Research Expo 2014

HERRICK LABORATORIES
PURDUE UNIVERSITY ™

GROUP A - THERMAL SCIENCES

GROUP D - ELECTROMECHANICAL SYSTEMS/CONTROLS & VIBRATIONS

PERFORMANCE TESTING OF UNITARY SPLIT-SYSTEM AIR CONDITIONER WITH VIPER ENERGY RECOVERY EXPANSION DEVICE

Research Assistants: Nicholas Czapla, Harshad Inamdar

Principal Investigator: Professor Eckhard Groll

Sponsor: Regal Beloit Corporation

ABSTRACT

Due to the rising demand of using energy resources more efficiently, the HVAC industry is constantly facing the challenge of meeting strict energy consumption requirements. The main objective of this project is to improve the efficiency of a vapor compression cycle using R410A as the refrigerant. R410A, as any sub-critical refrigerant, has a meaningful difference in potential energy savings when using a practically achievable partially isentropic expansion instead of an adiabatic expansion. As a result, there is a significant potential for efficiency improvements by replacing the expansion valve with a work-generating device - the Viper energy recovery expander. The Viper expander functions by using a nozzle to convert the internal energy and pressure of the refrigerant to a high speed flow. The nozzle is designed to ensure refrigerant phase change and accelerate the flow into a built-in pelton wheel turbine. The rotating turbine is connected to an internal generator which generates electrical energy. This electrical energy is used in the system to augment the power into the air conditioner's indoor fan motor. The Viper expander, which has been developed by the Regal Beloit Corporation, enables the realization of decreased power consumption and increased evaporator cooling capacity. All performance tests will be conducted in ASHRAE standard psychrometric chambers at Purdue University's Ray W. Herrick Laboratories. The test plan consists of initially testing an off-the-shelf 5-ton split system air conditioner as specified by ARI 210/240 at the standard SEER rating operating conditions (Tests A, B, C, and D). The next step is to modify the system by adding the Viper energy recovery expander in place of the conventional thermostatic expansion valve (TXV). Although most of the Viper's power comes from internal energy phase change, the last stage of the testing will be to modify the unit to ensure that there is a maximum pressure drop across the Viper. Many commercial units allocate pressure drop in various locations of the refrigerants path from the condenser to the evaporator.

PERFORMANCE OF FINNED HEAT EXCHANGERS AFTER AIRSIDE FOULING & CLEANING

Research Assistant: Harshad Inamdar

Principal Investigator: Professor Eckhard Groll

ABSTRACT

Overview

Fouling of enhanced surface heat exchangers (HX) by particulate matter may significantly reduce their performance. Hence, the effect of particulate fouling and subsequent cleaning on the performance of finned HX is being investigated. It is anticipated that factors such as geometry of HX, air velocity, air humidity and concentration of dust in air will impact the fouling and subsequent performance degradation of heat exchangers and heat sinks.

Methodology

The heat exchangers being tested are installed in a wind tunnel where all air-side parameters can be controlled. ASHRAE standard test dust is then injected into the air stream which leads to fouling of the heat exchanger. The mass of dust deposition on, pressure drop across, and heat transfer through the heat exchangers is measured and compared to evaluate degradation in performance, and correlate the degradation to the extent of fouling on the HX. In addition, a heat exchanger simulation model will be developed to predict the deposition rate as a function of time.

Extended benefits

With this project, and with results obtained from similar projects done by the PI, it is envisioned to predict the extent of fouling of HX/HS being operated in the field, and set target cleaning schedules based on the maximum degradation in performance of the HX/HS that can be tolerated by the system in which the HX/HS is installed. A comparison of prior-fouling and post-cleaning performances will enable an understanding of the efficacy of cleaning procedures.

HIGH EFFICIENCY MILITARY ENVIRONMENTAL CONTROL UNITS (ECUs) FOR HOT CLIMATE WEATHER

Research Assistants: Ammar Bahman, Xinye Zhang, Xiaoshen Wang, Stefan Hotz

Principal Investigator: Professor Eckhard Groll

Sponsors: Adams Communication & Engineering Technology (ACET) and Matern Professional Engineering (MPE)

ABSTRACT

This project focuses on enhancing the performance of transportable ECUs operated at high temperature climates. The aim of the project is to improve the efficiency of the ECU units by 10% to 30%, which could result in an annual fuel saving of nearly 3.3M gallons. The ECU project investigates four units with different capacities: One with 18,000 Btu/hr (1.5 ton of refrigeration), one with 36,000 Btu/hr (3 tons of refrigeration) and two units with 60,000 Btu/hr (5 tons of refrigeration).

To find a more efficient design for the ECUs, the project is divided into several sub-goals for the 18K and 36K ECUs. First, it is suggested to harmonize the airflow across the evaporator coils due to the high air maldistribution. In addition, air-louvers in the return/supplied air duct may avoid any air recirculation. To reduce the electrical power consumption new air blowers are to be selected.

The mid-term goal of the ECU project is to improve the refrigerant flow circuitry of the evaporator of the units. For this part of the study, the effects of interleaving the evaporator circuitries and a hybrid flow control is modeled and simulated. With a hybrid flow control system, it is possible to regulate every circuit of the evaporator individually. The model showed that the effect of power loss could be reduced to half with interleaved circuitries or could be avoided altogether using a hybrid flow control in comparison to the baseline evaporator.

Within the long term goals of the project, the system performance will be improved by evaluating the ECUs using vapor injection with economizing and liquid flooded compression with regeneration technologies.

In order to attain the overall objectives, the various ECUs will be tested in two side-by-side psychometric chambers, one simulating the outside conditions and the other simulating indoor environments. During the tests, data of temperature, pressure, mass flow and electrical power consumption of all components of the unit are collected together with data about temperature, volume flow rate and relative humidity of the flowing air. The proposed changes to the ECUs based on the theoretical analyses will be evaluated experimentally during this phase of the project.

APPLICATION OF A NOVEL CO_2 COMPRESSOR IN A MULTI-TEMPERATURE REFRIGERATED CONTAINER SYSTEM (MTRCS)

Research Assistants: Bin Yang and Dr. Orkan Kurtulus

Principal Investigator: Professor Eckhard Groll

Sponsor: S-RAM Dynamics

ABSTRACT

The mobile carbon dioxide (CO_2) refrigeration system is designed to provide the multi-temperature refrigerated container system (MTRS) with the required cooling capacities simultaneously at two temperature levels. Therefore, two-evaporator systems combined with two compression stages are considered. The high temperature (H.T.) evaporator is used to cool two-thirds of the 20' container to 38°F (3.33°C), while the low temperature (L.T.) evaporator cools the remaining one-third of the container to -5°F (-20.56°C). Four possible cycle configurations are investigated and compared with each other.

Two expansion valves are used in Cycle 1 enabling a low initial investment. However, there is an inevitable considerable amount of work loss through the expansion valves, which decreases the system's performance. Therefore, an expander is employed substituting the expansion valve between the high-side pressure and intermediate pressure in Cycle 2. The work recovered from the expander is used by the 2^{nd} stage compressor to conserve the power demand from the motor. Since the 2^{nd} stage compressor is running at a high pressure ratio, the discharge temperature at the outlet of the 2^{nd} stage compressor is extremely high, causing compressor reliability issues. Therefore, 3-stage compression coupled with intercooling technology is considered in Cycle 3. The intercooler is used to cool down the refrigerant discharged from the 2^{nd} stage compressor to a near-ambient temperature. The pressure ratio across the 3^{rd} stage compressor is expected to be much smaller than in the 2^{nd} stage, leading to a relatively low discharge temperature in comparison to Cycles 1 and 2. Compared to Cycle 3, Cycle 4 uses an expander to replace the expansion valve between the high-side pressure and intermediate pressure to recover the work loss during the expansion process.

By comparing the system performances of these different cycle options, Cycle 4 is shown to be the best choice due to the application of integrated work recovery and intercooling technology in this cycle. Nevertheless, the high-side pressure is very high if the system is running at the optimum COP.

STUDY ON ENERGY-SAVING PERFORMANCE OF ONE TRANSCRITCAL CO_2 HEAT PUMP WITH APPLICATION IN FOOD PROCESSING

Research Assistants: Dr. Yefeng Liu

Principal Investigator: Professor Eckhard Groll

ABSTRACT

In food processing, there are significant simultaneous requirements of heating and cooling. For example, in brewing technology, the malting, mashing, and pasteurization processes need heating. The fermentation, maturation, and cooling after pasteurization processes need cooling. In vegetable and fruit processing, the washing, blanching, and pasteurization processes need heating. The cold storage, and cooling after blanching or pasteurization processes need cooling. In addition, the CIP (Cleaning-in-Place) technique is used commonly in the food processing industry to clean and sterilize the equipment of a factory replacing manual strip down, cleaning and rebuilding of process systems. The process also needs lots of hot water to flush and clear the equipment. In general, in food processing, most of the requirement of cooling temperatures range is 0℃-15℃, and heating temperature range is 25℃-95℃. In the current heating and cooling systems, heating is supplied with natural gas boilers, and cooling is supplied with electrically driven HFC or ammonia refrigeration systems. The current systems consume large amounts of energy.

In order to reduce energy consumption, one transcritical CO_2 heat pump system is proposed to replace the current heating and cooling systems. The CO_2 heat pump system can supply cooling, warm water and 100℃ hot water at the same time, and meet the requirements of heating and cooling of food processing simultaneously. Based on the technical characteristics and primary energy-savings, the CO_2 heat pump system is simulated and compared to the current heating and cooling systems. The results show that the primary energy-savings rate of the CO_2 heat pump ranges from 40% to 55%.

INNOVATIVE OIL-FREE COMPRESSOR AND EXPANDER TECHNOLOGIES FOR AIR-CYCLE HEAT PUMPS

Research Assistant: Domenique Lumpkin

Principal Investigator: Professor Eckhard Groll

Sponsor: S-RAM Dynamics

ABSTRACT

OVERVIEW

The Herrick Laboratories at Purdue University and S-Ram Dynamics collude to produce a state-of-the-art gas cycle refrigeration technology with indistinguishable performance for various applications. The technology uses air as the refrigerant eliminating the use of hydrofluorocarbons (HFCs) with high global warming potentials, and incorporates oil-free compression and expansion resulting in improved heat exchanger effectiveness by eliminating forced oil system requirements. The technology is a high performance regenerative air cycle heat pump for industrial applications that will be two times more energy efficient than the current the heat pump equipment. The proposed system maintains high capacity and performance and generates customer paybacks in less than four years.

METHODOLOGY

The high performance heat pump is the result of the recent invention of a variable stroke piston compressor and variable expander using S-RAM technology, coupled in a modified Stirling/Ericsson closed cycle invented by ReGen. Purdue will perform heat pump performance modeling using the validated Oak Ridge National Laboratory's (ORNL) heat pump design model, design and commission a test stand and test control software that will be used to conduct tests to assess the heat pump performance and verify proper operation of the control system. Once this is completed Purdue will work with ReGen to optimize the controls for highest system efficiency.

EXTENDED BENEFITS

The innovative heat pump will not only eliminate the use of HFCs because air will be the working fluid but has the ability to operate at optimum efficiency under all operating conditions, delivering exceptional part-load and seasonal performance. This heat pump will generate annual energy savings greater than 50% as compared to current heat pump, packaged heating and rooftop units, resulting in a National Total Energy Savings of 1.0 quads for 100% adoption and 0.15 quads for a market penetration of 15%. The oil-free aspect of the technology allows for more diverse system designs, a higher quality air supply, and reduced maintenance costs.

