories: Thermal Systems and High Performance Buildings
Keywords : Residential kitchen, Thermal environment, Make-up air, CO_2 concentration, Air distribution.

Evaluation of the Thermal and Ventilation Performance of Displacement Ventilation System Coupled with Chilled Beams

Research Assistants:	Zhu Shi, Ph.D. Student and Yuchen Guo, Undergrad Student
Principal Investigator:	Professor Qingyan "Yan" Chen

Sponsor:	American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)

Abstract

Previous studies have shown that displacement ventilation (DV) could provide better air quality in buildings than mixing ventilation (MV), while saving energy at the same time. However, DV supplies clean air to occupants' breathing zones directly, so the temperature of air supplied by DV is usually higher than by a MV system. As a result, the cooling ability of the same amount of air from a DV system is limited as compared to MV. On the other hand, it has been demonstrated that passive chilled beam (PCB) systems are able to remove a large cooling load and can save energy. Thus, this research focuses on establishing a coupled system that combines both DV and PCB, and systematically studies the thermal and ventilation performances of the coupled system. In order to study the significances of different parameters (PCB types, cooling loads, heat source locations, room types etc.) in the performances of this coupled system, multiple tests were performed in a test chamber where a coupled system was installed. Airflow velocity, temperature and contaminant concentration levels were measured in each test. Experimental dataset was analyzed and was also used to validate a Computational Fluid Dynamics (CFD) model developed for simulating the airflow in test chamber. From both experimental and simulation results, it could be observed that the cold downward jet from PCB either collided with or crossed over the upward thermal plumes generated from heat sources. Cooling capability of a coupled system was compared with a DV only system. With the validated CFD model, supporting simulations were also conducted to come up with a guideline for the design and operation of a coupled system.

Areas at Laboratories: Heating, Ventilation and Air Conditioning (HVAC)

Key words: displacement ventilation, passive chilled beams, CFD, coupled system

A Sequential Approach for Achieving Separate Sensible and Latent Cooling

Research Assistant: Jie Ma

Principal Investigator: Professor W. Travis Horton

Sponsor: CHPB Center

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. The previous simulation results show an anticipated energy savings for a typical Indianapolis summer of more than 30%. The focus of the project will be to develop and optimize the system and its controls. By carefully controlling the system operation sequentially in dehumidification mode and sensible only mode it is possible to achieve separate sensible and latent cooling with a single vapor compression system. 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.

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

Research Assistant: Sugirdhalakshmi Ramaraj
Principal Investigators: Professor James E. Braun and W. Travis Horton

Abstract

With the furious economic development and population growth worldwide, the demand for energy is rapidly rising. This calls for efficient energy production along with handling the concerns about global climate change and energy security. Combined Cooling, Heat and Power (CCHP), also known as trigeneration, has a great potential to manage the ever increasing energy demand due to its ability to recover low-grade thermal energy resulting in higher energy efficiency, minimized primary energy consumption, reduced emission rate and lower operating cost. Trigeneration also offers a higher level of energy security by mitigating the reliance on centralized power grids. A large CCHP system consists of several boilers, turbine generators, chillers, pumps, fans, cooling towers and other auxiliary equipment to meet both the thermal and electrical demands. In order to fully realize the benefits of CCHP systems in terms of cost and performance, effective optimization and control strategy is required. It is very complex to effectively design optimal control strategies because of diverse characteristics and operational conditions of many different components, availability of resources, site operational changes, varying energy loads, environmental conditions and costs of fuel and electricity. This work presents an approach for optimizing the operation of the CCHP system using a detailed network energy flow model solved by genetic algorithm. The optimal energy dispatch algorithm provides operational signals associated with resource allocation that results in minimum operating cost while ensuring that the systems meet campus electricity, heating, and cooling demands. The tool is used along with the assumption of perfect forecasts to evaluate the benefits of optimal control for the Purdue's Wade CCHP plant as a function of different utility rate incentives. Preliminary results show cost savings potential of $2000 per day for optimal operation compared to the current operation strategy of Wade power plant.

Areas at Laboratories: Thermal Sciences
Key words: Optimization, CHP, CCHP, cogeneration, trigeneration

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

Research Assistants: Austin Nash, Ph.D. Student, Catherine Weaver, UG Researcher

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. Until methods of capturing and utilizing waste heat are further developed, an increase in the amount of energy needed to meet U.S. demand 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 in performance. 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. Through this research we aim 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) 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. 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. For the fuel cell, we utilize a low-order dynamic model of a proton exchange membrane (PEM) fuel cell. The result is a low-order, transient model of the complete system which can be used to study control and optimization of a small-scale waste heat recovery system.

Modeling and Design of Multi-Temperature Refrigerated Container System Using S-RAM Compressor in a Transcritical Carbon Dioxide Cycle

Research Assistant: Riley Barta, Ph.D. Student

Principal Investigator: Professor Eckhard A. Groll

Sponsor: S-RAM Dynamics, Inc. via U.S. Army SBIR

ABSTRACT

Transportation refrigeration requires robust, compact, and reliable technology, and these constraints must be met with especially rugged designs when used in a military application. Additionally, industry trends towards efficiency and environmental concerns have motivated the development of reduced global warming potential (GWP) refrigerants and efficient technologies to utilize them. This research focuses on the theoretical development and physical design of a mobile refrigeration container for the U.S. Army that utilizes the natural refrigerant carbon dioxide (CO_2) in a transcritical cycle and has two separate refrigeration compartments of variable size and operating temperature. The specific application is referred to as a multi-temperature refrigerated container system (MTRCS). The proposed system utilizes a novel compressor-expander unit called the Energy Recovery Compressor (ERC). The ERC is an axial multi-piston compressor-expander that uses the Sanderson Rocker Arm Motion (S-RAM) to convert the shaft rotation into linear piston movements. Integrating the ERC into novel refrigeration system architecture results in a coefficient of performance (COP) of 1.285 at an ambient air temperature of 57.2 °C. The research focuses on evaluating the system architecture and the analysis conducted to predict the system performance.

Keywords: HVAC&R, Natural refrigerants, Transcritical carbon dioxide cycle, Expansion work recovery, Transportation refrigeration, Military

Improvements to Unitary Heat Pump Systems

Research Assistants:	Riley Barta and Nicholas Salts, Ph.D. Students Florian Simon, Visiting Scholar
Principle Investigator:	Professor Eckhard A. Groll
Sponsors:	Regal Beloit Corporation

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. As such, solutions to increase overall cycle efficiency have been proposed to help meet these goals. This project evaluates and experimentally validates two such technologies.

The first technology 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 refrigerant 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 refrigerant by converting it into electrical energy that can be fed back into one of the system components, such as a fan or compressor motor. Future work will focus on maximizing the performance of this component and also validating models used to predict its performance.

The second technology is known as an inverter drive. The majority of residential heat pumps operated in the United States utilize fixed-speed compressors and fans. This situation presents an opportunity for future and existing fixed-speed units to be modified with variable-speed technology. The proposed inverter drive was developed by Regal Beloit Corporation and is designed to enable variable speed operation of traditionally fixed speed motors. The main focus of this research is to optimize the seasonal cooling performance of residential split-system single-speed heat pumps that have been modified with the previously mentioned inverter drive. The inverter drive has been tested for different heat pump systems. The seasonal performance of the heat pump systems has been optimized with respect to compressor speed, outdoor fan speed, and indoor airflow rate.

Future work will focus on continue testing the inverter drive and implementing it into new systems.

Vapor Compression Refrigeration System for Cold Storage on Spacecrafts

Research Assistant: Cai Rohleder, MSME Students

Principal Investigator: Professor Eckhard A. Groll

Sponsor: Air Squared, Inc. via NASA SBIR

Abstract

Manned missions in space are increasing in duration, causing the need for more enduring life support systems. As growing food aboard spacecrafts has proven difficult, an important aspect of life support is the long term cold storage of food. The use of a vapor compression cycle for refrigerated food storage is common practice on earth, but the benefits of this technology in space have scarcely been investigated due to the challenges associated with microgravity. As part of a NASA SBIR Phase I project, Air Squared Inc. and Purdue designed a vapor compression system for use in space that is energy efficient, lightweight, and requires little to no maintenance during operation. Below freezing temperature air is supplied to an insulated compartment to allow for freezing of food that is to be consumed later. To face the challenges associated with fluid flow in microgravity, appropriate flow pattern maps and heat transfer correlations have been considered in designing heat exchangers. In addition, passive components have been implemented in the design of the system. To assure availability in the future, and due to its favorable thermodynamic properties, R134a has been selected as the working fluid. The main components of the system are; a hermetic scroll compressor, in combination with a scroll expander to allow for power recovery, a fin and tube evaporator specifically designed for annular flow and a tube-in-tube condenser with twisted tape inserts to force liquid flow downstream. As the system is similar to those that are used on earth, enhancements made to the cycle to improve heat transfer, power recycling, or flow stability can also be used to improve the vapor compression systems on earth.

Chemical Looping for High Efficiency Heat Pumping

Research Assistant: Nelson James, Ph.D. Student

Principal Investigators: Professors James E. Braun and 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 achieve higher energy efficiencies than standard vapor compression technology. Multiple possible working fluids have been identified with isopropanol and acetone being 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. Preliminary data collected from the setup indicates that it is possible to drive the isopropanol-acetone reaction at the low voltages required for efficient CLHP operation. However, these reactions occur at very low rates. Current work is focused on examining various cell architectures and components to improve the rate of the desired reactions.

Testing of R245fa in a High-Temperature Waste Heat Recovery Organic Rankine Cycle (ORC) Utilizing a Scroll Expander

Research Assistants:	Alejandro Lavernia, MSME Student and Davide Ziviani, and Nigora Gafur, Visiting Scholars
Principal Investigator:	Professor Eckhard A. Groll

Sponsor:	Air Squared Inc. via ARPA-E SBIR

ABSTRACT

An organic Rankine cycle (ORC) test setup for applications in high-temperature waste-heat-recovery has been constructed. An experimental study of a subcritical ORC architecture working with a high temperature heat source is performed to evaluate the feasibility of employing an ORC to recover west heat from small-scale internal combustion engines (~10 kW). The market feasibility of all components including a prototype scroll expander, which contributes heavily to the cycle design, is considered. The cycle consists of a diaphragm pump, a plate heat exchanger as regenerator, a novel micro-tube evaporator, an air-cooled condenser, and scroll-type expander. Three expander prototypes of Oldham ring orbiting, idler shaft orbiting, and spinning scroll, are considered and evaluated for their performance within this ORC. Focus is given to constraining the high side temperatures of R245fa to minimize oil breakdown while decreasing exergy destruction. In this work, a performance comparison between R245fa for varying thermal inputs, expander types, and refrigerant superheating values is proposed.

KEYWORDS

Organic Rankine Cycle (ORC), Waste Heat Recovery, Scroll Expander, R245fa

Development of a General Purpose Simulation Tool for Postitive Displacement Compressors

Research Assistants: Xinye Zhang, Ph.D. Student and Davide Ziviani, Visiting Scholar

Principal Investigators: Professors James E. Braun, Eckhard A. Groll

Abstract

Detailed and comprehensive simulation models of hermetic, semi-hermetic and open-drive positive displacement compressors, including scroll, rotary, reciprocating, spool, Bowtie, Z-compressor, and 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. This project focuses on a new comprehensive positive displacement simulation platform based on the previous compressor modeling efforts to predict the performance of hermetic positive displacement compressors. The platform will include all of the main aspects of compressor modeling, such as the geometry (a library of multiple positive displacement compressor geometries is being 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 system of equations developed in this model describes a dynamic model of a positive displacement machine that needs to be integrated over time. Such formulation is general enough that can be applied to both mechanistic models of positive displacement machines that are crank-motion driven (e.g., reciprocating, rotary, etc.) as well as dynamic linear compressors, in which the stroke is determined by electro-mechanical forces.

The generic model platform has been validated using external compressor performance measurements, which are readily available from the previous testing efforts with various compressors and refrigerants using hot gas-bypass compressor load stands and a calorimeter. The ability of the PDSim modeling platform to accurately predict the performance of hermetic positive displacement compressors will be discussed in detail.

A System-Level Approach for Designing Multi-Family Sustainable Housing Communities

Research Assistants: Li Cheng, Ph.D. Student, Yeon Jin Bae, Post Doc

Principal Investigator: Professor W. Travis Horton

Sponsor: Center for High Performance Building

Abstract

This study is focused on a system-level assessment of various energy efficiency measures and energy delivery options that can be considered during the early stages of design and development of sustainable housing communities. The methodology presented in this paper is flexible and user-friendly, and can be implemented by both researchers and design practitioners. The overall goal of such a system-level process is to provide a quick and efficient approach for identifying various design trade-offs early in the design process, which leads to an acceptable final design.

