

Research Expo

2015



**HERRICK
LABORATORIES**

PURDUE UNIVERSITY

™

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EVALUATION OF PASSIVE CHILLED BEAM SYSTEM BASED ON EXPERIMENT, MODELING AND ITS APPLICATION TO BUILDING SIMULATION WITH ENERGY EFFICIENCY AND THERMAL COMFORT ASSESSMENT

Research Assistant: Janghyun Kim

Principal Investigator: Professors: J.E. Braun and A. Tzempelikos

Abstract

Existing modeling approaches for passive chilled beams are not adequate for assessing overall energy usage and occupant comfort within building simulation programs. In addition, design guidelines for passive chilled beam systems are needed for identifying appropriate applications and optimal configurations. This work will develop improved passive chilled beam testing approaches and semi-empirical modeling that will allow performance measurements from tests on a single chilled beam in a laboratory setting to be used in modeling multiple chilled beams in a building application within a building simulation tool. The research includes characterizing the performance of passive chilled beams by experimental investigations and development of models, and integration of these models into building simulation models for overall assessments of passive chilled beam systems. The integrated simulation tool will be used to perform comprehensive comparisons of passive chilled beam and conventional systems in order to provide guidelines for appropriate applications.

A single passive chilled beam is being tested under controlled conditions to acquire measurements that can be further used to develop a semi-empirical model. Comprehensive measurement parameters are considered to capture both convection and radiation cooling capabilities of the passive chilled beam. The performance of passive chilled beams is relatively more affected by the indoor conditions compared to conventional cooling systems due to the naturally convective cooling nature. For this reason, field measurements from a real occupied office space installed with multiple passive chilled beams are also taken to verify the validity of using the model developed from laboratory tests on a single passive chilled beam in a system simulation for spaces with multiple chilled beams.

The most cost-effective and precise method of estimating the annual performance of radiant heating and cooling systems (including passive chilled beam system) in terms of energy efficiency and thermal comfort is to use a dynamic building simulation tool due to the mix of convective and radiative heat transfer characteristics. Thus, an integrated building simulation model is chosen and is being developed in this study to assess and optimize the passive chilled beam at a system level and to compare it with conventional cooling systems. The computationally efficient semi-empirical passive chilled beam model that will be developed based on experiments will be implemented in the integrated building simulation model. This integrated building simulation model will be used to evaluate overall energy usage of chilled beam systems compared to conventional cooling systems and other passive ceiling cooling systems under different simulated weather conditions. Optimizing design and operation of the passive chilled beam system will also be performed with this integrated model in terms of sizing, control and installation layout, which will help for the penetration into the market.

RETROFITTED NEW-ZERO ENERGY, WATER AND WASTE (ReNEWW) HOUSE

Research Assistant: Stephen L. Caskey

Principal Investigator: Professor E. Groll

Sponsor: Whirlpool Corporation

Abstract

A 1920s era home is renovated with an overall goal of reaching net-zero energy, water and waste. Phase 1 conducted baseline monitoring of the home in its original state to obtain an initial energy profile before any improvements were made. Temperature and relative humidity sensors provided feedback on thermal comfort. Phase 2 commenced in the summer of 2014 with an extensive building envelope renovation and addition of onsite energy production with combined photovoltaic-thermal, PV-T, solar panels. Triple pane insulated windows replaced wood framed, single pane windows, spray foam insulation was applied throughout the wall and attic cavities, greatly reducing infiltration, and a vertical loop, water-to-water, geothermal heat pump provided an efficient electrical driven heating and cooling system. The PV array installed has a capacity of 8.1 kW and has generated approximately 5,000 kW-h in its first year of operation. Electric demand in the first year was roughly 9,800 kW-h leaving a deficit of 4,800 kW-h. Phase 3, starting summer 2015, has incorporated a rainwater collection and treatment system to supply the home with high quality drinking water collected from the metal roof of the home. Two underground cisterns store up to 3,000 gallons (~11,000 liters) before being pumped into the home for filtration and disinfection with ultra violet light. To improve the water efficiency of the home and reduce consumption of potable water, a greywater processing system was installed to supply the toilets with treated water collected from the shower drains