APPLICATION OF CO_2 HEAT PUMP SYSTEM TO MEETE SIMULTANEOUS HEATING AND COOLING DEMAND

Research Assistant: Supriya Dharkar

Principal Investigator: Professor Eckhard Groll

Sponsor: Cooling Technologies Research Center

ABSTRACT

Many commercial buildings, including data centers, hotels and hospitals, have a simultaneous heating and cooling demands depending on season, occupation and auxiliary equipment. Typically, the heat emitted by the electronic equipment in a data center is not used but rejected to the environment. This heat could provide a potential for cost-effective and energy efficient operation of buildings, if integrated appropriately. Liquid–liquid CO2 heat pump systems are a promising technology for such applications.

This project presents the investigation of a data center on the Purdue University, West Lafayette campus. The data center located in the Department of Mathematics is the most energy intensive data center on campus. The cooling load of the data center is approximately 750 kW/hour. On the other hand, the heating load of the buildings during winters is also very high. Winters in West Lafayette are harsh and typically, the heating season last for 7 to 8 months. The heating load of the Mathematics building can go as high as 600 kW/hour during the coldest days of the year. To suffice this simultaneous cooling and heating demand, a liquid-liquid CO2 heat pump is proposed. Presently, the cooling load of the data center is met by eight electrically driven and four steam-driven chillers and the heating load is satisfied by two coal-fired and two natural gas-fired boilers. Simulations are performed to compare the proposed CO2 heat pump system with the present system. The annual calculations show significant energy savings of approximately 20%. The system proves to be very beneficial during winters but does not seem to be an attractive option during the summers. Various system modifications are simulated to improve the efficiency of the system during the summer months. The energy savings can be increased to approximately 25% if two-stage compression with intercooling is used. This assessment also shows noteworthy fuel savings and reduction in the CO2 emissions.

The COP of a heat pump varies depending on the required temperatures for the cooling and heating supplies. Storing pre-produced cooling energy is a key to minimize the investment for the cooling supply systems while using the rejected heat to cover the heating demand which will increase overall building efficiency. Hence, finding optimum thermal storage capacity for reasonable response of time-dependent demands at minimum electricity becomes important. This approach can help reduce the amount of expensive chemical batteries with high penetrations of renewable power sources. Further research will be done to determine the optimum storage tank capacity which will lead to further increase in the system’s efficiency.

ANALYSIS OF A ROTATING SPOOL EXPANDER FOR ORGANIC RANKINE CYCLES IN HEAT RECOVERY APPLICATIONS

Research Assistant: Abhinav Krishna

Principal Investigator: Professor Eckhard Groll

Sponsor: Torad Engineering, LLC

ABSTRACT

The increasing cost of energy, coupled with the recent drive for energy security and climate change mitigation have provided the impetus for harnessing renewable energy sources as viable alternatives to conventional fossil fuels. Furthermore, recovering heat that is discharged from power plants, automobiles and various other industrial processes is of growing interest. Nevertheless, technologies attempting to provide small scale heat recovery solutions have seen very limited commercialization. This is broadly due to two reasons: lack of historical research and development in the area of waste heat recovery and small scale power generation due to technical and cost impediments; and technical challenges associated with scaling the technology from utility scale to commercial scale, particularly with regard to expansion machines (turbines). However, due to rising primary energy costs and the environmental premium being placed on fossil fuels, the conversion from low-grade heat to electrical energy as well as small scale distributed power generation is of increasing interest. In this regard, this project focuses on a novel rotating spool expansion machine at the heart of an Organic Rankine Cycle, which in turn is used as a heat recovery system.

A comprehensive simulation model of the rotating spool expander is presented. Apart from efficiency improvements compared with other rotary machines, the spool expander also has the ability to control the expansion ratio using a novel mechanically-driven suction valve mechanism. Another advantage is the relocation of the face sealing surfaces to the outer radius of the device. The spool expander is also scalable to a size range (50-200 kW) that is problematic for many conventional positive displacement machines, such as scroll or piston expanders, and too small for dynamic machines with respect to manufacturability, efficiency and cost. The simulation model includes detailed submodels for the geometry, suction valve mechanism, massflow, leakage and heat transfer processes. The results of the model reveal several details concerning the impact of design variables on performance. For example, the match between the design expansion ratio and the system imposed pressure ratio has a large influence on the performance of the expander. Further exploration shows that under-expansion is preferable to over-expansion to achieve better performance. The model is also able to provide insights on the dominant leakage paths in the expander. Additional insights can be obtained to assess the sensitivity of various design variables on expander performance. In future work, the model predictions will be validated using experimental data from a 50 kW prototype spool expander.

ORGANIC RANKINE CYCLE USING SCROLL EXPANDER

Research Assistants: Bensi Dong, Chaitanya Wani and Davide Ziviani

Principal Investigators: Professor Eckhard Groll, Jim Braun and Travis Horton

Sponsor: Cummins Inc.

ABSTRACT

Organic Rankine Cycles (ORCs) are one of the most promising and economically interesting technologies to convert waste heat (typically a low grade heat with a temperature range between 100-220^{o}C) into useful work. Thus, ORCs provide an exciting research area for investigators working towards sustainable energy alternatives. The thermal efficiencies of ORCs must be maximized to make them cost-effective. The expander in the cycle has the greatest effect on increasing the thermal efficiency of an ORC when recovering waste heat. To gain a better understanding of various expander efficiencies on the overall ORC performance, a test stand is being developed with R245fa as the working fluid and a rated power output of 5 kWe. This test stand is designed to be used with different expanders for testing their performances and hence facilitate the future research of ORC at the Herrick Laboratories. A scroll expander has been selected as the first expander type to be tested with the designed test stand. The scroll expander is supplied by Air Squared and is an oil-free expander with few moving parts and low noise and vibration. Scroll expanders are fixed volume ratio expanders that have consistently shown high efficiencies in the literature. The scroll technology has established itself as a highly efficient, very reliable, cost-effective alternative to dynamic expansion turbines.

LIQUID FLOODED ERICSSON POWER CYCLE

Research Assistant: Kunal Bansal, Nelson James and Branden Elkins

Principal Investigators: Professors Jim Braun, Eckhard Groll and Travis Horton

ABSTRACT

This research examines the use of liquid flooding to create a high efficiency Ericsson power cycle. The introduction of significant amounts of liquid into the compression and expansion processes of a gas leads to quasi-isothermal behavior approximating that of an Ericsson cycle. Through developing thermodynamic models integrating this phenomenon into an overall cycle, optimal system conditions were identified to maximize the thermal efficiency for various working fluid pairs. It was found that the performance of the power cycle depends greatly on the component efficiencies of the liquid-flooded expander and compressor.

There has been little work in regards to liquid-flooded expansion at the elevated temperatures of interest to the Ericsson cycle. To prove the feasibility and gain a better understanding of high temperature liquid-flooded expansion, a test stand was developed to investigate the performance of a prototype scroll expander operating at elevated temperatures. Nitrogen and thermal oil are used as the working fluids for the experimentation. This research will lead to a better understanding of the potential benefits of liquid flooding in a power cycle and may lead to the implementation of Ericsson cycles as low cost, efficient power cycles for distributed power generation. Of particular interest is solar thermal power generation, where the heat transfer fluid can be directly feed into the Liquid Flooded Ericsson cycle, reducing the need for an additional heat exchanger and driving down cost.

OPTIMAL MATCHING OF A SCROLL-TYPE EXPANDER TO AN ORGANIC RANKINE CYCLE WITH FINITE CAPACITY HEAT SOURCE

Research Assistant: Brandon Woodland

Principal Investigators: Professor Jim Braun, Eckhard Groll, Travis Horton

ABSTRACT

An organic Rankine cycle (ORC) is a power cycle employing an organic working fluid. The term ORC is also applied generally to any Rankine cycle with a low-grade heat source (80 °C – 300 °C). Often, these low-grade heat sources are designated as waste heat. Their energy will be discarded regardless of whether it is utilized. The low temperatures involved require that particular attention be paid to the finite capacity of the heat source. It cannot be regarded as a thermal reservoir. This consideration leads to different optimum designs than those found in traditional power plants.

A potentially promising application for ORC is their use in small-scale, distributed power generation. In this application, use of positive displacement equipment is favored over the turbo machinery (axial or centrifugal units) used in larger-scale power plants. A key feature of a positive displacement expander is its built-in volume ratio.

The interaction between an experimentally tested scroll-type expander and an ORC with a finite capacity heat source is investigated. It has been suggested that the adiabatic efficiency of the expander can be fully characterized by its filling factor and the expansion volume ratio imposed across it. In particular, the peak adiabatic efficiency occurs near a filling factor of unity and an expansion volume ratio near the built-in volume ratio of the expander. A procedure is presented which allows prediction of cycle performance based on knowledge of the expander efficiency as a function of expansion volume ratio, cycle operating conditions, and working fluid. The concept of an optimally matched expander to the cycle and working conditions is described. A graphical means is used to illustrate whether such a match exists. This graphical means makes it clear that, under mismatched conditions, efforts to improve expander efficiency are not as beneficial as they are under matched conditions.

PHYSICAL BASED INVERSE MODELING FOR DIRECT-EXPANSION AIR CONDITIONING SYSTEMS

Research Assistant: Zhidan Zhao

Principal Investigator: Professor Travis Horton

ABSTRACT

Direct-expansion systems are widely used as air conditioners in modern buildings. This type of system dominates the air conditioner market of residential buildings and is commonly used in most small and medium sized commercial buildings. Performance modeling plays an important role in the research of efficiency improvements of the equipment itself and analysis of building energy conservation solutions. Several different inverse models have already been developed for DX systems to capture their performance characteristics. Many of these models are black box models that require the use of massive data with high diversity to train the parameters in the polynomial equations. Once trained, these models are easy to use in an application; however, their extrapolation ability is generally very poor. Current physical-based models, that are also known as gray box models, on the other hand have better extrapolation ability and requires less training data, but they often require catalog data which may not be always available in real cases. The current study provides a physical based inverse model for DX systems, which can be trained using data that is easily measured on site. This model simulates the performance of the DX unit in residential and commercial buildings and provides an efficient method for system energy use analysis.

SIMULATION OF FAULT IMPACTS ON AIR CONDITIONING EQUIPMENT BY INVERSE MODELING

Research Assistant: Dr. Howard Cheung

Principal Investigator: Professor Jim Braun

ABSTRACT

A computer program to simulate the performance of air conditioning equipment under fault impacts is developed by inverse modeling. The equipment models in the program use the models of different faults, such as inappropriate charging of refrigerant and heat exchanger fouling, to estimate their effects on the change of the characteristics of the equipment, such as power consumption and refrigerant pressure, under various environmental conditions.

Multiple semi-empirical component models are combined to create the equipment models. Their empirical coefficients are estimated by training the models with experimental data, and the equipment models operate with fault models to simulate the impact of faults on the equipment performance. The capability of the method to create accurate equipment models is validated by comparing the simulation results with experimental data of eleven different systems.