The research team has utilized a sustainable housing community that is under development in Bloomington, IN, U.S. as the case study for this paper. Ten building variables that were deemed to have a significant influence on energy consumption and/or construction cost were considered for potential inclusion in the final design. During the process, a baseline building model was carefully defined according to applicable energy standards, available reference building models in the U.S., and community and developer preferences. All energy saving measures are considered relative to this baseline building model. The results of a sensitivity analysis show that advanced energy delivery options (such as geothermal heat pumps, energy recovery ventilators and heat pump water heaters) can significantly reduce the Energy Use Intensity (EUI) of the building as compared with adjustments to the envelope. In the final scenario, more than 45% of the annual baseline energy consumption is reduced from the initial design.

Areas at Laboratories: Thermal System and High Performance Buildings
Key words (4 or 5): Sustainable housing development system-level approach energy variable sensitivity

MPC Implementation of radiant floor cooling system in open space office environment

Research Assistant: Jaewan Joe

Principal Investigator: Professor Panagiota Karava

Sponsor: NSF

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 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. As a first step towards this realization, this research proposes a multi-agent framework for building systems where a shared HVAC source is used for comfort delivery in several zones or by multiple systems. The approach is demonstrated using a case-study for a radiant comfort delivery system with local control loops installed at the Living Lab at Herrick building. A grey-box inverse model is estimated and validated with the proposed agent-based approach. . Actual MPC implementations are carried out using Matlab environment via modbus communication with the existing building energy management system, Niagara. Centralized and distributed MPCs are conducted for zone and local radiant floor system control. The results show signbiffcant electricity consumption savings (up to 24%) due to the higher chiller COP and the temperature tracking.

Areas at Laboratories: Thermal (Architectural Engineering)
Key words (4 or 5): Model predictive control, Local radiant comfort system, System identification, Distributed optimization

Bayesian Classification and Inference of Occupant Visual Preferences in Private Offices of Perimeter Building Zones

Research Assistant: Seyed Amir Sadeghi, Ph.D.

Principal Investigators: Professors Panagiota Karava, Ilias Bilionis, and Athanasios Tzempelikos

Sponsors: CHPB, National Science Foundation

Abstract

The objective of this work is to understand the complex interactions related to visual environment control in private offices of perimeter building zones and to develop a new data-driven method for learning occupant visual preferences. The first step of our methodology includes field observations of occupants' perception and satisfaction with the visual environment along with data collection from room sensors, shading and electric light actuators. Consequently, in order to develop probability distributions for occupants' preference when exposed to variable daylight and electric lighting conditions, such as prefer darker, prefer brighter, satisfied with current conditions, we formulate a Bayesian classification and inference model using the Dirichlet process prior and multinomial logistic regression. Based on field observations, we encode within the model structure that occupants' visual preferences are influenced by a combination of observed environmental and control state variables describing the luminous environment, as well as latent human characteristics. The latter represent hidden random variables used to determine the optimal number of possible clusters of individuals with similar visual preference characteristics in the studied office building population. Finally, to learn the visual preference of new occupants in the dataset, we infer the cluster values and derive the personalized profiles using a mixture of the general probabilistic sub-models.

Areas at Laboratories: High Performance Buildings
Key words: Automatic Differentiation Variational Inference, Bayesian modeling, Classification, Inference, Personalized environments, Visual preference

Personalized Visual Satisfaction Profiles from Comparative Preferences Using Bayesian Inference

Research Assistants: Jie Xiong, MSME Student, and Seungjae Lee, Ph.D. Student

Principal Investigators: Professors Athanasios Tzempelikos and Panagiota Karava

Sponsors: National Science Foundation, CHPB

Abstract

This study presents the development of personalized models of occupant satisfaction with the visual environment in private perimeter offices. A set of experiments was designed and conducted to collect comparative preference data from four human test-subjects. A probit model structure, with assumed latent satisfaction utility model in the form of multivariate Gaussian function, was adopted for developing the preference model. Four distinctive satisfaction and preference models were trained with a Sequential Monte Carlo (SMC) Bayesian approach using experimental data. The posterior estimations of model parameters, visual preference probabilities and inferred satisfaction utility functions were investigated and compared, with results reflecting the different characteristics of the subjects. The developed visual satisfaction utility function was designed for use in personalized control, where occupants could balance their own satisfaction expectation and energy considerations.

Key words: Visual satisfaction, preference, personalized control, Bayesian inference

Low-Cost Sensing Network for Indoor Environmental Monitoring and Control in Buildings

Research Assistants: Michael Kim, Ph.D. Student and Iason Konstantzos, Post Doc.

Principal Investigator: Professor Thanos Tzempelikos

Sponsor: Center for High Performance Buildings

Abstract

Conventional sensor networks in buildings are expensive and often fail to monitor local environmental parameters. New types of low-cost sensors have the potential to replace existing sensor networks in buildings, which have high-cost and low flexibility. The objective of this work is to (i) investigate the reliability, accuracy, robustness and communication capabilities of low cost sensor networks and (ii) develop and implement an overall framework of monitoring and control of indoor environmental conditions (temperature, relative humidity, light levels, occupancy, luminance, etc.), embedded in existing control infrastructures or using new system typologies. Different low-cost temperature and humidity sensors, wired and wireless, are being tested and compared against calibrated ones, with promising results. The sensors can communicate with Raspberry Pi and with the building monitoring and control system, providing flexibility in monitoring (local sensing), processing (model-based) and communication (networking) with other devices. Low-cost and local sensing may provide higher comfort to occupants while reducing system costs and energy use for air-conditioning and lighting.

Areas at Laboratories: High Performance Buildings
Key words: Low-cost sensing, Wireless sensor networks (WSN), Raspberry Pi

A Mathematical Framework for Increasing Trust in Human Machine Interactions

Research Assistant: Kumar Akash, Ph.D. Student

Principal Investigators: Professors Neera Jain, and Tahira Reid

Sponsor: National Science Foundation

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 can 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 to allow machines to sense the trust level of the humans that they are interacting with. We have identified an adaptive classifier-based model of trust that relies on real-time psychophysiological measurements including galvanic skin response (GSR) and electroencephalography (EEG) along with behavioral responses. 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 modeling human trust variations to changes in specific machine UI features. We propose to conduct human subject studies to characterize how variations in transparency and shared control authority 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.

Keywords: human-machine interactions, supervised machine learning, psychophysiological measurements, brain-computer interfaces, control systems

Inference of Thermal Preference Profiles for Personalized Thermal Environments

Research Assistant: Seungjae Lee, Ph. D. Student

Principal Investigators: Professors, Panagiota Karava, Athanasios Tzempelikos, Ilias Bilionis

Sponsors: CHPB, National Science Foundation

Abstract

The objective of this work is to develop smart environmental control systems for office buildings that incorporate human thermal preferences. Towards this goal, in this poster, we present a new method for learning individual occupants' thermal preferences, using sensor data for indoor environment variables, and occupant feedback expressed through their preference votes.

To enable efficient and effective learning, we develop a generalized thermal preference model in which our main hypothesis, “Different people prefer different thermal conditions”, is explicitly encoded. Using data from a large population collected in different air-conditioned buildings in North America, the generalized model is trained with Bayesian approach. The model discovers clusters of people with similar preference characteristic, and develops sub-models for the clusters. The thermal preference profiles, i.e., personalized models, of new occupants are inferred from data by using a mixture of the general sub-model for each cluster. In the inference stage, we introduce additional model components to deal with variables difficult to measure in real buildings. To test the feasibility of our method, we designed a field study that was conducted in private offices on the first floor of Herrick building. The models developed based on our method show better prediction performance compared to existing approaches. In addition, the result show that the proposed method develops reliable models with relatively less data enabling faster learning, even though it considers more input variables.

Areas at Laboratories: Thermal Systems and High Performance Buildings
Key words: Personalized environments, Thermal preference, Learning Personalized Preference Profiles, Clustering, Bayesian inference

A Stochastic Model Predictive Control Framework for Building Operation with Solar System under Weather Uncertainty

Research Assistants: Xiaoqi Liu and Nimish Awalgaonkar, Ph.D. Students
Parth Paritosh, MSME Student

Principal Investigators: Professors Panagiota Karava and Ilias Bilionis

Sponsors: ASHRAE

Abstract

This study presents a general stochastic model predictive control (SMPC) framework for advanced building energy system applications. To optimally operate such complex systems aimed at minimizing net-energy consumption, while maintaining indoor thermal comfort, it often requires solving nonconvex optimization problems with stochastic environmental and occupant disturbances. Approximate dynamic programming (ADP) with value iteration algorithm can solve nonconvex stochastic optimization problems and find the global minima with affordable computational cost. To model an important stochastic disturbance source for renewable energy systems, namely, solar irradiance, we have developed a novel time-series forecast model that is able to quantify the uncertainty of solar irradiance predictions. An open plan office space is used as test-bed. The energy system includes a building-integrated photovoltaic-thermal (BIPV/T) system that is a source for an air-to-water heat pump, connected to a TES tank providing hot water to a radiant floor heating (RFH). An emulator built in TRNSYS representing the actual system incorporates the SMPC controller developed in Python. The results show that the SMPC controller saves up to 44% of the electricity consumption and reduces 75% comfort violations in the monthly simulation compared to a well-tuned rule-based controller (RBC).

Areas at Laboratories: High Performance Buildings
Key words (4 or 5): model predictive control, dynamic programming, uncertainty quantification, building-integrated solar systems

An Online Interactive Tool to Assess Visual Environment in Offices with Roller Shades

Research Assistants: Iason Konstantzos, Post Doc and Michael Kim, Ph.D. Student

Principal Investigator: Professor Thanos Tzempelikos

Sponsor: Lutron Electronics Co Inc.

Abstract

Visual Comfort, Lighting Energy Performance and Connection to the Outside are the three main factors of the visual environment in buildings. This work presents a synthesis of the most recent metrics (visual comfort autonomy, lighting energy use and view clarity) for assessing the visual environment performance of spaces with window shades, in the form of an interactive web-based tool. The tool has a user-friendly interface and either provides recommendations for selecting shade properties (based on the variation of the three visual performance metrics), or compares different configurations with detailed output information. The tool, currently available to the public, considers different locations, orientations, glazing properties and seating layouts and provides a straightforward and fast way to obtain preliminary information about the comfort, energy and view clarity performance of office designs will roller shades, without the need of high expertise or time-consuming simulations.

Areas at Laboratories: High Performance Buildings
Key words: Visual environment, window shades, daylighting, visual comfort, lighting energy use

Nandi Clean Kitchen Study: Mitigating Indoor Air Pollution in Kitchens in Western Kenya by Optimizing Passive Ventilation

Research Assistant: Danielle N. Wagner, MSEEE Student and Samuel R. Odhiambo, Moi University, Kenya

Principal Investigators: Professors: Brandon E. Boor and David K. Lagat (Moi University)

Sponsors: Purdue I^{2}D Lab, AMPATH Kenya

Abstract

Lacking access to electricity, 3 billion people across the world use biomass as a fuel for cooking and heating; and respirable contents of the resulting wood smoke often cause preventable health problems. This study is motivated by the goals of a healthcare organization, AMPATH, to design modified kitchens exhibiting reduced indoor air pollution (IAP) for rural women and children in Nandi County, Kenya. Measurements were taken in 3 modified and 6 traditional kitchens, in January and July of 2017. CO, CO_2, and fine and ultrafine particle number concentrations (10 nm to 2.5 μm) were passively sampled at breathing zone height for 3 days, using Pegasor Indoor Air Quality and carbon monoxide sensors. Pressure differentials and flow rates through façade airflow pathways and chimneys were manually logged for 15 minutes. Mass-balance modeling will be used to develop metrics to evaluate the efficacy of the kitchen design modifications to increase ventilation performance and reduce wood smoke exposure. Notable information was collected through daily conversations with women in each kitchen to parallel quantitative data. Preliminary results demonstrate that modified kitchens that preserve cultural features have the ability to reduce exposure to IAP as much as 80%. A parallel study carried out by the EPICS Global Air Quality Trekkers team is focused on replicating a Nandi kitchen at Purdue University to enable in-depth physicochemical characterization of field-like conditions. The most recently built kitchen will be used as a demonstration for community members to encourage scale-up.

Areas at Laboratory: Building Physics

Keywords: Kenya, wood smoke, indoor air quality, particulate matter, UFP

Urban Aerosol Size Distributions and Physiochemical Properties: Implications for HVAC Filtration

Research Assistant: Tianren Wu, Ph.D. Student

Principal Investigator: Professor Brandon Boor

Sponsor: ASHRAE

Abstract

HVAC filters help prevent fouling of cooling and heating coils in air handling units (AHUs), improve the quality of air that is delivered into the occupied indoor environment, and help to reduce human exposure to particulate matter (aerosols) of outdoor origin. However, the deposition and accumulation of aerosols within the HVAC filter fiber matrix reduces the porosity of the filters and causes a dramatic increase in airflow resistance and associated pressure drop. HVAC filters can contribute 25% to 75% of the overall resistance in the majority of AHUs and therefore, play an important role in determining the fan power draw required to overcome this resistance. In order to investigate the effect of outdoor aerosols on the filtration efficiency and pressure drop of commercial HVAC filters, we conducted a broad literature search on urban aerosol size distributions and physiochemical properties. Over 300 urban aerosol size distributions in 68 different cities in 27 countries in Europe, North America, South America, and Asia-Pacific have been extracted from the literature and analyzed. Statistical analyses have been conducted to obtain a representative, or characteristic, urban aerosol size distribution. The normalized median size distribution presents a relative broad profile with a peak diameter at around 45 nm. Aerosols larger than 100 nm contribute significantly to the mass loading of filters. The chemical composition, morphology, hygroscopicity, and phase state of urban aerosols were also summarized from previous studies. The results will guide our evaluation on the impact of the characteristics of urban aerosols on filtration mechanisms and filter loading kinetics through use of a synthetic urban aerosol in full-scale experiments.