ANALYSIS OF A NEW-TYPE DESICCANT WHEEL SYSTEM WITH CLOSED LOOP AIR REGENERATION

Research Assistant: Yefeng Liu

Principal Investigator: Professor E. A. Groll

Abstract

With the requirements of energy saving and emission reduction in the world, the application areas of desiccant wheel systems are expanded. However, significant heat energy is required for the regeneration process in a desiccant wheel. A new-type of desiccant wheel system with closed loop air regeneration is proposed and analyzed. The main feature of the system is that the air regeneration process occurs inside a closed loop, and a CO₂ heat pump is utilized inside this loop for air regeneration. A mathematical model of the system has been developed, and the operating performance of the overall system is simulated and analyzed. Based on the requirements of supply air with dew points of 5 °C to 0 °C for applications in the food and pharmaceutical industry, the energy consumption of the proposed system is simulated and compared to the ones of two conventional systems: System 1 is a traditional desiccant wheel-cooling system, which is chosen as baseline system, and System 2 is an advanced high temperature heat pump coupled to a desiccant wheel-cooling system with heat recovery. The results show that the proposed system is the most efficient system among the three systems analyzed, and that it can save more than 80% of energy compared to System 1, and 40% of energy compared to System 2.

INTEGRATED DESIGN TOOL FOR BUILDING LIFE CYCLE COST OPTIMIZATION

Research Assistant: Yeonjin Bae

Principal Investigator: Professor W.T. Horton

Abstract

According to energy usage data by the U.S. Energy Information Administration, residential and commercial buildings consume about 41% of total U.S. energy consumption, or about 40 quadrillion BTU's, and over the past 25 years residential energy use has increased by about 7.0 percent and commercial building has increased by about 10.4 percent (EIA, 2015). Many opportunities exist to design and construct energy efficient buildings; however, these opportunities need to balance the trade-offs between potential increase in construction costs versus the long-term savings of reduced utility bills. As energy consumption in the U.S. continues to increase, building energy modeling and simulation software is being incorporated more regularly into the building design process to simulate thermal loads and energy consumption, and to predict the energy performance characteristics of the building prior to construction. Energy simulation programs typically require hundreds of design parameters as inputs, which means they are not typically employed at a very early design stage because a large number of the design parameters are still uncertain (Augenbroe, 2002). Energy simulation software is commonly used today only to validate a chosen design alternative and not to explore the broad design space of potential alternatives (Caldas & Norford, 2002). Since any given building project can include a large number of design variables, and each variable may take on many different values, it is impossible to do an exhaustive search of the entire design space to find the variables that optimize the building design subject to various project constraints and objectives, such as construction cost, energy cost, and environmental impact. Also limited optimization methodologies can be used to find the optimal solution because of unique variable characteristics, which include both discrete and continuous choices, and objective functions.

The current study proposes an accurate and efficient method to perform the optimization, using detailed energy calculation with existing energy simulation software, and customized program of using actual construction costs. This optimization is normally prohibitive because of long calculation times and therefore it is processed with limited numbers of variables. The primary reason for the long running time is that there are too many input variables and the building energy simulation software takes a long time to predict energy consumption. To achieve the goal of performing the optimization within an acceptable time frame, several approaches are attempted in this study. First, it is important to reduce the number of variables if possible. Using variable (feature) selection, the most important variables for optimization are selected. To process the variable selection, it is necessary to generate a random data set, which takes a long time because of the energy simulation software. To expedite the variable selection process, a simplified energy modeling process using existing energy software is developed. Annual energy consumption is predicted modeling only a few days of the year. Finally with a reduced number of variables, the full optimization is processed.