The modeling method assists the evaluation of the third-party fault detection and diagnostics (FDD) tools in the market. It helps the generation of a large database of the performance of faulted equipment under a wide range of faults and environmental conditions. The FDD tools can be tested to see if they can detect and diagnose the faults in the database correctly under a variety of conditions and if their specification is accurate.

CHARACTERIZING THE IN-SITU PERFORMANCE OF PASSIVE CHILLED BEAMS

Research Assistant: Janghyun Kim

Principal Investigators: Professor Jim Braun and Thanos Tzempelikos

ABSTRACT

Standard EN 14518 is a testing and rating procedure for passive chilled beams that includes a means of characterizing performance using a simple model that relates cooling capacity to a temperature difference between room air and water supply. This study evaluates the ability of that model to characterize the performance of passive chilled beams that are installed in an open office space. It is found that this model characterization does not capture the important effect of ventilation air flow on chilled beam performance. As a result, an alternative empirical model is proposed and evaluated using data obtained from the office. In addition to temperature difference between room air and water used by the Standard EN 14518 model, terms for mass flow rate and space ventilation rate are included in the regression model. The measurements were conducted during unoccupied hours and the average cooling capacity of a single passive chilled beam unit was calculated by averaging results for all of the passive chilled beam units' installed within the office. The proposed model provides better estimates of the in-situ cooling capacity of passive chilled beams (and their surface temperatures) when installed in a typical space where typical ventilation for fresh air is provided.

EMBEDDED FAULT IMPACT EVALUATION STRATEGIES FOR RTU FDD

Research Assistant: Andy Hjortland

Principal Investigator: Professor Jim Braun

ABSTRACT

Recent advancements in virtual sensing technologies for packaged air-conditioning equipment have brought automated fault detection and diagnostics tools closer to realization. This is important because studies have shown that this type of equipment tends to be poorly maintained and significant energy may be wasted due to prolonged suboptimal operation. While earlier detection and isolation of faults is big step forward, making optimal service decisions may be more important to building managers or service organizations. In this research, embedded virtual sensors are used to determine degradations in cooling capacity and COP of rooftop air conditioners. Using a graybox fault impact inverse model, these degradations are characterized for different fault severities and driving conditions. Future work will be to use this understanding for determining overall energy and operating cost impacts as well as to determine optimal maintenance actions when multiple simultaneous faults are present.

VIRTUAL HVAC METERING FOR ROOF TOP UNITS WITH MICRO CHANNEL CONDENSERS

Research Assistant: Jebaraj Vasudevan

Principal Investigator: Professor Travis Horton

ABSTRACT

In order to improve existing fault detection and diagnostics methodologies for heating, ventilation, and air-conditioning (HVAC) equipment, virtual sensor technology has been applied to systems to provide more useful diagnostic inputs and reduce initial sensor costs. Virtual sensors are designed to measure quantities that are normally expensive or impossible to measure directly using other lower cost measurements and mathematical models relating these measurements to the desired quantity.

One of the motivations for improved FDD tools is the regulatory requirements of future HVAC equipment. In response to the 2013 California Title 24 requirements, manufacturers were required to provide tools capable of detecting and diagnosing problems associated with outdoor-air economizers (OAE) on rooftop air conditioners (RTU). The next revision of California Title 24 requirements may include more RTU diagnostics requirements such as improper refrigerant charge levels or condenser and evaporator fouling. Extensive laboratory studies aimed at developing virtual sensors for different types of equipment have been performed previously. These types of equipment include RTUs, split-type residential heat pumps, and variable refrigerant flow multi-split heat pumps. Different types of subcomponents were also tested, including single-speed and variable speed compressors, as well as different types of expansion valves including short-tube fixed orifices, thermostatic expansion valves, and electronic expansion valves (EXV).

In the recent past, RTUs with micro channel condensers have begun to appear more frequently in new production units. The micro channel condensers have the advantage of reducing the condenser coil size requirement with enhanced heat transfer characteristics as well as reducing the amount of refrigerant charge needed for the system to operate optimally. This reduction in charge can be significant, sometimes reducing the rated charge by as much as 50% over similarly sized units as compared to the conventional fin-tube condensers. But, how this reduction in normal charge affects the performance of virtual sensors has not yet been studied. Hence, this project would focus on extending the virtual sensors for refrigerant charge, COP, capacity and compressor power for roof top units with micro channel condensers.

LOW-COST VIRTUAL POWER AND CAPACITY METER FOR ROOFTOP UNITS

Research Assistant: Dr. Howard Cheung

Principal Investigator: Professor Jim Braun

ABSTRACT

A low-cost virtual sensor is developed to estimate the power consumption and cooling capacity of the rooftop units (RTUs) in small commercial buildings. The sensor package is designed to be inexpensive by not taking any direct measurement of cooling capacity for virtual sensor training and using low-cost sensors to measure the air and refrigerant temperature in the RTUs for reliable and accurate estimation of power consumption and cooling capacity.

The virtual sensor is constructed based on energy balance equations of the RTU operation and semi-empirical models of the compressor operation. The sensor is trained by estimating the unknown parameters in the equations with the temperature and power consumption readings. The accuracy of the capacity meter is validated by experimental data from four laboratory-tested systems, and the accuracy of the power consumption sensor is validated by experimental data from three field-operating systems.

The virtual sensing technology reduces the measurement cost in the field. This helps to make the advanced control strategies for efficient building control, which depend on more measurement than conventional strategies, more affordable to small business owners. This encourages them to use the new technology to reduce energy consumption.

HVAC SOLUTIONS FOR EXISTING SMALL- AND MEDIUM-SIZED COMMERCIAL BUILDINGS RETROFIT OPPORTUNITIES

Research Assistant: Bonggil Jeon and Janghyun Kim

Principal Investigator: Professor W. Travis Horton

Sponsor: DOE – Consortium for Building Energy Innovation (CBEI)

ABSTRACT

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

IMPACT OF CLIMATE CHANGE ON HEATING AND COOLING ENERGY USE IN BUILDINGS IN THE UNITED STATES

Research Assistant: Haojie Wang

Principal Investigator: Professor Y. Chen

ABSTRACT

Global warming has drawn great attention in recent years because of its large impact on many aspects of the environment and human activities in buildings. One area directly affected by climate change is the energy consumption by heating and cooling systems. In order to quantify the impact, this study used the HadCM3 Global Circulation Model (GCM) to generate weather data for future typical meteorological years, such as 2020, 2050, and 2080, for 15 cities in the U.S. on the basis of three CO_2 emission scenarios. By means of a morphing method, the weather data was downscaled to hourly data for use in building energy simulations by EnergyPlus. Two types of residential buildings and seven types of commercial buildings were simulated for each of the 15 cities. This study found that the impact of climate change varied greatly by geographical location and building type. There would generally be a net increase in source energy consumption by the 2080s, but it may decrease slightly in some locations. In addition, this study investigated natural ventilation performance in San Francisco, San Diego, and Seattle. The results showed that by the 2080s passive cooling would not be suitable for San Diego because of global warming, but it would still be acceptable for San Francisco and Seattle.

INTEGRATION OF OCCUPANT INTERACTIONS WITH SHADING DEVICES ON MODEL PREDICTIVE CONTROL OF MIXED-MODE BUILDINGS

Research Assistant: Seyed Amir Sadeghi

Principal Investigator: Professor Panagiota Karava

ABSTRACT

Occupant presence and behavior in office buildings has been shown to have large impact on space heating, cooling and ventilation demand, energy consumption of lighting and space appliances, and building controls. It is often one of the main causes of underperforming green buildings by a factor of two or more in energy performance. Occupant interactions with comfort delivery systems such as shading devices, lights and thermostats are exogenous inputs that can be implemented as stochastic disturbances into building automation systems.

This study presents a stochastic model predictive control (SMPC) framework for buildings with mixed-mode cooling and demonstrates a comparison with deterministic model predictive control (DMPC) and standard rule-based control (RBC). A probabilistic model of occupants' behavior on window blind closing event is used to represent the stochastic disturbance acting on the system over the prediction horizon. Monte Carlo (MC) simulation is used to capture this stochastic effect. The test-buildings located at the Architectural Engineering Laboratories of Purdue University. These advanced control strategies aim to optimize the switching between free (natural) and mechanical cooling. In the MPC framework, the decision space is the operating schedule of the motorized windows used for free cooling and the objective is to minimize the energy use with comfort constraints.

The simulation results show that SMPC may lead to higher amount of energy consumption which provides a more realistic prediction since it considers the occupant-building interactions. Also it was found that SMPC results in lower thermal comfort violations than DMPC and significantly lower compared to RBC. Future research will further develop the implementation of occupants' behavior prediction models into building automation systems.

SYSTEM IDENTIFICATION AND MODEL-PREDICTIVE CONTROL OF OFFICE BUILDINGS WITH INTEGRATED PHOTOVOLTAIC-THERMAL COLLECTORS, RADIANT FLOOR HEATING AND ACTIVE THERMAL STORAGE

Research Assistants: Jaewan Joe and Siwei Li

Principal Investigator: Professor Panagiota Karava

ABSTRACT

The present study explores efficient integration approaches of photovoltaic-thermal systems coupled with corrugated transpired solar collectors (building-integrated photovoltaic-thermal, BIPV/T), Heating, Ventilation and Air Conditioning (HVAC) systems and thermal storage devices, to enable optimal collection and utilization of solar energy in high performance buildings. The objective is to (a) develop models that capture the relevant system dynamics and are computationally efficient for subsequent use within model-predictive control (MPC) algorithms; (b) evaluate the energy saving potential of the integrated system and the predictive controller in comparison with baseline operation strategies. An open plan office space at Purdue's Living Laboratory is used as test-bed, in which the BIPV/T system preheats ventilation air, while also, it is coupled with the building through an air-to-water heat pump and a thermal energy storage (TES) tank that serves as the heat source for the radiant floor heating (RFH). A detailed energy prediction model developed in TRNSYS is considered as a true representation of the building and it is used to identify the parameters of low-order linear time-invariant state-space models. Both gray-box and subspace state-space system identification (4SID) methods are investigated. A simulation study is performed using TMY3 data for West Lafayette, IN during the heating period. The results show that implementation of a deterministic MPC algorithm for the optimal set-point trajectory of the TES tank can reduce the electrical energy consumption of the heat pump by 34.5 %. For the BIPV/T configurations tested, the energy saving of the integrated solar system can be up to 45 % compared to the baseline operation of the radiant floor heating. The study also investigates the impact of forecast uncertainty for the horizontal solar irradiance on MPC performance with the results showing a considerable impact on thermal comfort conditions when the prediction error is higher than 38 %.

MULTI-AGENT CONTROL FOR CENTRALIZED AIR CONDITIONING SYSTEMS SERVING MULTI-ZONE BUILDINGS

Research Assistant: Jie Cai

Principal Investigator: Professor Jim Braun

ABSTRACT

Coordinating different components in a complex air conditioning system is challenging for centralized controls due to the large number of optimization variables. Under this scenario, de-centralized controls are more appropriate alternatives. This study proposes a multi-agent control methodology for optimal control of centralized air conditioning systems that are typically adopted in multi-zone commercial buildings. A hierarchical multi-agent framework is developed in which the agents cooperate to find the optimal operating point. Two consensus distributed optimization algorithms are formulated for this specific type of problem, which form the underlying mechanism of intra-agent optimization and inter-agent cooperation. Finally, a 3-zone building case study is used to demonstrate the performance of the proposed approach.