Areas at Laboratories: Building Physics

Key words: HVAC filtration, energy consumption, filtration efficiency, urban aerosol

Early Childhood Exposure to Resuspended Biological Particulate Matter

Research Assistant: Tianren Wu, Ph.D. Student

Principal Investigator: Professor Brandon Boor

Abstract

Human-induced resuspension of settled dust is a dynamic process that can serve as a major indoor source of biological particulate matter (bioPM). Inhalation exposure to the microbial and allergenic content of indoor dust is associated with adverse and protective health effects. We have a limited understanding of the relationship between particle resuspension induced by different early-childhood forms of locomotion, such as crawling and walking, with the transient exposures of bioPM that are received by infants and children. In this study, concentrations and size distributions of airborne bioPM in a childcare facility classroom were characterized with a Wideband Integrated Bioaerosol Sensor (WIBS-NEO, Droplet Measurement Technology Inc.). It is based on laser-induced fluorescence (LIF) techniques, which allows us to investigate the bioPM individually and in real-time. During the measurement period, the children (2.5-4.5 years old) were asked to wear Actigraph Watches, which can record their activity intensity in real-time. By linking the bioPM concentration at their breathing zone height with their activity data, we investigated the relationship of their exposure to bioPM with different activity patterns. Our preliminary data indicates that the concentration of bioPM that the children are exposed to changes with different activities, such as napping, snacking, and free play. The bioPM concentration in the classroom is positively correlated to the activity intensity of children. bioPM size distributions exhibit a dominant diameter at around 3 μm, indicative of agglomerated bacterial cells and fungal spores.

Areas at Laboratories: Building Physics

Key words: Biological particulate matter, early-childhood exposure, indoor air quality, laser-induced fluorescence

Purdue AirSense: An Open-Source Air Quality Monitoring System

Research Assistants: Sungwoo Kim, MSCE Student, Briana McDaniel and Ruihang Du, Undergrad Students, Ray Samuel, Visiting Scholar

Principal Investigators: Professors Brandon Boor, Greg Michalski

Abstract

Since the passing of the Air Pollution Control Act in 1955 and the Clean Air Act of 1963, ambient air pollutants have received increasing attention. These pollutants are not only a concern for the planet, but have potential human health effects as well. Current monitoring of these pollutants usually happens on a large scale, such as GHG emissions for a whole city. The potential downsides to this are that this data is not localized, making it not very useful to the common citizen and the data is only providing the big picture, not the individual pieces. In recent years, as a means to address some of the issues listed above, researchers have introduced several unconventional methods of measurements. However, little concentration and size distribution data are publicly accessible through an online platform, despite the large quantity of research in this area. In order to address this issue, we designed and implemented an innovative low-cost mobilized sensor system that measures the concentration of ozone, CO, NOx, and particulate matter (PM) using commercial air quality sensors. Alongside the sensor system, a monitoring station for gas pollutants, PM, and ultrafine particles (UFP) was set up for both measuring and calibration purposes. A size distribution of particles was then produced from the measurements and integrated into a web platform, which presents the visualized data to the public for educational use. Furthermore, additional data will be collected using Raspberry Pi. This will allow for higher spatial variability and thus allow us to gain a better understanding of air quality on a localized scale. The current sensor system showed a moderately strong agreement with the high-precision instrument for each pollutant. The result implies the possibility of constructing a robust, finer resolution open-source monitoring network, and the size distribution will be valuable for estimating the respiratory effects associated with aerosol particles.

Areas at Laboratories:
Key words (4 or 5): Ambient Air Quality Monitoring, Data Integration Platform, Data Visualization, Low-cost Sensing

Thermally Integrated Residential Appliances (TIRA)

Research Assistant: Stephen L. Caskey, Ph.D. Student

Principal Investigator: Professor Eckhard A. Groll

Sponsors: Whirlpool Corporation

Abstract

With the United States as the world's second largest consumer of primary energy, research in areas of significant US consumption can create large impacts on global energy consumptions. Buildings account for 41% of US total energy consumption with a majority being from the residential sector. More specifically, household appliances consume the second largest percentage of site energy at 27%, after the HVAC system. Various opportunities exist to improve appliance efficiencies within their individual spaces but none have been explored that attempt to connect all appliances to the home through sharing thermal resources. Significant reductions can be realized by considering approaches that utilize resources outside any one individual appliance. For example, the refrigerator rejects heat to a centralized medium when cooling food while the dishwasher extracts heat during its wash and rinse steps to offset its inefficient electric heater. Some preliminary results focused only on waste heat recovery predicts about 2,000 kWh per year of domestic hot water energy can be saved by capturing waste heat from five major appliances; clothes dryer and washer, refrigerator, dishwasher, and cooking oven. To better predict the interactions between each appliance and a central thermal storage, Modelica models are created for 4 out of the 5 major appliances, excluding the cooking oven. Each appliance model is run independently and verified with experimental data from the manufacturer. Validated appliance models are combined to predict an overall energy savings and then validated against a benchtop prototype for verification. Upon suitable agreement and obtaining a desired savings level, additional simulations can comfortably explore the impact associated with different appliance/storage configurations or usage schedule/frequency. An ideal system for a retired couple in a condo requires a different layout and generates fewer savings versus one in an apartment for a family of four. A comprehensive, validated model can achieve these predictions.

Areas at Laboratories: Thermal Systems
Key words (4 or 5): Residential Appliances, Waste Heat Recovery, Modelica Modeling

The DC Micro-Grid House: Converting an Existing Home to DC Power to Improve Energy Efficiency

Research Assistant: Nicholas Salts, Ph.D. Student

Principal Investigator: Professor Eckhard A. Groll

Sponsor: Center for High Performance Buildings (CHPB)

Abstract

Advances in high voltage DC transmission lines and a national interest in the future of the electrical grid in the United States have prompted a discussion of the increased use of DC electricity in residential homes and commercial buildings alike. A number of studies have indicated that a DC powered home could lead to significant energy savings compared to the AC home of today. This is due to the high number of DC loads and subsequent losses from power conversion when these loads are supplied with AC power. A DC powered home also lends itself to the use of renewable energy sources that generate DC power, such as solar photovoltaics. The goal of this project is to demonstrate the energy savings and other benefits which result from converting an existing AC powered home to a DC powered home. The project is collaborative in nature and involves working closely with several industry partners to develop DC powered solutions for all systems used in the residential home. The project will measure how specific technologies, such as appliances and HVAC systems, perform when designed to run directly on DC power. It is the goal of this project to compare the performance of the new DC appliances to their modern AC counterparts. It is also the goal of this project to consider the home as a whole, and how the use of new DC appliances reduces the energy consumption of the entire home. Additionally within the scope of the DC Micro-Grid House are research and collaboration in the areas of onsite energy generation and storage, DC power distribution, advanced power conversion techniques, and smart control strategies.

Optimizing Residential Air-Conditioning Equipment for Demand Responsiveness, Energy Efficiency, and Environmental Impact

Research Assistants: Aaron Tam, MSME Student and Davide Ziviani, Visiting Scholar

Principal Investigators: Professor Neera Jain and James Braun

Sponsor: Center of High Performance Buildings

Abstract

In recent years, variable electricity pricing has become available to residential consumers to encourage a shift in load demand away from the traditional peak hours of midday. This is especially important in hot climates where air-conditioning (A/C) use is the primary cause for peak electricity demand. In order to take full advantage of variable pricing, consumers need the ability to store "cooling" when demand is low so as to minimize operation of the A/C during peak pricing periods. Storage could be in the form of ice or a phase change material, and/or the controller could take advantage of existing storage within the building structural mass. However, the use of ice storage for demand response can lead to reduced energy efficiency which conflicts with recent trends toward more efficient equipment. In addition, there is a need to move towards equipment that utilizes more environmentally friendly working fluids such as natural refrigerants. However, natural refrigerants for air conditioning typically are flammable (propane), toxic (ammonia), or have challenges associated with achieving competitive performance (carbon dioxide). This project will investigate innovative integrated and packaged solutions for residential cooling that (1) employ natural refrigerants and (2) could provide demand responsiveness with high efficiency, and at competitive costs, for both retrofits and new construction. A model of the proposed system is used to calculate the system performance and operating cost over a cooling season under different sample utility rates. Preliminary simulation results show that the proposed system offers operating cost savings under TOU utility rates. Moreover, modifications to the general control strategy under specific utility rates can further increase savings and system efficiency.

Areas at Laboratories: Thermal Systems Research Area

Key words (4 or 5): Thermal storage, secondary loop, residential cooling system, demand response using heuristic controls

AgBug: Autonomous Mobile Robot for Agriculture Crop Monitoring and Precision Agriculture

Research Assistants: Che Kun Law, MSME Student, Tianqi Ye and Ze An, Undergrad Students

Principal Investigator: Professor David J. Cappelleri

Abstract

Food production must increase dramatically due to a growing world population. Autonomous agriculture mobile robots have a vital role to play in improving farm productivity through automated crop yield estimation and monitoring of the health of crops in the field. Current manual yield estimation is labor–intensive, time–consuming, and inaccurate. Automation through robotics can make this process much more efficient. We propose AgBug as an autonomous mobile ground robot for crop monitoring which is low–cost, modular, and suitable for off–road terrain. This allows it to be economically feasible for adoption by farmers and customizable to fit their unique farm configurations. The AgBug will be able to autonomously navigate through the crops in the field and record information critical to the health of crops such as soil moisture level. This will enable the farmer to have automated monitoring of the health of the crops in the field and help improve farm productivity. We envision future improvements to the AgBug system to include heterogenous multi–robot coordination involving air and ground robots to leverage the complementary strengths of both types of platforms in the context of crop monitoring and precision agriculture. Such heterogeneous robot teams can function as an adaptable mobile sensor network to monitor crops as opposed to planting fixed sensors in the field, enabling the sensor network to be reconfigured on demand.

Interacting-BoomCopter UAV Design for Aerial Manipulation

Research Assistants: Daniel McArthur and Arindam Chowdhury, Ph. D. Students

Principal Investigator: Professor David J. Cappelleri

Sponsor: NSF

Abstract

Unmanned aerial vehicles (UAVs), when paired with an onboard camera, have proven to be useful tools in many applications, including surveillance, inspection, precision farming, and search and rescue operations. However, due to onboard computation and battery life limitations and complex flight dynamics, using UAVs to physically interact with the environment (e.g. to move objects or debris) is still a developing area of research. Considering these limitations, we aim to enable UAVs to help people perform dangerous and/or time-consuming tasks more safely and efficiently than they could on their own. Our present work is focused on the design and control of the Interacting-BoomCopter (I-BC), a novel UAV that can interact intelligently with the environment. With flexibility and efficiency in mind, we built the I-BC on a tricopter frame with an added forward-facing propeller and modular end-effectors (e.g., a hook or probe) that can apply horizontal forces (push and pull) while the I-BC remains in a stable hovering configuration. Force and distance sensors integrated into the end-effectors, and an onboard webcam and computer allow the I-BC to perform various aerial manipulation tasks such as mounting sensors in hard-to-reach places and opening small doors or panels. We have demonstrated through several successful tests that the I-BC can be teleoperated to open an electrical enclosure door on the ground, and remotely mount a sensor on a wall. In addition, we have shown that the I-BC can perform the sensor mounting task autonomously using custom flight control software developed in our lab. The I-BC's innovative approach to performing aerial manipulation tasks shows promise in areas such as infrastructure maintenance and inspection, and disaster relief operations.