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

Research Assistants: Bonggil Jeon, Janghyun Kim, Yeon Jin Bae

Principal Investigator: Professor W.T. 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.

RESEARCH OF ENERGY IMPROVEMENT FOR A FISH FARM BY COUPLED AIR, WATER, AND CO₂ SYSTEM ANALYSIS

Research Assistant: Li Cheng
Principal Investigators: Professor W.T. Horton

Abstract

The fish farm in this research is located in Albany, IN. The company is paying a lot when operating the air conditioning system, the water chiller, the ventilation fans and the water recirculating pumps. Because they don't have a detailed and integrated energy model to predict the energy requirement of the fish farm. So the operators have to run all the mechanical equipment in full power or speed. In the same time, the designer of the fish farm has overestimated the energy consumption of the fish farm.

Therefore, this research is aimed at building a comprehensive energy model for the fish farm. As a result, more energy-saving operation conditions can be generated from the model. TRNSYS, graphic programming software is being used to simulate the coupled air and water system and give a transient energy performance of the fish farm. The CO₂ loop, composed of CO₂ strippers and culture tanks, is depicted by a specific thermodynamic model, and finally coupled into the TRNSYS model as an equation component.

Now, data acquisition is underway which will specify the CO₂ mathematical model and validate the TRNSYS model. After modification to the TRNSYS model is done, optimization of the operating conditions will follow up.

A SEQUENTIAL APPROACH FOR SEPARATE SENSIBLE AND LATENT COOLING

Research Assistant: Jie Ma

Principal Investigator: Professor W.T. Horton

Abstract

Separate sensible and latent cooling (SSLC) systems offer an opportunity for substantial reductions in cooling energy required to maintain comfort conditions in commercial and residential buildings. The proposed project differs from other attempts to achieve separate sensible and latent cooling that typically rely on operating two systems in parallel, one for the sensible portion and a separate system for the latent portion of the heat load. This project will develop an SSLC system that handles the two loads sequentially rather than in parallel, which can be accomplished using a single vapor compression system with variable speed compressor and fan technology. Preliminary theoretical results at Purdue University indicate an energy savings potential of around 35%. The focus of the project will be to develop and optimize the system and its controls, and ultimately to implement the system in a Living Laboratory environment to assess the comfort impacts on the space in a real world scenario. It is anticipated that the proposed SSLC system will easily achieve deep penetration in both the new and existing building markets due to its simplicity and cost effectiveness.

MODELING OF AN OIL-FREE CARBON DIOXIDE COMPRESSOR USING SANDERSON-ROCKER ARM MOTION (S-RAM) MECHANISM

Research Assistants: Bin Yang, Orkan Kurtulus

Principal Investigator: Professor E. A. Groll

Sponsor: S-RAM Dynamics

Abstract

A comprehensive simulation model to predict the performance of a prototype CO₂ compressor is presented. This prototype compressor employs the Sanderson-Rocker Arm Motion (S-RAM) mechanism, which converts the rotary motion of the shaft into a linear reciprocating motion of the cylinders. There are no energy-robbing side forces on the pistons or crossheads common to crankshaft, swash plate and wobble plate drive mechanisms. Additionally, this drive mechanism can vary the piston stroke while keeping the constant clearance volume by changing the incline angle between the connecting rod and compressor main shaft centerline.

The compressor model is mainly composed of three main sub-models simulating the kinematics and dynamics of the drive mechanism and the compression process. A valve sub-model is included in the compression process model. Future work will focus on developing the frictional power loss sub-model, which will be built together with the dynamics model of the drive mechanism and compression process. In addition, the predicted results of the comprehensive model will be validated using external compressor performance measurements including the mass flow rate and input power. Finally, a parametric study will be conducted, which will investigate the effects of structural parameters including the stroke-to-bore ratio on the compressor performance.