EXPERIMENTAL DEMONSTRATION OF PLUG AND PLAY MULTIPLE RTU COORDINATION ALGORITHM

Research Assistants: Donghun Kim, Jie Cai, David L. Fugate, Phani T. Kuruganti, James J. Nutaro

Principal Investigator: Professor Jim Braun

ABSTRACT

There has been very few advanced control algorithms developed for small commercial buildings due to practical difficulties such as the spatial comfort variations, significant disturbances, high sensor costs, and high cost of site-specific engineering solutions. High implementation cost has been a major impediment to successful market penetration. The focus of this work is to develop and demonstrate plug-and-play optimal coordination of multiple roof top units (RTUs). The goal is to minimize the time required to configure the control strategy in order to enable a more cost effective control implementation for small commercial building applications. The approach includes an adaptive control strategy for learning building system response. The proposed algorithm has been implemented for a gymnasium served by 4 RTUs. The benefits are evaluated compared to a conventional feedback control.

IMPACT OF NET METERING PROGRAMS ON OPTIMAL LOAD MANAGEMENT IN US RESIDENTIAL HOUSING – A CASE STUDY

Research Assistant: Emeline Georges

Principal Investigators: Professors Jim Braun, Eckhard Groll and Travis Horton

ABSTRACT

In the US, buildings represent around 40% of the primary energy consumption and 74% of the electrical energy consumption. Incentives to promote the installation of on-site renewable energy sources have emerged in different states, including net metering programs. Net metering allows customers to supply their excess local electricity production to the electricity grid. This excess electricity is "bought-back" at a given tariff, therefore reducing the customer's electricity bill. The fast spread of such distributed power generation represents additional challenges for the management of the electricity grid hence the interest in smart control of building electrical loads and demand response programs.

This paper presents a study of a typical American house built in the 1990s in the Midwest and equipped with a single-speed air-to-air heat pump, an electric water heater and PV collectors. There are two ways for such buildings to interact with the electricity grid. On the one hand, they can offer flexibility (load shifting, peak shaving, etc.) in response to signals from the grid. On the other hand, when equipped with on-site generation, such as PV collectors, they can be used to diminish the impact of distributed energy production by promoting better load matching between the building electrical load and the PV production through load shifting in time. This study investigates the impact of different net metering tariffs on the optimal building electrical load management. The potential of load matching is characterized in terms of percentage of the electricity production consumed on-site and the proportion of the demand covered by local electricity generation.

Results show a potential increase of load matching greater than 9% through control optimization with a suitable net-metering tariff. The associated cost saving for the consumer is about 10% greater compared to no optimization. Depending on the PV panel area, pay-back time increase due to buy-back tariffs lower than the retail price can be reduced by 19 to 40% through optimal load matching.

APPLICATION OF NEAR-OPTIMAL TOWER CONTROL AND FREE COOLING ON THE CONDENSER WATER SIDE FOR OPTIMIZATION OF CENTRAL COOLING PLANTS

Research Assistant: Rita Jaramillo

Principal Investigators: Professors Jim Braun and Travis Horton

ABSTRACT

This work consists of an application of tower fan control for optimization of the performance of chiller plants combined with free cooling on the condenser water side. Mathematical models including all the main components of an existing cooling plant (Northwest Chiller Plant at Purdue Campus) were developed and implemented in MATLAB. Simulation results include a mapping of the performance of the plant working in free cooling mode which was used to select control parameters for free cooling operation. Then a mapping of the plant operating with chillers was developed to find the correlation between load and near-optimal air flow, which is the basis of the near-optimal tower control (NOTC) strategy. Finally, simulations were carried out using three consecutive years of historical data to predict the performance of the plant under three different control strategies: 1) tower fan control aiming to keep the temperature of the water supplied to chiller condensers at a constant set point (current control strategy), 2) NOTC and 3) NOTC and free cooling combined. Comparison of the performance of the plant with the baseline (constant condenser water temperature) shows that significant savings can be achieved through the implementation of NOTC along with free cooling. It is expected that the methodology and results of this study provide a useful framework for optimization of central cooling plants.

EVALUATION OF CONTROL MEASURES INCLUDING VENTILATION ON CRUISE SHIPS FOR INDOOR RESPIRATORY DISEASE TRANSMISSION

Research Assistant: Lijie Zheng

Principal Investigator: Professor Qingyan Chen

ABSTRACT

Cruise ships are becoming increasingly popular in the travel market. The respiratory disease featured the most common disease on cruise ships. However, the quantitative risk assessment of onboard respiratory disease airborne transmission hasn't been evaluated. This paper presented an integrated model incorporating Wells-Riley probability model, Competing-risks model and Susceptible-Exposed-Infected-Recovered (SEIR) individual-based model based on an onboard indoor social contact network built suitable for a typical cruise ship voyage. The model was validated by a previous influenza outbreak and could simulate the full dynamics. The model was used to assess the impacts of multiple control measures combining engineering control measures and public health interventions using influenza as an example of respiratory diseases. An infected passenger and an infected crew member were as the initial conditions, respectively. The results show that the infection risk initiating from one infected crew member is bigger than the infection risk initiating from one infected passenger. Crew cabins and restaurants have higher infection risks than other locations. Surgical face-masks worn by crew members can slow down the infection speed from passengers to crew members. Increasing air change rates in some or all locations will reduce the infection risk to some extent. The earlier to identify the original infector and adopt the isolation measure, the better to obtain the control efficacy. Using HEPA filters and UVGI devices will decrease the infection risk dramatically. Combining multiple control measures of wearing surgical face-masks, using HEPA filters and UVGI devices and isolating the original infector and other persons in the same stateroom or crew cabin after the first day from start day will obtain the best efficacy than other control measures, almost containing the influenza outbreak onboard. The model can offer an initiative applicable to a real cruise ship to investigate the airborne transmission, predict the optimal control measures and to protect susceptible passengers and crew from respiratory disease infection.

VENTILATION AND INDOOR/OUTDOOR OZONE CONCENTRATION

Research Assistant: Dayi Lai

Principal Investigator: Professor Qingyan (Yan) Chen

ABSTRACT

Ozone is known for its association with morbidity and mortality. It will lead to respiratory symptoms, such as asthma and decreased lung function. Indoor ozone mainly originates from outdoor and enters the building through three different ventilation mechanisms: infiltration, natural ventilation and mechanical ventilation. This study investigated the relationship between ventilation and indoor/outdoor ozone concentration by measuring indoor/outdoor ozone concentration and ventilation rate at a test chamber and an actual office space under different ventilation strategies. The ventilation rate is measured by the decaying of Sulfur Hexafluoride (SF_6) gas. The surface deposition rates were estimated from previous literature. The results show that the indoor/outdoor ozone concentration can be predicted by a simple steady state model within 80% accuracy. It is also found that higher ventilation rate will contribute to higher indoor/outdoor ozone ratio. Further study will employ the verified model to investigate the indoor ozone exposure level for different major U.S. cities under different climate for current climate and future weather under climate change. The knowledge gained would be helpful to propose particular building ventilation strategies to mitigate indoor exposure.

SIMPLIFIED MODELS FOR EXHALED AIRFLOW FROM A COUGH WITH THE MOUTH COVERED

Research Assistant: Chun Chen

Principal Investigator: Professor Y. Chen

ABSTRACT

Covering a cough can be useful in reducing the transmission of airborne infectious diseases. However, no simple method is available in the literature for predicting the exhaled airflow from a cough with the mouth covered. This investigation used smoke to visualize the airflow exhaled by 16 human subjects. Their mouths were covered by a tissue, a cupped hand, a fist, and an elbow with and without a sleeve. This study then developed simplified models for predicting the airflow on the basis of the smoke visualization data. In addition, this investigation performed numerical simulations to assess the influence of mouth coverings on the receptor's exposure to exhaled particles. It was found that covering a cough with a tissue, a cupped hand, or an elbow can significantly reduce the horizontal velocity and cause the particles to move upward with the thermal plumes generated by a human body. In contrast with an uncovered cough, a covered cough or a cough with the head turned away may prevent direct exposure.

MUNERICAL AND EXPERIMENTAL STUDY OF GASPER-INDUCED AIRFLOW IN AIRCRAFT CABIN

Research Assistant: Ruoyu You

Principal Investigator: Professor Qingyan (Yan) Chen

ABSTRACT

Gaspers are prevalently installed in the aircraft cabins as personalized ventilation systems to improve thermal comfort and provide clean air that may prevent the transmission of airborne infectious diseases. However, the interaction of the gasper jets with thermal plumes from passengers could lead to high turbulent intensity, which may lead to draft for the passengers. On the other hand, the jets could enhance flow and gaseous contaminant dispersion in longitudinal direction that may enhance the transmissions of airborne infectious diseases. Therefore, it is necessary to investigate how to use gaspers for enhancing cabin environment. The objective of the study is (1) to design a simple but reasonable experimental rig that can be dedicated to obtain high-quality experimental data of gasper-induced flow; (2) to identify a suitable CFD model by using the experimental data for studying the airflow and gaseous contaminant transfer in a fully occupied cabin with gaspers on; and (3) to investigate numerically how gaspers can be used in an airliner cabin to improve thermal comfort and to prevent airborne disease transmissions. Progress has been made in the first objective. This study constructed a half of a one-row, occupied, single-aisle aircraft cabin mockup, and then used a Particle Image Velocimetry (PIV) system to measure the airflow field at an area of the cross-section. The results showed that constructed aircraft cabin mockup and the PIV system can be used to measure the gasper-induced airflow field.

THE IMPACT OF ROLLER SHADE PROPERTIES ON DAYLIGHTING AND VISUAL COMFORT

Research Assistants: Ying-Chieh Chan and Iason Konstantzos

Principal Investigator: Professor Thanos Tzempelikos

ABSTRACT

Previous studies have shown that the solar optical properties of roller shades directly impact daylight availability and visual comfort, but these have not been quantified in detail. In the shade selecting decision-making process, visual comfort should be a priority; therefore, designers should first select shades which can eliminate daylight glare issues when shades are fully closed. Other factors such as daylight availability, view clarity, and energy should then be considered.

The objective of this study is to define proper ranges of roller shade properties under different scenarios. The considered scenarios include combinations of different climates, orientations, glazing properties, windows-to-wall ratios, and occupants' seating locations. A series of annual daylighting simulations have been conducted to investigate the annual glare probability and continuous daylight autonomy with closed shades. The simulation method accelerates the calculation process by utilizing a hybrid radiosity and ray-tracing model combined with visual comfort (DGP) calculations. An advanced semi-empirical model is used as a sub-module in the hybrid method to obtain detailed results of the solar optical properties of roller shades, which highly affect the accuracy of daylight metrics and glare.