Packaging Solutions: From Predictive Modeling Tools to Multi-Axis Vibration

Research Assistant: Amin Joodaky, Ph.D. Student

Principal Investigator: Professor J. M. Gibert

Sponsor: Purdue Research Foundation

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 two trends: 1) the demand for environmentally sustainable packaging, and 2) the need to reduce losses in product distribution. The work of the lab is concentrated in the two 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, and **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. In the area of shock, our focus is the development of closed forms solutions to the shock pulse in terms of material properties and geometry of known packaged foams, and to design novel negative stiffness elements from packaging materials to mimic the absorption characteristics of foam. The mulit-axis vibration work is motivated by the maturing the global economy matures causing the distribution and manufacturing of products to become increasingly decentralized, the importance of product packaging and distribution becomes paramount for continued economic growth. Concurrently, the packaging industry is coping with financial and environmental constraints. The importance of laboratory simulation of transport has become increasingly important as highlighted by the International Safe Transit Association (ISTA) testing procedures. There is a growing realization in the research community that vertical vibration is limited in its correlation to package durability

Understanding the Multiscale Behavior of Triboelectric Devices

Research Assistants: Hongcheng Tao and Amin Joodaky, Ph.D. Students and Sean Gauntt, Undergrad Student

Principal Investigator: Professor James Gibert

Sponsor: NSF

Abstract

Triboelectricity, which is the electricity generated due to contact of materials, has attracted continuous research interest throughout history. In recent years the emergence of triboelectric nanogenerators (TENGs) has revealed the significant potential of triboelectricity to be employed in energy harvesting. However, despite the long-established triboelectric series where materials are ranked by their tendency to acquire positive/negative charges, the fundamental mechanism of contact electrification remains under debate, especially for that among insulating materials such as polymers. The ongoing project aims at understanding such mechanism in multiscale. In microscale, controlled contact electrification tests with selected combinations of electret materials are compared to existing theoretical models of electron, ion, and material transfer to reveal the basic physics of charge transfer and hence to construct a quantitative triboelectric series. In mesoscale, charge transfer is measured under various surface configurations as well as environmental conditions such as humidity and temperature to quantify their impacts on the efficiency of triboelectric devices. In macroscale, dynamic models are established based on macroscopic electric field theories. The multiscale results are to be synthesized to predict the general response of triboelectric generators. In the preliminary work, a basic dynamic model has been derived using Lagrange's equation for a triboelectric generator in contact mode, assuming homogeneous surface charge distribution. Simulations of the model have been compared with the performance of lab-built paper and polymer base triboelectric generators. The complete outcome of the project should provide theoretical support for future improvements in triboelectric devices as well as for the concept of triboelectric foam composite to be utilized in smart packaging for concurrent energy scavenging and vibration suppression.

Areas at Laboratories: Vibrations & Dynamics
Key words: Triboelectricity, energy harvesting, nanogenerator, contact electrification

Nonlinear Dynamics in Metamaterials from Bistable Unit Cells: Application to Energy Harvesting

Research Assistant: Myungwon Hwang, Ph.D. Student

Principal Investigator: Professor Andres F. Arrieta

Abstract

A bistable element features two stable states, and its negative effective stiffness arising from snap-through nonlinearity has offered many interesting engineering applications. Recently, one-dimensional lattices formed by bistable elements with magnetic inter-element force have shown to support classes of solitary waves, which are highly localized nondispersive waves, retaining their forms over a long period of time. Inevitable existence of damping in actual physical systems eventually stops the propagation of the wave. In this bistable lattice, however, the dissipated energy is compensated by the stored energy from asymmetry in on-site strain energy potential, enabling unidirectional propagation of transition waves. We observe numerically and experimentally a unique input-independent behavior when a transition wave is generated, which suggests possibility for a broadband energy harvesting solution. We integrate power conversion mechanisms into the lattice, rendering the energy harvesting an intrinsic meta-material property. With the introduction of defects, we further generate a spatially localized, large oscillatory motion (breather-like mode) while retaining directional propagation of transition wave, which may serve dual purpose of efficient harvesting of energy and highly directional wave guiding. The potential of the lattice as an energy harvester has been investigated and compared through different performance measures under various kinds of excitations.

Areas at Laboratories: Vibrations & Dynamics
Key words (4 or 5): Nonlinear Dynamics, Energy Harvesting, Soliton, Breather

Additive Manufacturing of a Bi-stable Morphing Wing Demonstrator

Research Assistant: David Boston, MSME Student

Principal Investigator: Professor Andres F. Arrieta

Sponsor: Airforce Research Laboratory

Abstract

Morphing wing concepts provide significant potential for increasing the efficiency of aircraft. They allow for tailoring an airfoil's geometry to achieve the optimal aerodynamic performance of the wing at each point of the aircraft's mission. However, despite the potential of the technology, morphing wings see little use in practice, being either relegated to small scale unmanned vehicles, or requiring complex, difficult to maintain mechanisms that counteract any gains in efficiency by their added weight. This investigation builds upon previous research by the investigator presenting a novel morphing wing concept. This concept utilizes bi-stability in an airfoil rib with distributed compliance. Specifically chosen structural members are designed with two stable states presenting significantly different stiffness. By triggering one of the member's states, the structure is made selectively flexible or rigid. This bi-stability is traditionally accomplished using prestressed composites. However, composites face manufacturing limitations such as allowable thermal mismatch and fiber direction when trying to create a monolithic design. Additive manufacturing allows for a variety of complex shapes that are impractical or impossible to produce using other techniques. The goal of this research is to design and produce a similar morphing structure using additive manufacturing techniques. A bi-stable structural element is first designed utilizing geometric instability rather than prestress. A variety of materials available in this technique, including PLA, ABS, and fiber-reinforced Nylon, have been investigated for their ability to produce a geometrically bi-stable element. The element is then embedded in the structure and analyzed to ensure it maintains its bi-stability. The rib is then produced using fused deposition modeling.

Areas at Laboratory: Vibrations & Dynamics

Key Words: Morhping Wings, Bi-stability, 3D-Printing, Finite Element Modelling

Attaining and sustaining high-energy orbits of bi-stable energy harvesters

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West Lafayette, Indiana 47907, USA.

Abstract

Nonlinear multi-stable structural systems provide a unique potential for ambient vibration energy harvesting however; difficulties in attaining and sustaining high-energy inter-well oscillations restrict their applicability in practical scenarios. Most previous studies have focused on investigating strategies based on imparting external disturbance impulses designed to destabilize the intra-well solution branches as a route to achieve high-energy inter-well oscillations in multi-stable vibration energy harvesters. However, the careful selection of the disturbance signal parameters exploiting the pre-existing system dynamics leading to an energy efficient switch to the desired high-energy oscillations has not received adequate consideration. In this investigation we propose an actuation methodology employing external disturbance signals to switch the state of bi-stable harvesters from the low-energy intra-well configuration to the coexisting high-energy inter-well configuration without affecting the stability of the pre-existing dynamical states. The disturbance signals are designed to induce perturbations in the phase space of the forcing signal to manipulate the system's basins of attraction to transition to the desired limit cycle oscillations while leaving the amplitude and frequency of forcing input unaltered. Following numerical analysis of the proposed strategy, we present power budget calculations based on experimental data indicating that the energy spent in imposing an external perturbation to the system is swiftly recovered by the additional harvested energy, thus confirming the feasibility of the proposed approach. The presented experimental results warrant the practical use of the proposed strategy with the widely used low-strain piezoelectric transducers.

Smart Morphing Wing: Optimization of Distributed Piezoelectric Actuation

Research Assistant: Ashwin Clement Henry

Principal Investigator: Dr. Andres F. Arrieta

Sponsor: Air Force Office of Scientific Research (AFOSR)

Abstract

This research presents an investigation of the optimal structural parameters of distributed piezoelectric actuators on a compliant morphing wing for maximizing the performance, measured in terms of rolling moment and dive speed, under aeroelastic loads. A previous design obtained following a multi-disciplinary optimization technique, yielding the ideal structural and geometrical parameters maximizing roll controllability, is utilized as the baseline individual. The global design of the morphing, however, did not optimize explicitly, the size of the distributed piezoelectric actuators and thickness of the underlying skin. This investigation therefore focuses on further extending the design space by perturbing the original optimal individual and conducting a multi-disciplinary, multi-objective optimization for the ideal actuator width and thickness distribution between the piezoelectric actuators and the substrate morphing skin. The goal is to maximize the obtained rolling moment and achievable dive speed, while minimizing the mass. The rolling moment is estimated by implementing a concurrent aero-structural loop in which the servo-aero-elastic behavior is evaluated until convergence is reached. The dynamic aeroelastic stability of the wing is assessed for predicting the maximum feasible dive speed. The results show that the performance of the baseline design can be significantly improved by simply optimizing the width and thickness distribution of the bi-morph piezoelectric actuators. The maximum increase in rolling moment achieved by altering the geometrical parameters is 27.67% along with a 4.31% mass penalty. When constraining the mass, a potential increase of 25.17% is still possible. The rolling moment behavior is linear with respect to actuator width and cubical with thickness parameters, analogous to the deflection behavior of the cantilevered bi-morph actuator. The flight can be made considerably faster, while maintaining sufficient roll authority, maximum potential increase of dive speed is 83.4%. The two objectives, rolling moment and dive speed compete each other, on account of opposing stiffness requirements. The results suggest that to realize further performance enhancement without substantial mass penalty, the multi-functionality of the actuators should be exploited, thereby effectively substituting the skin material.

Areas at Laboratories: Vibrations & Dynamics

Keywords: Multidisciplinary Design Optimization, Finite element analysis, Aeroelasticity

Multistable Shape Programmable Shells from 3D Printed Induced Pre-Stress

Research Assistants: Katherine S. Riley, MSME Student and Karl Jin Ang, Undergrad Student

Principal Investigator: Professor Andres F. Arrieta

Abstract

Naturally occurring bilayer composites, such as those found in pinecones and ice plant varieties, have developed specialized material architectures in order to achieve advantageous shape changes in response to external stimuli [1, 2]. We draw on this bio-inspiration to design and manufacture bilayer shells with carefully designed, spatially distributed architectures using fused deposition modeling (FDM) 3D printing. Distributed pre-stress is generated by controlling the printer settings and the path of the filament throughout the shell on each layer. The pre-stress caused by stretching the filament during deposition produces fast, programmed deformations when the part is heated to its glass temperature [3]. Multistability is obtained directly from printing by carefully designing the generated pre-stress, thus producing a fast and elastically reversible reconfiguration mechanism arising from manufacturing. By combining the fast morphing resulting from opposing pre-stresses with the geometric freedom of 3D printing, we present a novel approach to achieving bio-inspired architectures in synthetic, shape programmable structures.

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[3] T. van Manen, S. Janbaz, and A. A. Zadpoor, "Programming 2D/3D shape-shifting with hobbyist 3D printers," *Mater. Horiz.*, no. June, 2017.

Areas at Laboratories: Solid Mechanics, Advanced Materials and Manufacturing
Key words (4 or 5): bio-inspiration, multifunctional structures, 3D printing, programmable materials, multistability

Electronic Feedback-Enabled Microresonators With Intentional Nonlinearities

Research Assistant: Nikhil Bajaj, Post Doc

Principal Investigators: Professors George T.-C. Chiu and Jeffrey F. Rhoads

Sponsors: ALERT (A Department of Homeland Security Center of Excellence)
(National Science Foundation)

Abstract

Bifurcation-based sensing uses aspects of nonlinear behavior (such as amplitude jumps between bistable dynamic states) in MEMS/NEMS devices to improve the performance of devices such as gas sensors, and enable device new functionality (such as threshold detection). Prior work related to the implementation of nonlinear feedback in MEMS/NEMS devices has largely focused on the mitigation of nonlinear behavior, improving linear mode performance, and widening operating regions. In addition, the majority of such efforts have been performed either only in simulation or using relatively low-frequency, macro-scale analogs of MEMS devices. Some of this prior work has incorporated nonlinear feedback for the purpose of creating bistable systems for bifurcation-based sensing, but these systems operate in the kHz frequency range, which is too low of bandwidth for many practical sensing tasks. A major differentiating factor between kHz and MHz operation is that time delays in electronic circuits become significant. It can be shown that as the time delay in the nonlinear feedback loop is increased, the difference between the jump frequencies in the response decreases, until there is no jump (indicating that no bifurcation behavior is present). While it is important to minimize the time delay to retain the jump feature critical for bifurcation-based sensing, it is difficult to completely remove the time delay, and it remains valuable to consider it present for the purposes of design. This works presents an alternative feedback circuit architecture for intentional nonlinearity that, inspired by piecewise-linear resonators, uses a diode-based circuit to create desirable bifurcation behavior. The impacts of this work are the demonstration of a successful implementation of nonlinear feedback in the MHz frequency range to produce a system appropriate for further applications, along with analytical modeling for design purposes, taking into account time delay and a polynomial-based model of the nonlinear feedback subsystem.

Areas at Laboratories: Vibrations & Dynamics, Noise and Vibration Control, Electromechanical Systems, Environmental Sensing

SecureMEMS: Microscale Nanothermite Deposition

Research Assistants: Allison K. Murray and Trevor Fleck, Ph.D. Students and Whitney A. Novotny, MSME

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

Sponsor: 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; the effect of geometric parameters on reaction propagation speed was investigated. A dual nozzle system which separates ink constituents and allows for *in situ* mixing of the deposited inks was developed. 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: Integration of Nanothermite with Electronics

Research Assistants: Miranda P. McConnell, MSME Student, Whitney A. Novotny, MSME, Allison Murray, Ph.D. Student

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

Sponsor: School of Mechanical Engineering, Purdue University

Abstract

This work demonstrates the ability to print initiators integrated with a nano-energetic material. Metallic initiators were printed on a mesoporous substrate using a piezoelectrically actuated nozzle without thermal curing. The effects of excitation voltages ranging from 7.5 V to 13.75 V on bridge wire failure were investigated using bridge wires 1 mm in length. These bridge wires successfully ignited nano-aluminum and nano-bismuth (III) oxide mixed at stoichiometric values in dimethylformamide (DMF) using a resonant mixer. After proving the feasibility of inkjet printed metallic initiators, the work shifted to printing organic initiators. Conductive polymer ink was printed on the same mesoporous substrate as the metallic initiators with another piezoelectrically actuated nozzle. Thermal curing was shown to increase the conductivity of the inks and initial testing has proven them capable of successfully igniting a thermite sample. Future work includes the integration of nano-energetic material directly with the conductive polymer ink in both spark gap and bridgewire initiator geometries.