CFD NUMERICAL SIMULATION OF THE COMPRESSION PROCESS IN A SCROLL COMPRESSOR

Research Assistant: Haibin Zha

Principal Investigator: Professor J. Braun

Abstract

What does it look like in the working chamber of a scroll compressor when the compression is proceeding? Many researchers (Nils Halm, Yu Chen and Ian Bell) built mathematic models to predict the mass flow rate, pressure, temperature, power input and efficiency. And some tests were accomplished to verify their models. But because it's closed working chamber, we cannot see how does the pressure, temperature and velocity distribute directly. The compression in the chamber is complex because the shape of the working chamber and the leakage are always changing with the orbiting angle.

A CFD numerical simulation (Fluent) can show a dynamic distribution process. The pressure, temperature and velocity on any point can be obtained at any orbiting angle. CFD numerical simulation can be combined with a test to verify the model we built. Especially when there is a little change about the scroll wrap or the size of the geometry, we do not need manufacture a new compressor; it will save time and money. So the methods of numerical simulation supply a new hybrid way to verify the model and show what happened in the chamber.

CHARACTERIZATION AND PERFORMANCE TESTING OF NATURAL GAS COMPRESSORS FOR RESIDENTIAL AND COMMERCIAL APPLICATIONS

Research Assistants: Xinye Zhang, Bin Yang, Orkan Kurtulus

Principal Investigator: E.A. Groll

Sponsors: BlackPak Inc.

Abstract

This project focuses on characterization and performance testing of natural gas compressors for residential and commercial applications. The aim of the project is to evaluate the efficiency, performance, and safety characteristics.

A three-step sequence of testing will be conducted as part of the project. Initially, the compressors will be tested while dynamically charging a tank with air as the working fluid. In the second step, steady-state tests will be conducted using the hot-gas compressor load stand with carbon dioxide (CO₂) as an appropriate substitute for pipeline natural gas. In the third step, the performance and safety characteristics will be reported during the dynamic charging of a tank using pipeline natural gas as the working fluid.

The first and third step compressor performance testing of the proposed project will be conducted during the dynamic charging of a tank. The new test stand will be set up for these compressor performance tests. For the second step, a new hot-gas compressor load stand will be designed, built, and commissioned. This test stand will then be used to conduct the compressor performance tests.

A membrane tank filled with the working fluid will be used in the new hot-gas load stand. The pressure inside the tank is held at a constant intermediate pressure using an appropriate back pressure on the membrane to ensure a fixed intermediate pressure as the anchor point of the cycle. Whenever gas is lost through leakage, the gas inside the tank is able to continue to hold the cycle at stable operating conditions.

During the tests, the following compressor measurements will be recorded: compressor mass flow rate, suction and discharge temperatures, suction and discharge pressures, and compressor power consumption. The theoretical performance of the compressor will be evaluated experimentally during this phase of the project.

Also, a simulation model to predict the compressor dynamic performance will be developed. In this model, the initial clearance factor for the compressor will be calculated based on available compressor maps and used as the input for the dynamic model. The entire process will be simulated to provide the compressor performance data, as the function of time. Finally, the predicted performance will be validated using the test data.

PERFORMANCE TESTS OF A SCROLL COMPRESSOR WITH VAPOR INJECTION USING A COMPRESSOR CALORIMETER

Research Assistant: Thomas Moesch
Principal Investigator: Professor E.A. Groll
Sponsors: Adams Communication & Engineering Technology (ACET)

Abstract

Current studies at Purdue University indicate that injecting vapor in a scroll compressor at intermediate pressure enhances the compressor performance. Combining vapor injection with an internal economizer cycle reduces the discharge temperature of the compressor, while increasing the evaporation capacity of the refrigeration system. This widens the range of application and increases the coefficient of performance (COP). For an accurate characterization of the compressor performance during vapor injection, a detailed compressor map is compiled. For the compressor map several steady state tests are conducted for various evaporating and condensing pressures, using a modified compressor calorimeter. For the modification of an existing compressor calorimeter a vapor injection line and appropriate data acquisition software are designed and integrated.