INTEGRATED OPTICAL AND THERMAL MODEL OF EXTERNAL COMPOUND PARABOLIC CONCENTRATOR IN THERMAL APPLICATION

Research Assistant: Donghao Xu

Principal Investigator: Professor Ming Qu

ABSTRACT

External compound parabolic concentrator (XCPC) is a type of stationary solar concentrators. Its cost effectiveness and high efficiency in medium temperature range, 100°C to 250°C, makes it a not only viable but also promising solution to solar thermal applications in medium temperature range. To investigate the performance and enable optimal design of XCPCs, we developed and validated an integrated optical and thermal model using experimental data. Even though previous researchers have studied optical and thermal performance of XCPCs, their models are mostly separate and seldom validated against experiments. In addition, the accuracy of these studies is diminished due to numerical approximations in ray tracing and assumptions for simplicity. To improve the research on XCPCs, we integrated both optical and thermal models. The optical model utilizes a novel ray tracing program of higher order of accuracy while the thermal model includes both convection and radiation heat transfer. Then the model was validated against experiments under various outdoor and operation conditions. The comparison shows a good agreement between model and experiments. The preliminary results show that the solar flux is non-uniformly distributed on absorber; vacuum between absorber and glass envelope is very critical to thermal performance once which is broken efficiency decreases significantly especially at high operating temperature; and that under outdoor conditions the convection in the XCPC cavity without cover is forced convection dominated.

DEVELOPMENT OF THE SORPsim SOFTWARE

Research Assistants: Zhiyao Yang and Xin Tang

Principal Investigator: Professor Ming Qu

Sponsor: Oak Ridge National Laboratory

ABSTRACT

Absorption systems are important alternatives to conventional vapor compression systems (VCS) in air-conditioning applications, as they are primarily heat-driven, and thus can work very well with renewable energy such as solar heat and other low-grade energy source such as waste heat from power plant. However, since both closed-cycle and open-cycle absorption systems (liquid desiccant systems) are more complex than typical VCS, the modelling of both types of absorption systems are often complicated, programming-demanding, and laborious, and this is hindering the research and development of new absorption systems. Thus an easy-to-use modelling tool with specialties in dealing with absorption systems is highly needed.

The SORPsim software has been develop to meet this avid need for a reliable and user-friendly modelling tool for closed-cycle absorption systems and liquid desiccant systems. The SORPsim software is equipped with a powerful yet flexible simulation engine as well as a versatile and intuitive Graphical User Interface (GUI) to provide the capability of both accurate and user-friendly modelling of absorption and liquid desiccant systems. The simulation engine of the SORPsim software is based on a modular code that enables it to model various absorption cycle configurations using different working fluids. Moreover, models of dehumidifier and regenerator have been developed, validated, and implemented in the engine to enable it with liquid desiccant system modelling capability. The GUI utilizes specially designed data structure to store and manipulate large amount of case data corresponding to that in the simulation engine. During system configuration and calculation, no programming is needed from the user, as the governing equations of standard components and properties of commonly used working fluid have been embedded in the code. The number of the equations and variables are closely monitored to provide hint for successful convergence. The simulation results can be displayed in various forms and easily exported for later use. After calculation, parametric analysis can be carried out within the software using its table and plot functions to study the trend of change and find optimized point.

The SORPsim software has been developed to provide capability for users to build any absorption and liquid desiccant cycle from scratch with ease, to define parameters of the system for convergence, as well as to conduct parametric study. It can be used to facilitate the modelling research and development of both closed-cycle absorption systems and liquid desiccant system.

PERFORMANCE ANALYSIS OF AN INTEGRATED SYSTEM OF VAPOR-COMPRESSION CHILLER AND ABSORPTION HEAT PUMP

Research Assistant: Yi-Shu Kung

Principal Investigator: Professor Ming Qu

ABSTRACT

Subcooling the refrigerant from the condenser in a vapor compression refrigeration system could be an effective approach to improve the efficiency. The effort in this research has investigated the efficiency improvement of a Vapor-compression chiller and Absorption heat pump Integrated System (VAIS) by using the approach. The VAIS uses the chilled water from the absorption heat pump (AHP) to subcool the refrigerant of the vapor-compression chiller (VC) by adding a heat exchanger, called a subcooler, between the condenser and the expansion valve of the VC. Additionally, the VAIS can also provide useful hot water provided from the AHP.

A test bed of the VAIS was constructed at Purdue University to test system performance. A series of tests have been conducted and the experimental data was collected from the tests. Meanwhile, models for the VAIS based on thermodynamic and heat transfer principles were developed to analyze the experimental data and further for the prediction of the system performances at variant conditions. These models developed are able to predict the working conditions of the VAIS including temperature, pressure, flow rate, enthalpy, energy, and others. The validated models will be also used for the establishment of VAIS control system and life cycle assessments.

The testing results indicate the VAIS of the test bed can increase around 30% of cooling power while consuming the same electricity. Additionally, the hot water produced by the VAIS shows additional strength of the technology. The hot water can be used for domestic hot water, swimming pool or space heating with additional heat inputs. Since the VAIS can provide both heating and cooling simultaneously, it is especially suitable for buildings with both demands at the same time like hotels, chain restaurants, and supermarkets.

HIGH FREQUENCY SOUND FIELD SIMULATION FOR MULTIPLE SOURCES USING LOCAL BASIS REPRESENTATIONS

Research Assistant: Yangfan Liu

Principal Investigator: Professor J. Stuart Bolton

ABSTRACT

In simulating high frequency sound fields, the method of local basis representation (in which each basis determines the sound field within a limited spatial region) has been proposed previously as an alternative to traditional acoustical holography methods. The new method was based on the approximation of the radial dependence of the spherical wave representation by $\exp(jkr)/(kr)$ where the sound field was assumed to have only one compact source at the origin. Here, a more general formulation for the local basis method is proposed for the case of multiple sources. The sound field is represented as a sum of multiple spherical wave series, with origins placed at the location of each source. For each spherical wave series, the same approximation as in the previous work, was used for the radial dependence, whereas the angular dependence is interpolated based on the nodal sound field values on the mesh generated on the unit sphere centered at its origin. These nodal values are then estimated by a least-square match to the measurements: thus the sound field in the whole space can be predicted. Numerical simulations with complicated high frequency sound fields have been performed to illustrate the validity of the proposed method.

OPTIMIZATION OF MULTI-LAYER MICROPERFORATED SYSTEMS FOR ABSORPTION AND TRANSMISSION LOSS

Research Assistant: Nicholas Kim

Principal Investigator: Professor Stuart Bolton

ABSTRACT

Since the impedance of microperforated panels (MPPs) was first derived by Maa, there have been continuing efforts to apply microperforated panels in various ways as clean, fiber-free sound absorbing materials. The acoustic properties of MPPs depend on whole diameter, thickness, porosity, mass per unit area, and air cavity depth. These five parameters control the peak location and the magnitude of both the absorption coefficient and transmission loss. It is possible to find a combination of these parameters that result in high levels of absorption over one or two octaves. However, to provide an appropriate solution for noise control over a broader range of frequencies, it is necessary to design multilayer MPPs. In this research, multilayer MPPs intended for use as functional absorbers are considered, and the focus is on the speech interference range, say 500 to 4000 kHz. The transfer matrix method has been used for calculating both the transmission loss and absorption coefficient. The design of a *N*-layer MPP depends on 5*N*-1parameters and to optimize the acoustic properties, a genetic algorithm has been used. From the results, the best combination of MPP properties and configuration has been identified to improve the acoustic performance in a prescribed frequency range.

THE USE OF MICROPERFORATED MATERIALS AS DUCT LINERS

Research Assistant: Hyunjun Shin

Principal Investigator: Professor Stuart Bolton

ABSTRACT

The acoustical performance of a microperforated panel and a fibrous material are compared to confirm that a microperforated panel lining can be used to replace a fibrous lining as a sound absorber in a duct. Fibrous materials are often used to line ducts in order to attenuate HVAC noise, for example. These treatments are often primarily useful in a limited frequency range owing to the characteristics of non-planar wave propagation in ducts. At the same time, microperforated materials backed by a finite-depth air space are effective in a limited frequency range owing to the nature of the reactive impedance of this combination. Here it will be shown that microperforated materials may be used to create duct linings that produce attenuation comparable with that of fibrous materials. The characteristics of the microperforated panel were studied based on the Maa model. To compare the performance of these two linings, theoretical, numerical and experimental cases were studied. In the case studies, both extended reaction and locally-reacting treatments are considered. For the analytical approach, Morse's theory was applied in the local reaction case. On the other hand, Scott's analysis was used to study the extended reaction case. In the experimental work, the transmission losses of various samples were measured in the square impedance tube. To tune these performance of a microperforated sheet to reproduce that of a fibrous material, the hole size, porosity, thickness, density, and air-backing depth were modified. To validate the experimental and analytical data and to handle situations that are not easily modeled using an analytical approach, a finite element model was used for the calculation. For the finite element model analysis, COMET/VISION and SAFE were used. Since the software does not include explicit microperforated material models, an alternative approach was used. The alternative model was based on the Attala and Sgard model. Alternative rigid porous material successfully handles the microperforated panel in the finite element model. Furthermore, it was demonstrated that the microperforated panel can successfully reproduce the acoustical performance of glass fiber as a duct lining material.

DESIGN OF MULTI-CHAMBER SILENCERS WITH MICROPERFORATED ELEMENTS

Research Assistant: Seungkyu Lee

Principal Investigator: Professor Stuart Bolton

ABSTRACT

The objective in this study was to develop a compact, multi-chamber silencer incorporating dissipative microperforated elements that could be used to reduce transmitted noise in a flow system. Two expansion mufflers in series were used to create a relatively compact system that attenuated sound effectively over the speech interference range. The microperforated elements were used both to increase the acoustic performance of the silencer and to reduce the system pressure drop with respect to a muffler without a microperforated lining. Both Finite Element Modeling (FEM) simulation and experimental methods were employed in the detailed design of the multi-chamber silencer. In the FEM simulations, the microperforated lining was modeled as a fluid layer having complex properties, and the model was used, for example, to identify the optimal flow resistance of the microperforated lining. The predicted results were successfully compared with full-scale experimental results that were obtained by using a four-microphone standing wave tube.

INFLUENCE OF INFLOW CONDITIONS ON TURBINE LOADING AND WAKE STRUCTURES PREDICTED BY LARGE EDDY SIMULATIONS USING EXACT GEOMETRY

Research Assistants: Nina Zhou and Xiangyu Gao

Principal Investigator: Professor Jun Chen

ABSTRACT

A Large Eddy Simulation (LES) is performed on a NREL Phase VI wind turbine (10-meter diameter), using the exact blade geometry, to gain insight about the influence of different inflow conditions on the aerodynamic loadings and the near wake characteristics. The effects of three inflow conditions: uniform inflow, linear wind shear, and linear wind shear with turbulence, are investigated. The presence of wind shear results in periodic variations in the power production and aerodynamic loading with an additional force component exerted along the lateral direction. Significant separation occurs in high wind region on the suction side of the blades, resulting in unstable loading in off-design inflow conditions. Due to the shear effect between near-blade tip vortex and ambient flow, the strong vortex core in the helical structure dissipates and transforms to a continuous vorticity sheet when $x/D > 1.5$. The combination of inflow turbulence and wind shear enhance the turbulence generation mechanism in the near wake, where energy is withdrawn from large wake structures and converted into energy of small-scale structures.