Additive Manufacturing of Reactive Materials using Fused Deposition Modeling

Research Assistants: Trevor J. Fleck and Allison K. Murray, Ph.D. Students

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

Sponsor: Purdue University

Abstract

This paper demonstrates the ability to 3D print a fluoropolymer based energetic material which could be used as a multifunctional reactive structure. The work presented lays the technical foundation for the 3D printing of reactive materials using fusion based material extrusion. A reactive filament comprising of a polyvinylidene fluoride (PVDF) binder with 20% mass loading of aluminum (Al) was prepared using a commercial filament extruder and printed using a Makerbot Replicator 2X. Printing performance of the energetic samples was compared with standard 3D printing materials, with metrics including the bead-to-bead adhesion and surface quality of the printed samples. The reactivity and burning rates of the filaments and the printed samples were comparable. Differential scanning calorimetry and thermal gravimetric analysis showed that the onset temperature for the reactions was above 350°C, which is well above the operation temperature of both the filament extruder and the fused deposition printer.

The Dynamics of Reactively Coupled Crystal Resonator Arrays

Research Assistants: Conor S. Pyles, Ph.D. Student

Principal Investigator: Professor Jeffrey F. Rhoads

Sponsor: National Science Foundation, National Science Foundation GRFP

Abstract

The study of large-scale coupled systems has been an area of growing interest in recent years due to the wide range of dynamic behaviors which may be observed in even the simplest of topologies. While some progress has been made in the development of analytical tools for modeling said systems, experimental work has generally been limited to studying the dynamics of either singular uncoupled resonators or small numbers of coupled resonators (on the order of 2-4). This work seeks to help close this gap by developing an experimental apparatus incorporating a scalable array of quartz resonators coupled through a single reactive element. An equivalent electrical model was developed and was found to agree with the experimental results. The dynamic effects of real-world nonidealities are examined and notable collective and emergent behaviors are identified including system-wide detuning, attenuation with variations in the array size and coupling strength, and desynchronization of otherwise nominally identical resonators and the emergence of secondary resonance peaks in the vicinity of the crystals' antiresonance frequencies.

The Influence of Formulation Variation and Thermal Boundary Conditions on the Near-Resonant Thermomechanics of Mock Explosives

Research Assistant: Allison R. Range, Ph.D. Student

Principal Investigator: Professor Jeffrey F. Rhoads

Sponsor: Air Force Research Laboratory

Abstract

The thermomechanics of energetic and inert particulate composite materials are of pronounced interest in the defense community. This work seeks to further characterize the macroscale, thermal and mechanical response of these materials under various near-resonant mechanical excitations. The fabrication of mock energetic samples based on the PBXN-109 formulation, comprised of hydroxyl-terminated polybutadiene (HTPB) binder with 85% solids loading and varying additive content (0%, 15%, and 30%) of sucrose and/or spherical aluminum crystals, enabled a systematic investigation into the effect of formulation variation on the thermal and mechanical response. Experiments were also performed on insulated plate samples of identical composition to examine the effect of varying thermal boundary conditions. In each of these experiments, the samples were mechanically excited using an electrodynamic shaker, while their thermal and mechanical responses were recorded using an infrared camera and scanning laser Doppler vibrometer, respectively. The investigation of these responses aids in the effort to characterize and understand the behavior of polymer-bonded explosives under mechanical excitation.

Areas at Laboratories: Vibrations & Dynamics
Key Words: Explosives, Thermomechanics, Vibration, Viscoelastic Materials

Experimental and Mechanical Characterization of Particle-Binder Surrogate Energetic Materials

Research Assistant: Ankit Agarwal
Principal Investigators: Professors Marcial Gonzalez and Jeffrey Rhoads
Sponsor: Air Force Research Laboratory (AFRL)

Abstract

Energetic composite materials, composed of energetic (explosive) crystals embedded in a polymer binder, have critical military and defense applications, especially in fueling propellants and making explosive devices. Understanding the mechanical response of energetic materials is extremely important from the point of view of handling, storage and detection. These materials have been found to exhibit a significant nonlinear elasto-plastic stress-strain response in the range of finite deformations under cyclic load, without a distinctive yield surface. Consequently, assumptions of small deformations, linear-elastic material, and plasticity modeling using classical plasticity theories that require a yield surface, may prove to be insufficient in characterizing and predicting their mechanical response, necessitating the use of a finite-strain formulation that accounts for nonlinear elasticity and yield surface-free plasticity. This study presents research efforts in the direction of modeling cyclic loading behavior of surrogate (mock) energetic materials composed of hydroxyl-terminated polybutadiene (HTPB) binder embedded with Sucrose ($C_{12}H_{22}O_{11}$) and Aluminum (Al) crystals, with the goal of building a computational tool capable of characterizing and predicting such non-linear behavior. To aid the formulation of a fully descriptive model, experimental characterization has been performed using compressive cyclic loading tests on surrogate energetic material specimens of three different particle-binder compositions, namely P85 S100 Q00 (85% HTPB, 15% Sucrose), P85 S085 A15 (85% HTPB, 12.75% Sucrose, 2.25% Al), and P85 S070 A30 (85% HTPB, 10.5% Sucrose, 4.5% Al). A finite strain formulation using compressible Ogden's model to predict the elastic response, and a yield-surface free endochronic plasticity model to account for irreversible deformations, has been developed. A computationally efficient central difference method-based numerical algorithm has been implemented to perform the necessary calculations at each load step. Preliminary calibration results suggest a good agreement between the model and the experimental measurements, encouraging further efforts towards building of a predictive computational tool for characterization of surrogate energetic materials.

Areas at Laboratories: Solid Mechanics
Key words (4 or 5): Energetic materials, nonlinear elasto-plasticity, endochronic plasticity, computational mechanics

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

Research Assistant: Jelena Paripovic, Ph. D. Student
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 an excitation may be tuned to produce signatures that are indicative of the presence of explosives. The goal of this work is to 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 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 damping terms, higher order viscoelastic models, and sample size effects. 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.

Areas at Laboratories: Vibration and Dynamics
Key words: System Identification, Dynamics, Vibrations, Modeling

Characterization of the Dynamic Properties of CONFOR^{TM} Foams

Research Assistant: Revati Chowgule, MSME Student

Principal Investigators: Professors Patricia Davies, Anil Bajaj and James Gibert

Sponsor: Department of Mechanical Engineering, Purdue University

Abstract

The purpose of this research is to understand and model the static and dynamic behavior of high resilience CONFOR^{TM} foams. These high-density polyurethane foams are used in shock isolation of electronics and as cushioning elements along with other lighter polyurethane foamsin car seats.CONFOR^{TM} foams are used in many systems and are thus exposed toa wide range of excitation and compressions and can exhibit both nonlinear and viscoelastic behavior. The foams have a long *memory* meaning to takes a long time for the foam to relax back to its original formafter being compressed and exposed to vibration. Currently, the response of these foams to impulse excitation is being examined. Impulse excitation tests have beenperformed on 3 inch CONFOR^{TM} foam cube to which a mass has been attached. By changing the mass, various compression levels can be attained. The relative acceleration of the mass to the base of the foam is measured and analyzed by fitting a sum of damped exponential terms (Prony Series) model to it. As shown by Azizi and Sundaram, the Prony series model parameters at various compression levels can be related to the systems and material model parameters. Robustness of parameter estimation and repeatability of results is being examined, and the range of compressions used by previous researchers is being extended to improve the estimation of the material parameters. The models, which will predict each type of foam's behavior over a wide range of excitation and compression conditions, can be used in models of systems that include these foams to predict and optimize system responses. If the models are accurate, this will reduce the need for extensive prototyping once the system is built.

Areas at Laboratories: Vibrations & Dynamics; Mechanics; Materials
Key words: System Identification, Viscoelastic, Memory Foam, Polyurethane

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

Research Assistant: Trevor A Kyle, MSME Student

Principal Investigators: Professors Jeffrey F Rhoads and J Stuart Bolton

Sponsor: United States Office of Naval Research

Abstract

Because energetic materials, notably through the use of improvised explosive devices (IEDs), pose a significant threat to the armed forces of the United States, it is critically important to develop a comprehensive way of both detecting and defeating them. It has been shown that energetic materials are highly susceptible to mechanical perturbations, which, given enough power, induce an increase in the temperature of the materials. Given the positive correlation between temperature and vapor pressure of these materials, mechanical excitations have the potential to increase the vapor concentration of energetic materials significantly enough to allow for detection, and ultimately defeat. Preliminary experimental results suggest that the same kind of excitation can be achieved through acoustic waves, which can be generated at a large standoff distance from the material. While acoustic energy is generally reflected when sound waves hit an air-solid boundary, it is possible to create a spatially decaying inhomogeneous plane wave that transmits a significant portion of its energy into the material. This wave is created through an array of loudspeakers, with each speaker tuned to the appropriate power and relative phase, such that the interference pattern yields the desired waveform at the target surface. The current effort focuses on (i) generating specifically tailored pressure waveforms using the source array, and (ii) characterizing the material properties of the target energetic and mock energetic materials.

Area at Laboratories: Acoustics & Vibrations
Keywords: Inhomogeneous, plane waves, energetic, reconstruction

Characterization of the Acoustic Material Properties for Binder and Mock Energetic Materials

Research Assistant: Caleb Heitkamp, MSME Student

Principal Investigators: Professor Jeffrey Rhoads and J. Stuart Bolton

Sponsor: Office of Naval Research

Abstract

Energetic materials have been shown to be susceptible to weak, external insults, such as mechanical loads inducing an increase in 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 improvised explosive device (IED) defeat. Based on promising, preliminary experimental results, it has been theorized that tailored acoustic waves could serve as a suitable *stand-off* excitation. For this theory to be applied, the acoustic material properties of the IEDs must be characterized. One important property needed is the material wave speed. Prior work has provided few wave speed measurements for the binder materials commonly used with plastic-bonded energetics. Furthermore, those measurements that have been reported are largely based upon rudimentary, 'pitch and catch' methodologies, which involve sending a pulse from one transducer to another transducer at a set distance apart and measuring the time of flight. Given this, a more rigorous method for determining longitudinal and shear wave speeds in this important class of materials was desired. In this work, an alternative method for measuring material wave speeds is presented and conducted. The technique involves measuring the vibrational response of a 2D line across the surface of a beam in response to a mechanical excitation and analyzing the data in the frequency-wavenumber domain via wavenumber decomposition. Wave speed measurements for neat Sylgard 184, a common binder material, and 50% sugar loaded Sylgard 184 (a mock energetic) samples were found and are reported. A numeric model of a 2D neat Sylgard beam was also created to replicate the experimental results. This work has provided an alternative method for measuring wave speeds in materials as well as wave speed measurements for neat binder and mock energetic composite materials.

Areas: Acoustics, Vibrations & Dynamics

Key Words: Wavenumber decomposition, wave speeds, binder materials, energetics

Heat Generation at HMX Inclusions due to Ultrasonic Excitation

Research Assistant: Zane A. Roberts, MSME Student

Principal Investigators: Professors Jeffrey F. Rhoads, I. Emre Gunduz, Steven F. Son

Sponsor: U. S. Air Force Office of Scientific Research

Abstract

Explosives can be initiated from mechanical deformations causing intense localized heating called 'hot spots', which are not well understood in composite energetic materials such as polymer bonded explosives (PBXs). The objectives of this work were to investigate and isolate the possible heat generation mechanisms of frictional and viscoelastic/viscoplastic dissipation in a simplified composite subjected to ultrasonic acoustic insult. This was accomplished with discrete cyclotetramethylene-tetranitramine (HMX) crystals embedded in a silicone elastomer (Sylgard 184) which was excited with a contact piezoelectric transducer at 210.5 kHz. Two diagnostics were used to monitor temperature. First, observations of light emitted by second harmonic generation (SHG), or frequency doubling, of an incident 1064 nm laser indicated when and which β-HMX crystals transitioned to δ-phase around 170 °C. Second, infrared thermography captured the temperature field of the top surface of the samples. In-situ temperature correlations from SHG measurements showed heating rates of approximately 20 °C/s at the inclusion locations. HMX crystals were also show to be driven to decomposition in <20 s. Infrared thermography measurements indicate that frictional heat dissipation occurs at points of crystal contact and at delaminated/damaged crystal-binder interfaces. Viscoelastic heating of the polymer binder appears to be minor for these conditions, although it could play a role at early times. Safety concerns and heating rates are addressed as well as important insights about mechanical and binder properties to mitigate heating from vibration, as potentially seen during transportation.