HUMAN INTERACTIONS WITH SHADING AND ELECTRIC LIGHTING SYSTEMS IN PRIVATE OFFICES OF PERIMETER BUILDING ZONES

Research Assistants: Amir Seyed Sadeghi and Iason Konstantzos

Principal Investigators: Professors T. Tzempelikos, P. Karava, and R. Proctor

Abstract

As a result of architectural trends, technological advances, and increasing focus on energy efficiency, buildings with high performance envelope and HVAC systems, large window-to-wall ratio, motorized window shades, smart lighting controls, and Building Automation Systems (BAS) have found their way into the market. With a focus on this building type and dynamic environments such as offices in perimeter zones, this study presents results of a long-term field study with a large number of human test-subjects, aiming to advance our understanding of (a) occupants' interactions with shading and electric lighting control systems; and (b) their preferences and satisfaction with the visual environment.

Four identical side-by-side offices with different control setups and interfaces, ranging from fully automated to fully manual and from low-level of accessibility (wall switches) to high-level of accessibility (remote controllers or modular web interfaces) were selected. The experimental study includes monitoring of physical variables, actuation and operating status of building systems and online surveys of occupants' perception of environmental variables as well as their personal characteristics and behavioral attributes.

Compared to previous studies conducted in buildings with non-motorized blinds and artificial lights without dimming options, our results show substantial differences in dynamics and frequency of human-shading and –electric lighting interactions for buildings equipped with this technology. Moreover, it was found that occupants' lighting preferences remained the same between setups but they were achieved through different dynamics of interactions undertaken by occupants. Understanding of these dynamics is important as they prove to have different energy impacts.

Comfort with the amount of light and visual conditions, satisfaction with window view, and subjective productivity were all seen to be maximized in office setups equipped with interfaces for control access and occupants were comfortable with a wider range of indoor illuminance when they had control over their environment. These results demonstrate occupants' strong preference for customized indoor climate and also introduce occupants' level of control over their environment as an important parameter to be accounted for when determining occupants' comfort in generalized forms.

INFERENCE OF THERMAL AND VISUAL COMFORT PORFILES FOR PERSONALIZED CONTROL OF BUILDINGS

Research Assistant: Seungjae Lee

Principal Investigator: Professor T. Tzempelikos

Abstract

Environmental control systems (e.g. HVAC, shading, lighting) in office buildings have been automated based on the use of “widely acceptable” visual and thermal comfort metrics. However, field studies have shown that occupants have a strong preference for personalized indoor climate, and there is a relationship between occupants’ perception of control over their environment, comfort and productivity. Moreover, considering personal preferences instead of using widely acceptable comfort metrics has the potential to reduce energy consumption. The goal of this project is to develop personalized control algorithms and the main hypothesis is that occupant satisfaction or dissatisfaction with the indoor environment is tied probabilistically to thermal and visual perception and expressed via interactions with the indoor environment. The objectives are to develop: (a) methods for learning thermal and visual preferences and behavioral patterns of occupants in private and open-plan office spaces from their control actions and physical data; (b) technological solutions for human-building interfaces and self-tuned comfort delivery devices (thermostats, shading and lighting actuators). The first phase of this work is focused on a field study with human test-subjects in four identical side-by-side private office spaces located in the Herrick Lab building. The experimental study includes monitoring of physical variables as well as the actuation and operating status of building systems. During the learning phase, occupants can control the shading position and temperature in the room by overriding default algorithms set by the building management system. The dataset is used to develop personal comfort profiles, based on the probability to accept/reject certain room conditions, which are consequently used to control the office spaces (implementation phase). The personalized control performance is evaluated considering the number of occupants’ overrides along with feedback from surveys, in which they report their satisfaction with the indoor environment. Our preliminary findings suggest that individual occupants – despite the fact that their accumulated response is stochastic – undertake control actions relatively more consciously and consistently. However, inferring human comfort profiles from actions requires carefully designed identification experiments and user-interfaces in order to provide relevant feedback.