NUMERICAL SIMULATION OF AXIAL FAN NOISE

Research Assistant: Nina Zhou

Principal Investigator: Professor Jun Chen

ABSTRACT

Axial fans are used in a wide variety of applications. The noise radiated by CPU cooling fans is receiving increasing attention recently. Identifying and quantifying the exact noise source in the fan assembly are of great importance for designing quieter cooling fans. In the present study, a Large Eddy Simulation (LES) is performed on an axial cooling fan (10.5 cm diameter) to obtain unsteady flow fields, and a boundary element method (BEM) is employed to accurate predict the blade passing frequency (BPF) noise and its harmonics. Significant pressure fluctuations on blades are observed, which serve as a strong source of unsteady loads (rotating dipole). The BEM analysis shows the peak value of sound pressure level (SPL) is 30 dB at the BPF, which agrees with laboratory measurement under identical conditions. The SPL decreases from the first harmonic to the forth harmonic.

WAKE AND LOADING ANALYSIS OF WIND TURBINE ARRAYS

Research Assistants: Xiangyu Gao and Nina Zhou

Principal Investigator: Professor Jun Chen

ABSTRACT

A numerical simulation of unsteady flow is performed on a wind turbine array to characterize the wake and aerodynamic loadings of wind turbines under yawed inflow conditions. The computations are carried out by incorporating Actuator Line (AL) Method into Large Eddy Simulation (LES) within OpenFOAM (Open Field Operations and Manipulations) CFD toolbox. This methodology is validated by comparing the results with predictions obtained by large eddy simulation using exact 3D blade geometries of a two-blade NREL Phase VI turbine (10-meter diameter). Then it is used to simulate the wake development in a wind farm with six NREL Phase VI turbines under yawed inflow conditions. It is discovered that in the partial wake setting the upstream turbines have a significant influence on the wake structure of the downstream turbines. Then the dynamic loadings and power output of downstream turbines are analyzed with Blade Element Momentum (BEM) method. It is observed that the existence of the upstream turbines will result in decreased streamwise loadings, but increased loadings in lateral directions. Present work also demonstrates that the LES-AL simulation in OpenFOAM can be an effective tool to characterize turbine wake and loading in a wide variety of inflow conditions.

AN ANALYTICAL METHOD FOR CALCULATIG THE MESH STIFFNESS OF HELICAL GEAR WITH PROFILE MODIFICATION

Research Assistants: Cong Liao and Chongjie Gu

Principal Investigators: Professors Kai Ming Li and Charles Krousgrill

ABSTRACT

Helical gears are largely used in industry for low noise application with a high load to volume ratio. Research on the time-varying mesh stiffness has received significant attention from researchers in their endeavors to improve the performance of quiet running of helical gear systems. This study presents an analytical method to calculate helical gears time-varying gear mesh stiffness that provides an indication of different factors affecting the condition of gear tooth approaching and recessing. One of the factors for changing the mesh stiffness can be achieved by modifying the gear profiles. The calculations based on the finite element analysis have also been applied to validate and ameliorate the analytical model. The evaluation of excitation induced by mesh stiffness variation can be applied to for modifying gear profile to develop a less noisy helical gear system.

REDUCTION OF NVH SOURCES OF THE HELICAL GEAR SYSTEM BY MODIFICATION OF GEAR PROFILES

Research Assistants: Darioush Kevian Esfahani and Cong Liao

Principal Investigators: Professors Kai Ming Li and Charles Krousgrill

ABSTRACT

Helical gears are largely used in industry for high speed, high power and low noise mechanical systems. Noise, Vibration, and Harshness (NVH) engineering aims to be referred as the sound quality analysis that provides an important factor to distinguish a helical gear system with low noise levels. The vibration of the helical gear system is generated by three kinds of excitation. The first cause is micro-geometry deviations in gear tooth surfaces due to manufacturing errors. The second is a parametric excitation by the periodical change of the tooth mesh stiffness. The third is a moving load on the tooth surface during the progress of mesh of the teeth. In this study an analytical method to calculate helical gears time-varying gear mesh stiffness is developed which provides effective information about the evaluation of NVH sources of the helical gear systems. It is aimed to study the influence of profile modifications on reduction of NVH sources in the helical gear systems.

A BOUNDARY ELEMENT APPROACH FOR COMPUTING OUTDOOR SOUND FIELD REFLECTED BY OBSTACLES LOCATED IN THE VICINITY OF A POROUS INTERFACE

Research Assistant: Yiming Wang

Principal Investigator: Professor Kai Ming Li

ABSTRACT

The boundary element method (BEM) is a powerful computational technique, providing numerical solutions to a range of scientific and engineering problems. Instead of computing the whole outdoor domain, one only needs to analyze the boundary, e.g. road surface and barrier surfaces, with the BEM method. Our mission is to improve the technique and to develop a faster numerical algorithm when the BEM method is applied for the prediction of the acoustic performance of roadside noise barriers. Indoor experiments will be conducted to validate the computational scheme. The outcome of this research will bring more accurate and faster numerical methods for tackling outdoor acoustic scattering problems, which have applications in the noise barrier design, sonar and radar technologies, architectural design, and a number of other related fields in noise control technologies.

WIND TURBINE NOISE PROPAGATION THROUGH WAKES AND TURBULENT ATMOSPHERE

Research Assistant: Yuan Peng

Principal Investigator: Professor Kai Ming Li

ABSTRACT

It's well known that atmospheric variations have great impacts on sound propagation over long ranges. In the issue of wind turbine noise, such impacts can be extremely complicated, since either the flow wakes generated by rotating turbine blades or the small scale atmospheric turbulence can affect the propagation of sound over ground surfaces from individual turbines. In the present study, the effects of wake and atmospheric turbulence on the propagation of wind turbine noise are investigated. By introducing the Parabolic Equation (PE) method, the effect of atmospheric changes in sound speeds can be incorporated at each marching step as the prediction of sound field advances in horizontal ranges. With a simulated wake profile near the wind turbine, more accurate predictions in sound field can be achieved for realistic atmospheric conditions. The present work aims to improve the current prediction schemes for assessing the impact of wind turbine noise on the neighborhood communities of the wind farms.

ATMOSPHERIC EFFECTS ON NOISE PROPAGATION FROM AN EN-ROUTE AIRCRAFT

Research Assistant: Bao Tong

Principal Investigator: Professor Kai Ming Li

ABSTRACT

As aviation becomes a more dominant mode of transportation, en-route aircraft noise in quieter environments such as national parks, public recreational areas, and residential neighborhoods have gained greater attention. Excessive noise exposure has been linked to sleep disturbances, decreased productivity, poor visitor experiences, among other concerns. Due to the increase in fuel prices and environmental concerns, a renewed interest in developing propfan driven aircrafts has emerged. An accurate noise propagation model is needed to predict the sound field at the ground for a wide variety of potential atmospheric conditions. The outcome of the present study helps in assessing en-route aircraft noise impact. It offers an improved understanding of the combined effects of atmospheric propagation, ground reflection, and source motion on the impact of en-route aircraft noise. A numerical model has been developed to compute pressure time-histories due to a source moving uniformly at high speeds above a flat ground surface in the presence of a linear sound speed profile. The analysis, which is based on a retarded-time formulation, is an analytical ray model adapted from the Weyl-Van der Pol formula. It can be shown that the effect of atmospheric absorption is dominant in shaping the leading edge of the acoustic signature. The effect of source directivity is more prominent along the trailing edge of the predicted waveform. In the absence of wind effects, the predicted sound field from a single overhead flight trajectory can be used to interpolate pressure time-histories at all other receiver locations. The proposed approach provides an efficient method for estimating the sound field at non-measurement locations.

HUMAN RESPONSE TO SUPERSONIC AIRCRAFT NOISE WHEN HEARD INDOORS

Research Assistant: Daniel J. Carr

Principal Investigator: Professor Patricia Davies

Collaborators: Alexandra Loubeau, Jonathan Rathsam, Jacob Klos, NASA Langley Research Center

Sponsor: FAA/NASA/Transport Canada PARTNER Center of Excellence on Noise and Emissions Mitigation

ABSTRACT

Manufacturers of business jets have proposed designing and building a new generation of supersonic jets that produce shaped sonic booms of lower peak amplitude than booms created by the previous generation of supersonic aircraft. To determine if these “low” booms are less intrusive and the noise exposure is more acceptable to communities, new testing to evaluate people’s responses must occur. Because of the limitations on commercial supersonic flight overland in the US, and the lack of precise control of noise exposure in those settings, these studies must initially be done in a laboratory setting. To guide aircraft design, objective measures that predict human response to modified sonic boom waveforms and other impulsive sounds are needed. In previous research, it was also found that, for outdoor booms, startle and annoyance were highly correlated. Loudness alone did not fully explain annoyance or startle judgments, and so recent research was focused on startle and annoyance model development. Models that include maximum loudness, rise time, and sharpness metrics predict responses well. The next research phase is focused on understanding how people will react to booms when heard inside. House type and the indoor acoustic environment modify the outdoor booms, and this must be considered when predicting indoor sounds and annoyance ratings. A test was conducted in NASA Langley’s Interior Effects Room (IER), with the collaboration of NASA Langley engineers. This test was focused on the effects of low-frequency content and vibration. A second test is being designed and will be conducted at Herrick Labs, using similar sounds played back over earphones. This test will have less realistic playback, less low-frequency content, and no vibration; but it will utilize Purdue’s recently revised binaural simulation code. The predictive tools being developed are immediately applicable to supersonic aircraft design, but they may also be helpful in situations involving other transient sounds.

DEVELOPMENT OF SOUND QUALITY METRICS FOR GEAR RATTLE IN DIESEL ENGINES

Research Assistant: Brandon Sobecki

Principal Investigators: Professors Patricia Davies and J. Stuart Bolton

Sponsor: Cummins Inc.

ABSTRACT

Sound quality is an important factor in the design of competitive diesel engines. The noise produced by specific components and mechanisms in the engine can play a significant role in determining the perceived quality of the overall noise and in turn the perceived quality of the engine. The goal of the present research is to characterize the sounds produced by the phenomenon known as gear rattle and to develop a model that can be used to assess gear rattle levels in a way that connects directly with human perception of rattle. Most previous work in this area has been focused on rating the overall sound quality of diesel engines, but little has been done to develop models of perception of rattle noise in particular. Various engine recordings in which gear rattle was present were compiled with help from Cummins. These signals were analyzed to identify how sounds changed with increased levels of rattle. A method to simulate gear rattle noise and incorporate it into a no-gear-rattle (baseline) recording was developed. This procedure enabled controlled variation of rattle for use in a psychoacoustic test. The test was designed to quantify detectable levels, perception of growth, and increases in annoyance due to the presence of gear rattle noise. The responses of people who reported having experience around diesel engines were compared with those of a more general population. The subjects with diesel engine experience were found to be better at detecting gear rattle noise. The outcome of this research will be a method to predict how people perceive gear rattle noise so that Cummins can set component noise targets that directly relate to human perception of gear rattle. When coupled with noise generation predictions, this approach can be used to optimize the quality of the component noise.