Key words (4 or 5): hot spots, energetic materials, ultrasonics, composites

Model Order Reduction of Lumped Parameter Systems Via Fractional Calculus

Research Assistant: John Hollkamp, Ph.D. Student

Principal Investigator: Professor Fabio Semperlotti

Sponsor: Air Force Office of Scientific Research

Abstract

This research studies the implementation of fractional order differential equations to analyze the dynamic response of heterogeneous discrete systems and to develop a model order reduction methodology capable of maintaining the dynamic behavior of the active degrees of freedom (DOF) across a wide frequency range. Traditional model order reduction methodologies that use integer orders impose strict tradeoffs between accuracy and computational performance. However, the use of non-integer orders in fractional calculus provides an alternative approach where complicated, non-uniform systems can be reduced without compromising on accuracy. Furthermore, these fractional models have known analytical solutions to study complex systems which usually could only be solved using numerical methods. Different approaches are explored in order to transform the integer order model into a reduced order fractional model capable of matching the dynamic response of the original system. Specifically, methodologies are developed and implemented for three different cases: 1) Conversion of integer order single degree of freedom (I-SDOF) to fractional order single degree of freedom (F-SDOF), 2) Reduction of integer order multiple degrees of freedom (I-MDOF) to fractional order single degree of freedom (F-SDOF), and 3) Reduction of integer order multiple degrees of freedom (I-MDOF) to fractional order multiple degree of freedom (F-NDOF). Analytical and numerical results show that, under certain conditions, an exact match is possible and the resulting fractional differential models have both a complex and frequency-dependent order of the differential operator. The implications of this type of approach for both model order reduction and model synthesis are discussed.

Areas at Laboratories: Vibrations & Dynamics

Key words: Model order reduction; fractional calculus; complex order; non-homogeneous systems; model synthesis

Acoustic Topological Edge States in Phononic Elastic Waveguides

Research Assistant: Ting-Wei Liu, Ph.D. Student

Principal Investigator: Professor Fabio Semperlotti

Sponsor: Air Force Office of Scientific Research

Abstract

In this study we present the acoustic analogue of quantum valley Hall effect originated from condensed matter physics. Consequently acoustic waves can be generated at, and propagate along the structure boundary or internal domain walls, while acoustic waves are forbidden in the bulk interior of the structure, within certain frequency range. Furthermore, these edge propagating states are immune to backscattering even at the presence of local defects. We proposes a phononic thin plate that is an artificial periodic structure, to demonstrate this phenomenon. Numerical simulations shows that the elastic wave propagating along the designed path in the topological phononic structure is robust against back-scattering, and have very low loss or attenuation. While elsewhere in the bulk domain of the phononic structure, elastic waves are forbidden, therefore it is free from vibration or noise. This study connects the fields of condensed matter physics and acoustics, and creates new acoustic metamaterials that has high potential in various application situations such as vibration/seismic wave isolation and energy harvesting, highly efficient 1D waveguides and acoustic circuits, and acoustic multiplexer in telecommunications and acoustic tweezers in microfluidic devices, etc.

Areas at Laboratories: Noise and Vibration Control, Acoustics, Vibrations & Dynamics

Key words: Topological acoustics, phononic crystals, quantum valley Hall effect

Theoretical and Numerical Demonstration of Thermoacoustic Response in Solid Media

Research Assistant: Haitian Hao, Ph.D. Student

Principal Investigators: Professor F. Semperlotti and C. Scalo

Abstract

The exploration of thermoacoustic oscillations could be traced back to the 19th century and it is also one of the most impressive discoveries of the physics of fluids. The experiment conducted by Sondhauss in 1850 is considered to be the first to present the modern concept of thermoacoustic oscillations. Since then, several practical applications of the basic thermoacoustic effects were explored for the design of engineering devices. To-date, this fascinating mechanism was believed to occur only in fluid media. In our study, we developed a quasi-1D, linear theory and conducted 3D validations with Finite Element Method to show theoretical and numerical evidence of the existence of thermoacoustic oscillations in solid media. Although this mechanism shares common aspects with the more familiar thermoacoustics of fluids, our analysis shows that the underlying physical mechanism presents some important and non-trivial differences with the traditional theory. The discovery and validation of this mechanism may provoke new ideas and application to robust and reliable practically-useful solid-state devices.

Areas at Laboratories: Vibrations & Dynamics

Key words (4 or 5): Thermoacoustics, Solid Media, Energy Conversion, Theoretical and Numerical Demonstration

Aircraft Directivity Modeling with Spherical Harmonic Expansions

Research Assistants: Yiming Wang, MSME Student and Jianxiong Feng, Ph.D. Student

Principal Investigator: Professor Kai Ming Li

Sponsor: Federal Aviation Administration

Abstract

Aircraft directivity is one of the most important features of aircraft noise which influences the noise received at different locations on the ground. The modeling of the source directivity pattern is based on the simultaneous GPS data recorded on the aircraft and the sound pressure level data measured at several ground locations. A method using the spherical harmonic expansion method with a sphere centering around the aircraft is used in this approach. During the curve fitting with the spherical harmonic functions, the receiver locations are adjusted to one meter away from the aircraft accounting for the air absorption, Doppler's effect and divergence effect. The air absorption effect is calculated with the data obtained from the weather balloon. The Doppler's effect and divergence effect are calculated with GPS data recorded on the aircraft and at the receiver locations. Each frequency band (varying from 63 Hz to 2000 Hz) is modeled in the study and A-weighted source directivity pattern is calculated with the measured noise spectra. Prediction based on the modeled three-dimensional directivity pattern shows a reasonably good agreement with the measurement data which was not used in the directivity modeling.

Areas at Laboratories: Noise and Vibration Control
Key words: aircraft noise, spherical harmonics, atmospheric effect, Doppler's effect

Quantifying Uncertainties in Predicting Aircraft Noise in Real-world Situations

Research Assistants: Yiming Wang, MSME Student and Jianxiong Feng, Ph.D. Student

Principal Investigator: Kai Ming Li

Sponsor: Federal Aviation Administration

Abstract

The purpose of this study is to quantify the uncertainties in predicting aircraft noise during the propagation of sound from the aircraft to the receiver on ground. There are significant impacts of atmospheric conditions and ground properties on accurate predictions of aircraft noise. It is well known that the accuracy of these inputs is critical for the predictions. To assess the uncertainties in aircraft noise prediction, an integrated approach including theoretical acoustic modeling and statistical methods is used to understand uncertainties in the aircraft state and resulting noise levels and directivity (source), the atmospheric and meteorological conditions (propagation), and ground impedance and terrain model (receiver). This approach will include all predominant uncertainties between source and receiver. In the recent years, the project team has obtained measurement data from NASA/VOLPE, and Vancouver Airport Authority, which form a vital part in the assessment of uncertainties in predicting aircraft noise at various atmospheric, typographic and ground conditions. One of the main motivations of the current project is to guide these recent advancements for reaching a sufficient Research Readiness Level (RRL) that leads to a possible implementation in AEDT in near future. The current finding shows that the predictions of the uncertainties due to Doppler effect between approaching and receding events of a same aircraft has shown excellent agreement with the measured data.

Areas at Laboratories: Noise and Vibration Control
Key words: aircraft noise, noise uncertainties, atmospheric effect, Doppler’s effect

Acoustical Condition Monitoring of Printers

Research Assistant: Nicholas Kim, Post Doc

Principal Investigator: Professor J. Stuart Bolton

Sponsor**:** HP Printers

Abstract

Printers of the type widely used in the office or at home, are composed of many parts, for example, motors, rollers, gears, fusers, etc., that are required to print in a page after receiving image data. Since there are so many parts, it is often difficult to identify the specific part involved when a malfunction occurs. If it were possible to find the defective part automatically, the cost to repair a faulty printer could be made lower, and environmental impact can be reduced by replacing specific parts instead of the whole machine. Moreover, if we can detect an incipient malfunction before it occurs, customer confidence will be increased and repair time, an hence inconvenience, will be minimized. Here we are particularly concerned with faults that result in noise signals such as "squeaks" since such noises can become very annoying in office spaces. The squeaking noise originates from from stick-slip phenomena related to rollers and usually appears in the 3 to 5 kHz frequency range. To analyze the squeaking, the noise was recorded inside the printer by using a MEMS microphone. From the recorded data, when an unusual peak in the 3 to 5 kHz range is detected, the modulation frequency of filtered tone noise is calculated, and finally, the defective component can be identified by matching the modulation frequency and the rotation frequencies of the rollers in the paper path.

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

Research Assistant: Tongyang Shi, Ph.D. Student

Principal Investigators: Professors J. Stuart Bolton and Patricia Davies

Sponsor: Cummins Inc.

Abstract

Diesel engine noise is a concern in boththe municipal environment and in an occupational health and safety context due to the use of diesel engine in heavy industry and transportation. A precise knowledge of the primary noise source locations is required to guide the efficient application of noise control resources. Acoustical Holography is a general method that can be used to visualize the sound field around noise sources. However, due to the complexity of diesel engine noise sources (i.e., combustion noise, mechanical noise, etc.), in order simultaneously to ensure good spatial resolution while avoiding spatial aliasing, a large number of measurements must be conducted when using conventional holography approaches. Thus, it would be useful if there were an approach that allowed a relatively small number of spatial measurements to give accurate noise source locations: the objective here is to demonstrate such a system. The proposed solution in the present work is to combine the equivalent source method with partial field decomposition. The equivalent source model used in the present work is a monopole distribution at fixed location in combination with a so-called wideband holography regularization process. With partial field decomposition, uncorrelated noise sources can be separated. With this method, a diesel engine noise source visualization can be performed with one set of measurements from a thirty-five channel irregular array.

Area of Laboratories: Noise and Vibration Control, Acoustics
Key words (4 or 5): Acoustics holography, Noise source identification, Inverse problem, Wideband Holography

Active Noise Control Headrest for Automobile Interior Environment

Research Assistant: Xuchen Wang, MSME Student

Principal Investigators: Professor J. Stuart Bolton and Yangfan Liu, Post Doc

Abstract

The active control of the low frequency noise in an automobile environment is increasingly demanded in recent years, due to the requirement of driving comfort and lightweight design as well as the ineffectiveness of the traditional passive noise control alternatives at low frequencies. In this project, an active noise control headrest has been designed for the driver's seat in an automobile, which has the advantages of better low-frequency performance and lower modification cost compared with passive noise control methods. FIR filters were used in the controller structure to cancel the primary noise, the coefficients of which were determined by Wiener Filter theory. A feedback-path cancellation process was included in the controller to remove the effect of the anti-noise generated by the secondary sources that can propagate to the reference sensors. Both feedforward and feedback control strategies were implemented: additional considerations of robust stability and disturbance enhancement were included in designing the feedback system. The designed controllers were experimentally implemented in real time and their experimental performance was shown to agree well with the off-line simulation results. Finally, the characteristics of the different control strategies and different controller structures were commented upon based on comparisons of the resulting performance of the various implementations.

A Generalized Spatial Filtering Method in Broadband Active Noise Control based on Independent Sound Field Component Analysis

Research Assistants: Xuchen Wang, MSME Student, Shenwei Wang, Undergrad Student

Principal Investigators: Professor J. Stuart Bolton and Yangfan Liu, Post Doc

Abstract

Spatial filtering techniques have been used to reduce the computation load required of multi-channel active noise controllers. Normally, signals from each microphone are typically weighted by scalars and summed to construct the input signal to a single-input-single-output (SISO) controller, and then he actual output signals to the loudspeakers are generated by applying different weighting factors to the controller output. Because of this SISO nature, only one statistically independent sound field component can be controlled; thus, in the proposed spatial filtering method, the component with the highest noise level is extracted and used as the single input signal to the controller. This is accomplished by, instead of using scalar weightings, filtering the microphone inputs through FIR filters which represent the transfer functions that project the input signals to the targeted independent sound field component. It is demonstrated that filters of relatively low orders can lead to satisfactory results if the noise control region is not large. Simulation and experimental results of an active noise control headrest in an interior environment were used to validate the proposed approach, the reduction of the computation load was demonstrated and the potential of selectively controlling particular sound field components was also commented.

The Application of Acoustic Radiation Modes in Structural Optimization for Noise Reduction

Research Assistants: Jiawei Liu, Ph.D. Student, Yangfan Liu, Post Doc

Principal Investigator: Professor J. Stuart Bolton

Sponsor: Cummins Inc, Department of Research and Development

Abstract

In modern engine design, downsizing and reducing weight while still providing an increased amount of power has been a general trend in recent decades. Traditionally, an engine design with superior NVH performance usually comes with a heavier, thus sturdier structure. Therefore, modern engine design requires that NVH be considered in the very early design stage to avoid modifications of engine structure at the last minute, when very few changes can be made. NVH design optimization of engine components has become more practical due to the development of computer software and hardware. However, there is still a need for smarter algorithms to draw a direct relationship between the design and the radiated sound power. At the moment, techniques based on modal acoustic transfer vectors (MATVs) have gained popularity in design optimization for their good performance in sound pressure prediction. Since MATVs are derived based on structural modes, they are not independent with respect to radiated sound power. In contrast, acoustic radiation modes are an orthogonal set of velocity distributions on the structure’s surface that contribute to the radiated sound power independently. As a result, it is beneficial to describe structural vibration in terms of acoustic radiation modes in order to identify the velocity distributions that contribute the majority of the radiated sound power. Measures can then be taken to modify the identified vibration patterns to reduce their magnitudes, which will in turn result in an unequivocal reduction of the radiated sound power. A workflow based on multibody dynamic simulation and acoustic radiation modes to optimize an engine oil pan design is proposed in this project.