MODEL PREDICTIVE CONTROL OF BUILDINGS WITH INTEGRATED SOLAR SYSTEMS

Research Assistant: Xiaoqi Liu

Principal Investigator: Professor Panagiota Karava

Abstract

Building-integrated photovoltaic-thermal (BIPV/T) systems can be attached to the building façade or replace conventional cladding, enabling on-site generation of solar electricity and heat. However, due to the variability of solar radiation, energy storage technologies and advanced control strategies are essential for the efficient integration of BIPV/T systems in building operation. This study presents an integrated solar system and examines its performance when a stochastic model predictive control (MPC) strategy is implemented to optimize the solar energy utilization in a building heating system over a prediction horizon. This poster presents the emulation framework that was developed for the solar-integrated system considering the impact of weather forecast uncertainty.

An open plan office space is used as test-bed, in which a BIPV/T system preheats ventilation air; while also, it is coupled with the building through an air-to-water heat pump and thermal energy storage (TES) tank that serves as the heat source for the radiant floor heating (RFH). A detailed model developed in TRNSYS is considered as a true representation of the building and it is used to identify a control-oriented state-space model. Autoregressive models have been identified to account for the prediction error in solar radiation and dry bulb temperature based on archived forecast data and corresponding in situ measurements. The error prediction models have been incorporated in the augmented stochastic form of the state-space model. The objective function minimizes the total power consumed by the air-to-water heat pump and the backup heater and the results show that the control strategy ensures that the heat pump utilizes effectively the thermal energy of the BIPV/T system. It is also shown that the stochastic controller achieved energy savings that are close to those obtained with the deterministic control strategy, assuming perfectly known weather conditions, and maintained a comfortable thermal environment.

METAL HYDRIDE HEAT PUMPS USING ADSORPTIVE SLURRY AND ISOTHERMAL COMPRESSION

Research Assistant: Nelson James

Principal Investigator: Professor J.E. Braun and E. Groll

Abstract

Metal hydrides have been investigated for use in environmentally friendly and efficient heat pumps. These systems operate on the reversible adsorption and desorption of hydrogen from metallic compounds and can be driven by a compressor or thermal energy. Some challenges faced by compressor driven metal hydride heat pumps are poor heat transfer in the metal hydride beds and high compressor discharge temperatures. To address these issues the use of metal hydride slurry in conjunction with various isothermal compression techniques such as liquid flooded, electrochemical and liquid piston compression were modeled and integrated into slurry based metal hydride heat pump in order to assess the benefits of these methods on the performance of metal hydride heat pump systems.

ORGANIC RANKINE CYCLE USING SCROLL EXPANDER

Research Assistant: Felipe Accorsi
Principal Investigator: E. A. Groll
Sponsor: Cummins

Abstract

Organic Rankine Cycles (ORC) are thermodynamic power cycles designed to generate work from low temperature sources, typically between 80 °C to 270 °C. The low temperature heat input makes this technology attractive for applications in waste heat recovery from industrial processes, exhaust gas from diesel engines, solar systems, geothermal systems, and others. The operating principle of ORC contains four major steps. The working fluid evaporates at high pressure using the heat transfer from the low temperature heat source. Then, the working fluid reduces its enthalpy in an expander producing mechanical work, which is turned into electricity by an electric generator. The low-pressure fluid leaving the expander outlet is passed to the condenser, where it is liquefied. From there, the fluid is pumped which pressurizes the liquid and restarts the cycle.