IMPROVED MODEL FOR COUPLED STRUCTURAL-ACOUSTIC MODES OF TIRES

Research Assistant: Rui Cao

Principal Investigator: Professor Stuart Bolton

ABSTRACT

Experimental measurements of tire tread band vibration have provided direct evidence that higher order structural-acoustic modes exist in tires, not just the well-known fundamental mode. These modes display both circumferential and radial pressure variations. The theory governing these modes has thus been investigated. A brief recapitulation of the previously-presented coupled tire-acoustical model based on a tensioned membrane approach will be given, and then an improved tire-acoustical model with a ring-like shape will be introduced. In the latter model, the effects of flexural and circumferential stiffness are considered, as is the role of curvature in coupling the various wave types. This improved model accounts for propagating in-plane vibration in addition to the essentially structure-borne flexural wave and the essentially airborne longitudinal wave accounted for in the previous model. The longitudinal structure-borne wave "cuts on" at the tire's circumferential ring frequency. Explicit solutions for the structural and acoustical modes will be given in the form of dispersion relations. The latter results will be compared with measured dispersion relations, and the features associated primarily with the higher order acoustic modes will be highlighted. Finally, the effect of tire rotational speed on the natural frequencies of these various modes types will also be discussed.

THE THERMAL AND MECHANICAL RESPONSES OF COMPOSITE ENERGETIC MATERIALS WITH COUNTABLE INCLUSIONS UNDER ULTRASONIC EXCITATION

Research Assistant: Jacob Miller

Principal Investigator: Professor Jeff Rhoads

ABSTRACT

Some of the greatest threats to the Armed Forces of the United States are improvised explosive devices (IEDs), which typically consist of disguised homemade explosive charges, a mechanical structure, and associated electronics. Despite the significant amount of IED-related research that has been conducted in recent years, no unilaterally effective and mass-deployable detection and defeat mechanism has been developed to date. The current research effort seeks to examine the utility of electromagnetic and acoustic excitations in stand-off detection systems. Due to the vapor pressure characteristics of composite explosives, even a small temperature rise may lead to an outgassing of detectable vapors. Targeting this phenomenon, the aim of this project is to elicit a thermal response within various energetic materials to enhance stand-off vapor detection. Specifically, the work seeks to develop and evaluate various experimental methodologies for pumping large amounts of energy into shielded energetic materials of arbitrary geometries using carefully-shaped acoustic and electromagnetic excitation signals. To this end, the thermal and mechanical responses of isolated energetic crystals within an elastic binder were characterized. The temperature and velocity responses of the sample surfaces suggest that heating due to frictional effects occurred near the particles at excitation frequencies near the transducer resonance of 215 kHz. An analytical solution involving a heat point source was used to estimate heating rates and temperatures at the particle locations in this frequency region. Heating located near the sample surface at frequencies near and above 1 MHz was attributed to viscoelastic effects related to the surface motion of the samples. At elevated excitation parameters near the transducer resonance frequency, embedded particles of ammonium perchlorate (AP) and cyclotetramethylene-tetranitramine (HMX) were driven to chemical decomposition, illustrating the effectiveness of this type of excitation.

CHARACTERIZING AND MODELING OF DYNAMIC BEHAVIOR OF MATERIALS USED IN IMPROVISED EXPLOSIVE DEVICES

Research Assistant: Jelena Paripovic

Principal Investigator: Professor Patricia Davies

Sponsor: Department of Defense Office of Naval Research – Semiwave Multi-University Research Initiative

ABSTRACT

The mechanical response of energetic materials, especially those used in improvised explosive devices, is of great interest in the defense community. It is believed that by understanding the dynamic behavior of the energetic material a remote acoustic or electromagnetic excitation may be tuned to produce signatures that can be used to indicate the presence of explosives. The goal of this project is to develop a robust model for low frequency uniaxial behavior of surrogate polymer energetic materials. Focus is on the uni-axial deformation of hydroxyl-terminated polybutadiene (HTPB) binder embedded with ammonium chloride crystals (NH_4Cl), this is similar in structure to common improvised explosive devices. A series of swept sine-wave case-excitation tests were conducted 0% and 50% crystal/binder volume fraction materials attached to a mass to examine the behavior and repeatability of the material-mass system dynamic responses. A continuous-time system identification approach is applied to develop models that predicted the harmonic base excitation responses. Various linear, nonlinear and viscoelastic models have been fitted to the experimental data. Including a one-term hereditary viscoelastic term was necessary to fully capture the frequency response function shapes. Increasing the order of the relaxation kernel from one to two improved the fit between 65Hz-80Hz (near resonance), and produced good estimates of the response behavior below resonance, however above resonance the predictions are well below the envelope of the measured response data, but no worse. The system identification procedure is currently being adapted to allow for estimation of more complicated nonlinear viscoelastic and damping terms. This research will provide an important step in the development of a more general model that can relate stress, strain, temperature and strain-rate for the types of materials used in improvised explosive devises. The models developed and estimated material properties are being shared with the researchers in the other projects who are studying other systems that incorporate these surrogate materials.

THE THERMOMECHANICAL RESPONSE OF PARTICULATE COMPOSITE BEAMS AND PLATES UNDER INERTIAL EXCITATION

Research Assistants: Daniel Woods and Jacob Miller

Principal Investigator: Professor Jeff Rhoads

ABSTRACT

There is currently a significant need for new technologies capable of detecting and identifying energetic materials, preferably from a stand-off distance. In light of this need, the present work seeks to characterize the thermomechanical response of polymer-bonded energetic composites prior to their detonation or deflagration. Specifically, this work investigates the response of mechanical surrogates of traditional energetic compositions, and the effects of crystal-to-binder ratio variations. This research is grounded in the fact that polymer-based materials demonstrate significant self-heating when subjected to dynamic loading due to out-of-phase stress and strain oscillations (which cause internal dissipation) and poor heat diffusion characteristics (attributable to the poor thermal conductivity of most polymers). Interestingly, the conditions for vapor-based detection of many explosives can be greatly improved by heating due to the increase in vapor pressures at higher temperatures. As such, the thermomechanics of explosive materials are investigated as a technical pathway for stand-off detection.

In this work, a thermomechanical model for polymer-based composites under mechanical loading is presented. Beam and plate geometries are considered, where the mechanical responses are determined using Euler-Bernoulli beam theory and Warburton's solution functions, respectively. The material is modeled as a homogenized linear viscoelastic material and forcing is in the form of harmonic base excitation. The system is forced near its first resonant frequency to elicit large displacements and, in turn, maximum heating. The heat generation under harmonic loading is derived from the system's hysteretic characteristics and the Fourier Law of Conduction is used to obtain the thermal response.

In addition to the modeling efforts highlighted above, experiments were conducted with beam and plate samples composed of a hydroxyl-terminated polybutadiene (HTPB) binder with embedded ammonium chloride (NH_4Cl) crystals. Several crystal-to-binder ratios were investigated for the plate compositions. The samples were subjected to broadband and single-frequency base excitation, and the thermal and mechanical responses were recorded through the use of infrared thermography and scanning laser Doppler vibrometry, respectively. The experimental results were directly compared to the theoretical predictions for several distinct excitation levels. The results reveal the strong dependence of the temperature distribution on the stress and strain fields generated by mechanical excitation.

In conclusion, the authors hope to build upon related research efforts and improve the understanding of the responses of energetic materials subject to dynamic loading prior to detonation and deflagration. The authors further hope that this work constitutes an important step in advancing the ability to detect and defeat hidden explosive materials.

MODELING OF A RESONANT NANOELECTROMECHANICAL SYSTEM

Research Assistant: Scott Calvert

Principal Investigator: Professor Jeff Rhoads

ABSTRACT

The mass production and very large scale integration (VLSI) of micro/nanoelectromechanical systems (M/NEMS) require the development and use of accurate modeling and simulation techniques, which are capable of rapidly evaluating various device designs. Because of the large range of applications that have been proposed for M/NEMS, the most useful models are those that can accurately respond to a wide variety of inputs and in an assortment of operating conditions. It is towards this end that a first-principles based model is proposed for an electrostatically-actuated, fixed-fixed, nanoscale beam resonator which is inclusive of the device, test equipment and other system parasitics. The model focuses on the electrical characteristics of the system, which are dominated by the interplay between capacitance modulation and piezoresistive effects in the resonator, which arise from the beam's mechanical motion. The complexity of the model reinforces the need for studying and modeling M/NEMS at a system level. The narrow bandwidth of the device makes it an ideal candidate for filter design, while the nonlinearity of the electrostatic actuation, combined with the nonlinearities of the various current transduction effects, result in a system with a tunable resonance frequency. The prospect for a tunable, narrow bandpass filter makes these systems a promising area of study.

DEVELOPMENT OF A MULTI-BODY MODEL TO PREDICT THE SETTLING POINT AND INTERFACIAL PRESSURE DISTRIBUTION IN A SEAT-OCCUPANT SYSTEM

Research Assistant: Yousof Azizi

Principal Investigators: Professo**rs** Patricia Davies and Anil Bajaj

ABSTRACT

The location of the hip-joint (H-Point) of a seat occupant is an important design specification which directly affects the seat static comfort. Most car seats are made of polyurethane foam and so the location of the H-Point is dependent on the quasi-static behavior of foam. In this research a previously developed model of the seat-occupant system is refined by incorporating an improved foam model which is used to study seat and occupant interactions and the location of occupant's H-Point. The seat is represented by a series of discrete nonlinear viscoelastic elements that characterize the seating foam behavior. The nonlinear elastic behavior of these elements is expressed by a higher order polynomial while their viscoelastic behavior is described by a hereditary type model with parameters that are functions of the compression rate. The nonlinear elastic and viscoelastic model parameters were estimated previously using data obtained from a series of quasi-static compression tests on a car seat foam sample. The occupant behavior is described by a constrained two-dimensional multi-body model with five degrees of freedom. A Lagrangian formulation is used to derive the governing equations for the seat-occupant model. These differential equations are solved numerically to obtain the H-Point location. These results are then used to calculate the force distribution at the seat and occupant interfaces. The force distribution at the seat-occupant interface is also investigated experimentally and is found to match qualitatively with the results obtained using the seat-occupant model. Also the model is used to study the effects of variation of different system parameters on the system responses.

MODELING AND SYSTEM IDENTIFICATION OF STRUCTURAL SYSTEMS INCORPORATING NONLINEAR VISCOELASTIC MATERIALS

Research Assistant: Udbhau Bhattiprolu

Principal Investigators: Professors Anil Bajaj and Patricia Davies

Sponsor: Partially sponsored by the National Science Foundation

ABSTRACT

Muscle tissue, skin and several other biomaterials used in the biomedical industry as well as flexible polyurethane foams used for cushioning in the furniture and automotive industries, all exhibit nonlinear viscoelastic behavior. To design systems that incorporate these materials, it is important to be able to model their mechanical behavior and thus be able to predict the dynamic response of the systems. Because of the nonlinear and memory (viscoelastic) properties of the materials, this is a challenging research area. The results and understanding developed here for a pinned-pinned beam on a foam foundation interacting with flexible polyurethane foams should be applicable to more complicated systems incorporating many of the materials mentioned above. The approach to modeling is to start with linear models of the foam, gradually increase the complexity by incorporating, in stages, elastic nonlinearity and then viscoelasticity. Unlike most of the studies reported in the literature, the foam foundation was assumed to react only in compression to encapsulate a wider range of problems seen in practical applications. Thus the model has to be equipped with the ability to predict the changing contact length – this makes the modeling and analysis much more challenging. An experiment is designed to verify the applicability of the model and initially, harmonic excitation of the system is being studied. Based on the preliminary tests, the natural frequencies and the qualitative behavior of the beam along, and the beam-foam system are in a close agreement with the model predictions. However, the model is currently being improved so that it is much closer to the reality based on the experimental results to explain the behavior like stretching of beam, foam pre-compression and viscoelasticity of the foam. In the near future, a system identification procedure will be developed based on the model structure and the types of excitation that are feasible in the experiment. The procedure will be applied to the experimental system and the range of the applicability of the resulting model will be explored. The system identification approach and simulations of various model structures will be used to extend the capability of the beam-foam system model to predict responses observed in experiments under a wider variety of loading conditions and excitation levels.