Prediction of Tire Cavity Acoustic Mode Effect on Structure-Borne Noise by Use of a Finite Element Tire Model

Research Assistant: Rui Cao, Ph.D. Student

Principal Investigator: Professor J. Stuart Bolton

Sponsor: Ford Motor Company

Abstract

Tire vibration can propagate through various structural transfer paths into the vehicle and then cause different interior surfaces to vibrate thus creating vehicle interior noise, and such noise is usually referred to as structure borne sound. The reduction of relatively low frequency structure-borne tire noise is the focus of many auto manufacturers, since it is very noticeable in the vehicle cabin. Among all the structure-borne tire noise mechanisms, the tire internal cavity acoustical resonance is a very strong contribuor and can easily be perceived by passengers. Numerous tire manufacturers have started to attach sound absorptive material to the tire tread inner surface to reduce this cavity resonance. Some reduction of vehicle cabin noise can be achieved through this method. However, apart from the additional cost for such kind of tires, there is also an increased complexity to repair such tires without damaging their sound absorptive material arrangement. Considering these additional requirements and the cost of adding material to defeat tire cavity resonances, a better design of the tire-rim and suspension system to decrease the cavity noise influence from transfer path optimization would still be beneficial. Here, a fully coupled finite acoustic-structurally finite element tire model with rigid ground contact was established, in order to study how the internal air cavity will affect the force transmissibility characteristics. The tire was first inflated and then pressed against a rigid ground by a static loading. The radial mobility of the tire was first calculated to prove model validity, and acceleration at the rim center in three directions were also derived. Cavity resonances were captured and their influence toward the rim center acceleration data was investigated by manipulating the tire material properties. A study of the resulting model has identified a way of reducing the structure-borne noise transmission by arranging that there is a spatial mismatch between the interior acoustic mode and the tire structural modes that are close in frequency to the acoustic mode.

Weight Minimization of Noise Treatments by Balancing Absorption and Transmission Performance

Research Assistant: Hyunjun Shin, Ph.D.

Principal Investigator: Professor J. Stuart Bolton

Sponsor: Ford

Abstract

Generally, heavier noise treatments are favored over lighter treatments since heavier acoustic materials generally insulate (block) the noise source more effectively. For automotive applications, however, heavier materials cannot necessarily be adopted because of concerns about the total weight of the vehicle. Thus, it is desired to have lighter acoustic materials to mitigate the vehicle interior noise for the purpose of the weight minimization. Acoustic materials used in automobiles have both absorption and transmission characteristics, and there is necessarily a tradeoff between these two. Therefore, it is important to study the exchange between the absorption and transmission of acoustic materials particularly as it pertains to weight. The idea of tradeoffs between absorption and transmission performance of noise treatment was introduced in a previous study. Here, a method of weight minimization by adjusting the acoustic properties of a porous layer and a flexible microperforated panel surface treatment to balance the absorption and transmission characteristics to yield the acoustic performance of conventional (heavier) materials at a lighter weight is demonstrated. This research proves that reducing the weight of noise treatments can be achieved while maintaining acoustic performance equivalent to that of heavier noise treatments by properly balancing the absorption and transmission performance.

Advanced Modeling of Noise Control Materials

Research Assistant: Yutong (Tony) Xue, Ph.D. Student

Principal Investigator: Professor J. Stuart Bolton

Sponsor: 3M Company

Abstract

In this study, state-of-the-arts models developed using analytical and numerical methods are serving as powerful tools for predicting the acoustical or damping performance for sound absorbing materials or structures. These models can be divided into three categories: (1) Airflow resistivity models (AFR) to predict porous materials' airflow resistivity and to help connecting the microstructure of the materials and their bulk properties; (2) Acoustical models (ACM or TMM) to predict acoustical properties based on the inputs of the bulk properties; (3) Near-field damping models (NFD) to predict the structural damping effect of fibrous layers based on their acoustical properties. With the application of these models, for different materials or layered structures, the noise or vibration control performance can be directly evaluated knowing the material microstructure details. On the other hand, based on the calculation of bulk properties required for realizing the optimal acoustical or damping results for different frequency regions by ACMs, TMMs and NFDs, the design and optimization of the porous material microstructure can be achieved by AFRs. Moreover, experimental methods have also been developed for validating the models, which ensures that noise or vibration control insights are obtained from accurate predictions. These insights then can be used to design different types of passive noise control solutions or enhance the performance of 3M products such as Thinsulate Acoustic Insulation (TAI) fibrous material. Future study will focus on understanding the material micro-macro-acoustical connections and exploring the attenuation characteristics of multi-layer structures involving porous elastic material, elastic solids, stiff panel, micro-perforated film, etc.

A Desktop Procedure for Measuring the Transmission Loss of Automotive Door Seals

Research Assistant: Weimin Thor, Undergraduate Student

Principal Investigator: Professor J. Stuart Bolton

Sponsor: Ford Motor Company

Abstract

Due the increasing concern with the acoustic environment within automotive vehicles, there is an interest in measuring the acoustical 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 chamber, 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. Since the clamp partially blocks the channel, thus impacting the measured transmission loss, a correction is necessary to determine the transmission loss of the seal by itself. Therefore, an initial set of measurements was performed to identify the correction factor required to adjust the measured transmission loss of the clamp plus 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 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 arrangements in the vehicle is crucial to ensuring their optimal performance.

Effects of Sharpness on Sound Quality of Wind Noise in Automobiles

Research Assistant: Daniel J. Carr, Ph.D. Student

Principal Investigator: Professor Patricia Davies

Sponsor: Ford Motor Company

Abstract

Predictors of people's responses to wind noise in cars are used by car companies to identify and address potential wind noise problems from wind tunnel tests. Currently used predictors need improvement and in recent research, a model based on both loudness and sharpness metrics performed better than existing predictors. To validate this finding, a test was conducted in which the influence of the sharpness of a sound was examined more directly. Forty-five subjects listened to 150 sounds and rated them on an acceptability scale. The sounds were based on recordings made in various automobiles in a wind tunnel. Some recordings were modified by amplifying/attenuating energy above and below 1000 Hz, to vary sharpness while keeping loudness constant. Sounds were also created by high-pass filtering a sound, and then adding the low-frequency content of a quieter reference sound. This was done to examine how low-frequency wind noise energy affected people's evaluations, because the low-frequency interior noise is usually dominated by tire/road noise. Linear models containing Loudness and Sharpness metrics again gave significantly more accurate predictions than did models containing Loudness alone. Including a third metric did not significantly increase accuracy. The Loudness-and-Sharpness model estimated by using only the information from the low-frequency energy equalized sounds gave predictions of similar accuracy to those from a Loudness-and-Sharpness model estimated by using the information from all sounds. The results are in agreement with those of the previous test, and model predictions also match informal evaluations by vehicle engineers of wind noise in other vehicles. A third test has been planned for further validation of the models and to determine whether an additional sound characteristic needs to be flagged as an error-state during wind noise tests. These types of two-metric models are now being implemented to improve acoustic benchmarking.

Area at Laboratories: Acoustics
Key words: Psychoacoustics, Vehicle interior noise, Wind, Sound Quality

Sound Quality of HVAC&R Systems

Research Assistant: Weonchan Sung, Ph.D. Student

Principal Investigators: Professors Patricia Davies and J. Stuart Bolton

Sponsor: UTC/Carrier

Abstract

Some HVAC&R equipment noise can irritate people who are exposed to it. HVAC&R noise can cause sleep disturbance or reduce work efficiency. HVAC&R equipment designers would like to have better noise criteria to lead their designs so that they have fewer noise complaints from customers. The goal of this study is to develop better sound quality models for HVAC&R equipment that can be used in system design. To build an annoyance prediction model, three rating tests have been conducted. Recently, the third test, which itself has three parts, was conducted. The test sounds were a mixture of recordings and modified recordings and the modifications were developed based on the results of the two previous rating tests. Fifty sounds were evaluated in each part of the third test and fifteen sounds were common to all three parts. Two annoyance models were developed, one for each of the two types of HVAC&R equipment examined. The possibility of using one annoyance model was examined, but separating by application produced better results. A linear combination of Zwicker Loudness and modified Aures' Sharpness was used to predict annoyance due to a noise of mobile truck units. For residential units, the annoyance model included the ARI Sound Quality Indicator based on sound pressure, modified Aures' Sharpness, modified Tonality, and Roughness. By combining these annoyance prediction models with a physical noise source and path models that predict the noise heard, the designer can determine how potential changes to sources and paths will affect the acceptability of the sound generated by the HVAC&R equipment. The combination of the physical and human models means that sound optimization can become an integral part of early product design, reducing the need for fixing noise problems during and after the prototyping stage when noise modification options are more limited.

Areas at Laboratories: Acoustics, Signal Processing
Key words (4 or 5): Sound Quality, Psychoacoustics, HVAC&R, Annoyance

Ordering Effects in Sound Evaluations

Research Assistant: Yiyun Zhang, Undergraduate Student

Principle Investigator: Professor Patricia Davies

Sponsor: Undergraduate ME497 Project and Purdue SURF Program

Abstract

In machine design it is important to incorporate the impact of the machinery noise. Both acoustic and non-acoustic factors affect people's judgments of sounds, and when gathering data to generate models that predict people's responses to sounds, it is important to understand all the elements that affect those responses. In this research, sound ordering effects in sound annoyance evaluations were examined. Most annoyance prediction models are functions of the strengths of sound characteristics only, but here how the response to a sound was affected by the previous sounds being played was also examined. A memory term was added to prediction models that are functions of sound attributes alone, by using the annoyance rating from the previously heard sound. Individual subject and group models were re-estimated with the memory term. Inclusion of a memory term could increase the prediction accuracy of some individual subject models but the effect was test dependent. The improvement was greater in a test where subjects evaluated transient environmental sounds than in a test where subjects evaluated steady-state sounds. In addition, improvements in individual subject model's accuracy, when a memory term was added to the model, was found to be greater when the sound characteristics only subject models are less accurate. The commonly used approach to dealing with this problem is to randomize sound presentation order with different presentation orders for each subject, but any testing method that attenuates ordering effects would also be helpful in increasing sound impact model prediction accuracy. An experiment is now being conducted to determine whether the cursor placement on the given rating scale would attenuate or strengthen the observed ordering effects. Outcomes of this research could be used to improve psychoacoustic test design and thus improve sound impact models.

Areas at Laboratories: Acoustics
Key words: Psychoacoustics, Ordering Effects, Transfer Bias, Short-term Memory, Sound Quality

PIV Testing of a Residential Gas Furnace

Research Assistants: Puyuan Wu and Weixiao Shang, Ph.D. Students

Principal Investigator: Professor Jun Chen

Sponsor: Carrier/UTC

Abstract

Nearly 40% of the residential site energy in the US is consumed by gas furnace for space heating. Recently, DOE proposed to increase the minimum furnace efficiency standards to 92%. This stringent requirement presents a major challenge to manufacturers. CFD has been frequently adopted as advanced design tools to optimize this thermal-fluids system. However, the effectiveness of different CFD predictions must be validated by benchmark experimental data. In this project, we measure the detailed flow field in a residential gas furnace, by applying Particle Image Velocimetry, with high spatial resolution, so flow details with key design concerns can be captured. An experimental set up is constructed by connecting a modified gas furnace to a big exhaust chamber, which simulates the supply-return loop of a typical heating system. Several optical windows are installed on the furnace for laser/camera access. Fog particles (diameter ~ 1 um) are introduced as seeding particles moving with the air flow. Measurement are to be done at 24 target locations, including the inlet and outlet of the furnace, the gap between the heat exchangers, and near the limit switch. The results will reveal the three-dimensional flow structure under a series of typical operation conditions when differential pressure between the inlet and the outlet of the furnace ranges from 29.9 to 401.0 Pa. The experimental database established by this project will serve as benchmark for validating CFD predictions.

Areas at Laboratories: Fluid Dynamics
Key words: Residential Gas Furnace, PIV, HVAC

Gas Exchange Management for Cleaner and Greener Diesel Engines

Research Assistants: Matthew VanVoorhis, Troy Odstrcil, and Ife Ibitayo, MSME Students, and Aswin Ramesh, Cody Allen, Dheeraj Gosala, Alexander Taylor, Kalen Vos Mrunal Joshi, Ph.D. Students

Principal Investigator: Professor Greg Shaver

Sponsors: Cummins Inc and Eaton Corporation

Abstract

To meet consumer demands for improved fuel economy while also satisfying stringent emission regulations, many engine manufacturers are investigating the benefits of variable valve actuation systems. This study focuses on the quantification of the effects of variable valve actuation (VVA) to improve aftertreatment thermal management and engine efficiency. To meet current emission levels, diesel aftertreatment systems include a diesel oxidation catalyst, diesel particulate filter, urea injection and decomposition reactor and a selective catalytic reduction (SCR). Diesel aftertreatment systems, specifically the SCR, require the catalyst bed and decomposition reactor to be at a high temperature to convert the hazardous emissions such as NOx (oxides of nitrogen) into nitrogen, water and carbon dioxide efficiently. Attaining elevated aftertreatment temperatures at idle and loaded idle conditions is difficult without a fuel consumption penalty. VVA strategies such as early exhaust valve opening (EEVO), internal exhaust gas recirculation (iEGR) and reverse breathing are currently being studied as solutions to aftertreatment thermal management. The experimental test bed to investigate these strategies includes a 2010 Cummins ISB 6.7L engine with OEM parts with the exception of the VVA system, which replaces the valve timing, and actuation system. This unique multi-cylinder test bed is outfitted with a fully-flexible electro-hydraulic VVA system which enables cylinder-independent and cycle-to-cycle control of both the intake and exhaust valves. A fully functional active urea dosing aftertreatment system designed for the ISB engine is attached along with a Power Test AC dynamometer which allows for the transient engine operation required for drive cycle analysis. These various VVA strategies allow for faster aftertreatment warmup times as well as lower fuel consumption once the aftertreatment is at efficient operating temperatures. The steady state results of these VVA strategies can be quantified on the active urea dosing aftertreatment system over standard drive cycles with the AC dynamometer. Advancing the knowledge of VVA strategies can help improve the performance, emissions, and operating costs of diesel engines.

Cylinder Deactivation – A Next Generation Diesel Engine Technology

Research Assistants: Matthew VanVoorhis, Troy Odstrcil, and Ife Ibitayo, MSME Students, Dheeraj Gosala, Cody Allen, Aswin Ramesh, Mrunal Joshi, Kalen Vos And Alexander Taylor, Ph.D. Students

Principal Investigator: Professor Gregory Shaver

Sponsors: Cummins Inc. and Eaton

Abstract

Cylinder Deactivation (CDA) is a technology for multi-cylinder engines where a fraction of the total number of cylinders in the engine are deactivated, such that only the remaining set of active cylinders produce torque. Typically, CDA is achieved by disabling intake and exhaust valve motion and fuel injection in the deactivated cylinders. Extensive study has been performed on one-third engine CDA, half-engine CDA and two-third engine CDA on a six-cylinder Cummins mid-range diesel engine at Purdue. CDA has been studied to show a better tradeoff between fuel consumption and engine-outlet temperatures, achieving up to 70 deg C higher engine-outlet temperatures at fuel-neutral conditions and up to 25% reduction in fuel consumption at similar engine-outlet temperatures, during steady state idle and low load operating conditions. During highway cruise half-engine CDA and two-third engine CDA can be used to reach engine outlet temperatures of 520–570°C, a 170–220°C increase compared to normal operation. Lower exhaust flow rates during CDA help maintain higher aftertreatment component temperatures for a longer duration. A study on transient diesel engine performance was undertaken when CDA is implemented at idle operation, and it was concluded that there was no deterioration in transient response of the engine when a transition from CDA to six-cylinder operation was made at the onset of an acceleration. When dynamically implemented at low load and idle operating conditions over the heavy duty federal test procedure (HD-FTP), a 3.4% improvement in fuel economy was demonstrated with similar predicted tailpipe-out NOx emissions on account of similar aftertreatment thermal management. A fuel economy improvement of 5.6% is predicted over the Orange County Bus Cycle and a 35% reduction is predicted over the port drayage creep cycle. Research is ongoing in understanding the differences between various charge trapping strategies during deactivation of cylinders. Further, evaluation of the noise, vibration and harshness (NVH) of CDA, and study of potential mitigation strategies is also underway.

Areas at Laboratories: Engine Test Cell 1

Keywords : Cylinder deactivation, aftertreatment warm-up, fuel efficiency, NVH

Enabling High-Efficiency Control Systems for Connected and Automated Class 8 Trucks

Research Assistants: Alexander Taylor, Cody Allen, Ph.D. Students

Principal Investigator: Professor Gregory Shaver

Sponsors: U.S. Department of Energy, ARPA-E

Abstract

Line-haul Class 8 trucks account for approximately two-thirds of greenhouse gas (GHG) emissions of all commercial trucks. Industry leaders have continued to develop and take advantage of new technologies to increase fuel efficiency and reduce GHG emissions by looking at the vehicle as a system. However, the engine and transmission have remained largely isolated from emerging Connected and Automated Vehicle (CAV) applications such as cooperative adaptive cruise control, predictive cruise, speed harmonization, and freight signal priority. In response to this technology void, the ARPA-E sponsored project "Next-Generation Energy Technologies for Connected and Automated On-Road Vehicles," or "NEXTCAR," aims to develop technology that takes advantage of emerging connectivity infrastructure. A Purdue University-led team includes innovative industry leaders Peloton Technology, Cummins, ZF, and Peterbilt, as well as NREL. The goal is an integrated, connectivity-enabled, vehicle-dynamic and powertrain control system for diesel-powered on-highway Class 8 trucks. Concepts to be studied include (1) remote powertrain calibrations that take into account variables such as application variation, component aging, terrain, and weather, (2) real-time powertrain control and optimization from the cloud that allows for more sophisticated algorithms to be implemented, and (3) more efficient two-truck platooning using connectivity-enabled shifting coordination and lead truck predictive cruise. The combination of these concepts is hypothesized to reduce fuel consumption by up to 20% from the 2016 Peterbilt 579 baseline.

SuperTruck II - Model Validation

Research Assistants: Kalen Vos and Aswin Ramesh, Ph.D. Students

Principal Investigator: Professor Gregory Shaver

Principal Investigators: Cummins Inc., Eaton, Paccar, Bridgestone, Meritor, Great Dane, Exa Corporation, Oak Ridge, NREL, Purdue University

Abstract

In effort to meet stringent emissions regulations while continuing to improve upon fuel economy, novel strategies are being studied and modeled to understand their impact on the overall vehicle's efficiency. The Class 8 vehicle simulation model being developed at Purdue will be used to influence the design of the SuperTruck II vehicle.

Autonomie software is being used as the tool to develop and validate a Class 8 simulation model against pre-existing SuperTruck I data. The goal is to prove the validity of the model such that future innovative results obtained from the model are credible and can therefore influence the design of the SuperTruck II vehicle.

The overarching objectives of the SuperTruck II project will focus on breakthrough advances in Class 8 vehicle freight efficiency technologies that are cost-effective enough to be used in real-world applications. Specifically, the intent is to aid in developing and demonstrating 55% or greater engine Brake Thermal Efficiency at a 65 MPH cruise condition, along with greater than 100% improvement in vehicle Freight-Ton Economy over the 2009 baseline vehicle.

Powering What's Next in Freight Transportation

Research Assistant: Ana Guerrero de la Peña, Ph.D. Student

Research Scientists: Professors Navindran Davendralingam, Ali K. Raz

Principal Investigators: Professors Neera Jain, Gregory Shaver, and Daniel DeLaurentis

Sponsor: Cummins, Inc.

Abstract

Although it may be easiest to model the expected future of freight transportation simply as multiple decoupled autonomous transportation technologies, future concepts in transportation and logistics will likely take the form of connected and collaborative systems-of-systems (SoS), each system with optimized levels of autonomy. Current and future trends show that trucks carry a majority of the load of freight transportation, and therefore, the future of internal combustion engines and the role they play in powering these systems poses an equally important question. Emerging transportation concepts will be analyzed through the development of a mathematical simulation model for a connected and collaborative line-haul and urban-delivery system-of-systems. This research aims to define the correct network topology, the interaction of resources for optimal performance and safety of freight transportation, and the implications of policy and infrastructure provisions on driver behavior and vehicle operation. We will quantify projections for the adoption of different levels of vehicle autonomy and emerging vehicle powertrain system designs that will provide an efficient, cost effective, and environmentally friendly propulsion mode for the U.S. freight transportation system.

Key words: System-of-Systems, freight transportation, emerging technologies, vehicle autonomy, connected vehicles

SCR Urea-Dosing Control for Diesel-Electric Hybrid Car

Research Assistants: Kaushal Kamal Jain, Ph.D. Student, Harshil Angre, MSME Student, Jagdish Hiremath, MSME

Principal Investigator: Professor Peter H. Meckl

Sponsors: Delphi, Faurecia, Argonne National Labs, General Motors, Department of Energy, Discovery Park Energy Center Purdue, Hoosier Heavy Hybrid Center of Excellence

Abstract

Urea-SCR (Selective Catalytic Reduction) is an essential component of the diesel engine after-treatment system to meet increasingly stringent NOx emission regulations. It reduces the engine-out NOx using NH_3, which is injected into the system as Diesel Exhaust Fluid or DEF (mixture of urea and water). An optimum amount of DEF needs to be injected into the system to maximize the NOx reduction and minimize the NH_3 slip. Since the amount of NH_3 stored into the catalyst is an important part of the system dynamics, an NH_3 storage-based urea-dosing control must be developed for optimal DEF injection. The goal of this work is to design and implement such controller to achieve maximum NOx reduction with minimum NH_3 slip for dynamometer and on-road drive cycles. However, it is not possible to measure the amount of NH_3 stored in the catalyst. Therefore, a parameter identification method has been formulated and an observer has been designed to model the system and estimate the amount of NH_3 stored in the system, respectively. To test the observer, it was run offline against the highest-fidelity lumped-parameter single-cell model and steady-state experiment data. The observer showed good performance for NH_3 slip, NOx emission, and NH_3 storage against the single-cell model. After plugging the identified parameters in the observer, it showed good performance for NH_3 slip and NOx emission estimation against the experiment data as well. However, the observer's NH_3 storage estimation can't be verified in this case because of unavailability of NH_3 storage measurements. Hence, a higher-fidelity multi-cell model is being developed to evaluate the observer's NH_3 storage estimation better. The work on NH_3 storage-based control design is underway as well, and will be followed by combined controller-observer compensator's online implementation on EcoCAR2.

Key words: Urea-SCR, DEF, parameter identification, observer, controller.

Control of a Hybrid Diesel Vehicle

Research Assistant(s): Mingyu Sun, Abhilash Yedla

Principal Investigator(s): Professor Peter H. Meckl

Sponsor(s): dSPACE, 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 dynamic-programming-based regression strategy, and neural network strategy.

Physically-Based Battery Degradation Modeling for Li-ion Batteries

Research Assistants: Vaidehi Hoshing, Aniruddha Jana, Tridib Saha, Xing Jin

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Sponsor: Cummins Inc.

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. Within electrified vehicle powertrains, lithium-ion battery performance degrades with aging and usage, resulting in a loss of both energy and power capacity. As a result, models used for system design and control algorithm development would ideally capture the impact of those efforts on battery capacity degradation, be computationally efficient, and simple enough to be used for algorithm development. The battery degradation models available in literature do not satisfy this requirement. They are either very accurate but slow (e.g. electrochemical models) or fast but inaccurate (e.g. empirical and semi-empirical models). This poster illustrates the degradation model developed by our group which is as accurate as the electrochemical model (as shown for LFP/Graphite chemistry) and 24x faster. This degradation model captures two dominant anode side degradation mechanisms (viz SEI layer growth and AM loss). One other dominant cathode side degradation mechanism affecting the NMC/Graphite chemistry is discussed as a potential improvement to the demonstrated model.

Key Words: Battery Degradation Modeling, Physics Based Modeling, Electric Vehicles

Designing a Post-Hazard Building Inspection Model Based on Human Experts Inputs

Research Assistant: Ali Lenjani

Principal Investigators: Professor Shirley Dyke and Chul Min Yeum, Post Doc

Abstract

A major section of disaster resilience is urban resilience that evaluates the ability of the city to overcome challenges through reducing casualties, damages and socioeconomic impacts of the hazard (e.g. hurricane, earthquake, and tsunami). To improve the resilience of a city, recovery phase is the most expensive and longest step of post-hazard emergency management life cycle. The efficiency of recovery phase depends on fast and reliable post-hazard infrastructure inspection of the affected region. Currently, Post-hazard inspections are done based on human experts decisions that rarely are accurate and never works better than a mathematical model in such a complicated problem. On the other hand, humans experts still outperform machines in collecting damage evidence such as determining whether there is gas or toxic material leakage through smell. Experience is a critical factor that although it is a negative point for the model in beginning, during the time and after accessing sufficient samples would be an indisputable characteristic of the model. In this paper, a decision-making model for post-hazard building inspection is presented to integrate computers and human experts strengths. We developed a classifier model based on decision trees to automate the inspection decision making. 712 sample of buildings affected with 5 different earthquakes to estimate structural damage level of the buildings based on 20 variables that is measured by human experts are used to validate the model accuracy.

Key words: Decision-making, Post-hazard inspection, Structural damage level, Uncertainty quantification, Decision tree.

Autonomous Image Localization for Visual Inspection of Civil Infrastructure

Research Assistant: Jongseong Choi, Ph.D. Student

Principal Investigators: Professors Shirley Dyke and Chul Min Yeum,

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.

Areas at Laboratories: Vibrations & Dynamics
Key words (4 or 5): Computer Vision, Automated Inspection, Image Localizaton