SYNTHESIS METHODS FOR NONLINEAR RESONATORS FOR 1:2 INTERNAL RESONANCE BASED SENSING

Research Assistant: Astitva Tripathi

Principal Investigator: Professor Anil Bajaj

ABSTRACT

There has been renewed interest in the research community on the use of materials other than silicon to construct micro-electro mechanical systems (MEMS) which can provide several desired properties such as low cost, weight and bio-compatibility. One of the major classes of these materials being used extensively is hyperelastic polymers, some of whom may have electrostrictive properties. In parallel, there has also been renewed interest in the use of nonlinear dynamics principles to enhance device functionalities. In this work the authors propose to merge these two streams of thought and develop a framework for synthesizing structural configurations representing hyperelastic plate resonators that can undergo nonlinear 1:2 internal resonances. These various configurations can be used in a variety of sensing or other applications. For structural synthesis, a heuristic computational method based on the finite element method is employed to iteratively design candidate plates for 1:2 internal resonances. The method is designed so as to yield topologies which are easy to fabricate. Assuming a two-parameter Mooney-Rivlin Model for the material behavior, a reduced-order model that can be used to obtain the nonlinear equations of motion for the structure is derived by following a Lagrangian approach. These equations retain dependence on the constitutive material parameters and are analyzed to understand the nonlinear dynamics of various plate structures, all exhibiting the 1:2 internal resonance response behavior.

The potential applications of such resonators include mass and chemical sensors which can circumvent the difficulties encountered in linear designs such as high dependence on quality factors and thus low resolution of detected quantities. Further the ability to produce topologically optimized hyperelastic resonators using modern techniques such as 3D printing allows much better performance repeatability through better dimensional tolerances.

MICRO AERIAL VEHICLES

Research Assistants: Daniel McArthur (Purdue University)
Yangbo Long (Stevens Institute of Technology)

Principal Investigator: Professor David Cappelleri

ABSTRACT

This research is focused on an original configuration of a micro aerial vehicle (MAV), the Omnicopter. Two central counter-rotating coaxial propellers provide a major part of lift force, and three perimeter-mounted tiltable ducted fans are used to supplement the lift force, provide lateral forces and adjust its attitude. Different from traditional underactuated MAVs, the presence of the tilt-rotor mechanism, composed of three ducted fans and three servo motors, on the Omnicopter makes it over-actuated. The characteristic of over-actuation enables the Omnicopter's position dynamics to be decoupled from its attitude dynamics. Based on a complete description of its dynamic model derived using the Newton-Euler motion equations, we propose attitude and position controllers and control allocation for the Omnicopter MAV. Simulation and experimental results are shown to demonstrate its performance.

FUEL TYPE DETERMINATION USING FUEL SYSTEM PARAMETERS

Research Assistants: Shambhavi Balasubramanian and Mukta Kulkarni

Principal Investigator: Professor Peter Meckl

Sponsor: Cummins Fuel Systems

ABSTRACT

A number of factors are responsible for an increased interest in alternative fuels for transportation and other uses. Among the most widely available alternative fuels are biodiesel and vegetable oil, both of which can be used to power a diesel engine. It is generally accepted that diesel blends containing up to 20% biodiesel in volume do not require modification of existing diesel engines. Biodiesel has higher density, viscosity, surface tension, sound velocity, and bulk modulus of elasticity than regular diesel fuel. This affects the fuelling, injection timing, and fuel spray and consequently the emission characteristics.

Estimation of fuel type is critical to the performance of the engine. Knowing the fuel type allows the engine controller to determine the proper fuel quantity and timing to provide the best balance of performance, emissions and fuel economy. Based on the fuel type, the calorific value will change. Knowing this, the engine controller can use the best air-fuel mix, compression, and injection pressure for that type of fuel. Fuel injection characteristics depend on both the type of injection system and the fuel properties. Fuel density, viscosity, sound velocity and bulk modulus of elasticity influence the injection characteristics significantly.

The objective of this project is to estimate the fuel type by identifying these critical parameters that characterize a fuel and devising suitable strategies to detect these parameters to determine the fuel type. The focus will be on using sensors available on the XPI fuel system to extract properties of the fuel that will help to identify it. Initially, the distinction between regular diesel fuel and biodiesel fuel will be the main emphasis. But we also hope to be able to differentiate between different diesel blends (such as D1 and D2).

OPTIMIZATION OF UREA SCR CONTROL FOR MITIGATION OF COLD START EMISSIONS AND DEVELOPMENT OF AMMONIA SENSOR BASED FEEDBACK CONTROL

Research Assistant: Jagdish Hiremath

Principal Investigator: Professor Peter Meckl

ABSTRACT

In the Urea-SCR system, aqueous urea is dosed into the exhaust stream which decomposes to NH_3 (Ammonia) and reacts with NO_x over the SCR (Selective Catalytic Reduction) Brick. Urea-SCR Technology is increasingly seen as a critical pollution control technology in current and future diesel-based automotive applications, specifically for NO_X control. The warm-up phase of the exhaust system, which is typically the pre-light off temperature region for the catalysts, has an adverse effect on overall emissions due to the low activity of the catalysts in the aftertreatment system. Effective thermal modeling of the catalysts is needed to better predict Light-Off temperatures and the Catalyst Temperature in general as it is central to the urea dosing control.

The Urea-SCR aftertreatment research is performed on the Purdue EcoCar platform, an experimental hybrid version of a Chevrolet Malibu. The focus is on real-time catalyst Mean Bed Temperature estimation using thermocouples embedded in the catalyst core. The characterized model is to be used to predict catalyst temperatures only from Exhaust Gas temperature sensors. This work also explores the basis and development of ammonia sensor-based feedback control for low surface coverage at high catalyst temperatures.

OPTIMIZATION OF SMALL DIESEL ENGINE FOR REDUCED NOISE USING AN ELECTRONIC FUEL INJECTION SYSTEM

Research Assistant: Jiajun Cao

Principal Investigator: Professor Peter Meckl

ABSTRACT

The present research involves the feasibility study on a 3kW Tactical Quiet Generator (TQG) to assess current noise sources and evaluate the potential for further noise reduction using rate shaping for the diesel engine fuel injector. Based on previous research, the noise generation in a diesel engine is directly related to the shape of the combustion pressure pulse, thus associated to the injection timing. The overall objective of this study is to develop optimized parameters for multi-pulse fuel injections that achieve reduced engine noise and improved fuel economy while maintaining power flow. To generate suitable fuel rate shapes, all three objectives (noise, fuel consumption, and power) must be simultaneously considered. In the current study, an electronic injection system is set up to allow better control and real-time adjustment of injection timing to tailor needs for performance and provide resistance to environmental variations. Preliminary sound pressure measurements have already been conducted and optimization realized by multipulse injection with different injection timings has been tested. Further measurements are yet to be conducted to verify these results and construct a data-based model for the engine. This will help in better understanding the combustion characteristics and the corresponding impact on noise generation, and developing a controller to help optimize the overall performance.

IMPROVING DIESEL ENGINE EFFICIENCY AND EMISSIONS CONTROL USING VARIABLE VALVE ACTUATION

Research Assistants: Aswin Ramesh, Soumya Nayyar, Cody Allen, Mayura Halbe, Xueting (Sylvia) Lu, Yuntian (Lucius) Wang and Dheeraj Gosala

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, engine manufacturers have begun to investigate the benefits of variable valve actuation systems. This study focuses on the quantification of the effects of varying valve timing events and optimization to achieve improved engine efficiency and hotter exhaust gas. Exhaust aftertreatment systems clean the harmful emissions from the exhaust gas; however, to be most effective, the systems must be maintained within a certain temperature range. Therefore, using variable valve actuation (VVA) to control exhaust temperatures can assist in the control of emissions. Characterization of the valve modulation effects mentioned above is being performed both analytically with computational engine model simulations and experimentally with a fully variable valve actuation system implemented on a diesel engine. The experimental test bed is a 2010 Cummins ISB 6.7L engine with almost exclusively stock hardware (stock pistons, injectors/nozzles, turbocharger, etc.). A very unique capability of this multi-cylinder test bed is that it is outfitted with a fully-flexible electro-hydraulic variable valve actuation (VVA) system that enables cylinder-independent and cycle-to-cycle control of both the intake and exhaust valve events. Results from this study have shown that by modulating the intake and exhaust valve events, the combustion and gas exchange processes of the engine are directly affected and, depending on the change, improvements on emissions, fuel economy, or both are possible. In a standard drive cycle, the engine operates at part load conditions for a significant portion of the cycle. Under these conditions, it is often not required that all cylinders are firing. For example, by deactivating several cylinders, fuel economy benefits have been seen as well as an increase tailpipe temperature which can lead to aftertreatment performance improvement. In addition to raising exhaust temperature, trapping or re-inducting burned gases with certain valve events are being investigated to reduce emissions. The transient response of CDA at different speeds using different fueling strategies is also studied. This leads to other interesting modes of operation such as reverse and re-breathing in which the charge is inducted from the exhaust manifold instead of the intake manifold in certain combinations of cylinders. This reduces the overall air-fuel ratio thereby improving performance. Knowledge of how VVA can improve efficiency and after-treatment systems will help make the operation of diesel engines cost less and emit less harmful gases into the environment.

IMPACT OF BATTERY LIFE ON HEV COMPONENT SIZING AND CONTROL

Research Assistants: Xing Jin, Ashish Vora, Vaidehi Hoshing, Xiaofan Guo

Principal Investigator: Professor Greg Shaver

Sponsor: DOE, Cummins Inc.

ABSTRACT

Hybridization of heavy-duty powertrains can help reduce fuel consumption, greenhouse gas emissions and tailpipe emissions. The battery, which can recover the braking energy through regenerative braking and store it as electrical energy, plays an important role in heavy-duty hybrid electric vehicles (HEVs). Previously a model based heavy-duty hybrid powertrain optimization algorithm was developed to determine the tradeoff between system performance and cost of hybridization. However battery life implications were not considered for either system cost (i.e. replacement cost of a battery) or impact of battery degradation on fuel consumption. This study aims to explore the impact of battery life on HEV powertrain component sizing, control, and system performance. Design of Experiment is utilized to setup parametric simulation studies on the powertrain simulation software Autonomie. To simulate the battery degradation effect, an electrochemical model (S-function block from Li-ion battery simulation software AutoLion ST) is integrated with Autonomie. The impact of component-level and system-level design and control parameters on system-level metrics such as fuel consumption, system cost, and battery life is captured in a single financial metric such as Net Present Value (NPV), which is the present value of all the costs and benefits associated with the powertrain throughout its life. A regression-based optimization technique is then utilized to maximize the NPV to arrive at optimal values for the variable parameters. Since other system level metrics, such as emissions and critical component life can be easily captured with the NPV regression model, this model and methodology can be used to achieve optimization in the component as well as system domains with the use of appropriate parametric models.