The expander has the greatest effect on increasing the efficiency of an ORC. The test conditions that the expander is subjected to are directly related to its efficiency. This research includes experimental testing of a traditional ORC cycle by measuring the expander overall isentropic efficiency and the cycle efficiency. The expansion device is a 5 kW scroll expander with a displacement of 73.6 cm³ per revolution, operating at speeds from 500 RPM to 3600 RPM. The working fluid is R245fa. The operating temperature range for the heat input is 80°C to 200°C and pressure ratios vary from 2.5 to 5.

DYNAMIC MODELING, CONTROL, AND OPTIMIZATION OF MICRO-CHP SYSTEMS

Research Assistant: Austin Nash

Principal Investigator: Professor N. Jain

Abstract

Around the world, there is a growing penetration of distributed energy resources (DERs) into the power generation landscape. Blackouts continue to cause major disruptions in many countries, including the U.S., but a more distributed energy generation landscape can offer more robustness to these types of failures. From an efficiency standpoint, transmission losses can be minimized by generating and consuming electricity at the same location through an increase in the use of DERs. Micro-combined heat and power systems (micro-CHPs) are especially useful as DERs because unlike renewables, micro-CHPs can be directly controlled. While CHP has been traditionally used in the industrial and commercial sectors, micro-CHP systems typically produce less than 5kW of electricity and are primarily aimed at the residential and small building market to meet electricity and domestic hot water needs. A major challenge with the use of micro-CHP systems concerns reconciling synchronous generation of electricity and heat with asynchronous demand. In this research we will first model and study the relationship between energy storage dynamics (specifically sensible thermal storage) and those of a prime mover (specifically a PEM fuel cell) to understand how storage sizing affects system bandwidth. This analysis will then guide the design of optimal control strategies to meet time-varying, and asynchronous, electricity and heating demands. The use of second law based metrics for characterizing efficiency of the micro-CHP system will be a critical aspect of the optimization problem formulation.

SELF-LEARNING OPTIMAL CONTROL OF TASK LIGHTING FOR ENERGY SAVING AND PERSONAL VISUAL COMFORT

Research Assistant: Monyu Yan

Principal Investigator: Professor Ming Qu

Abstract

According to 2014 data from U.S. energy Information Administration [1], the energy consumption due to building lighting is about 15% of the total electricity consumed by both residential sector and commercial sector. Residential lighting energy consumption is about 14% of total residential energy consumption. As for commercial lighting energy consumption, it is about 19% of commercial sector electricity consumption. An appropriate lighting control to providing a visual comfortable and saving energy is highly desired.

Lowering task-ambient light levels and adding high efficiency task lights for user control could save over 40% of lighting energy, improve light levels for task by over 100 lux, and increase user satisfaction (Gu 2011). It is often required the adjustment of people and installation of illuminance sensors to gain the most comfortable illuminance for a person. The adjustment is typically done by manual. The setting strongly depends upon the individual visual condition and preference. The project aims to develop a framework on a hand-held device to automatically control task lights for obtaining both energy savings and visual comfort.

We will develop a data-driven expert system enabling interacting with people for energy saving and visual comfort. According to the data collected from an individual reference and a mini illuminance sensor mounted on a hand-held device, the algorithm for proper illuminance level can be developed. The lighting control keeps learning the strategies of the control from point of individual and energy saving. Along with the data collection, the control will optimize itself to maximize the energy saving and incorporating the preference of individuals.

This framework will integrate human in the loop of sustainable building design and operation. It potentially serves as a protocol or an example of the data-driven smart living in sustainable buildings. [1]

U.S. Energy Information Administration <<http://www.eia.gov/tools/faqs/faq.cfm?id=99&t=3>>

MODEL-BASED SHADING AND LIGHTING CONTROLS CONSIDERING VISUAL COMFORT AND ENERGY USE.

Research Assistant: Jie Xiong

Principal Investigator: Professor Thanos Tzempelikos

Abstract

Dynamic facades with high performance glazing and automated shading have the potential to balance daylighting, comfort and energy use, when integrated with lighting and thermal control systems. This paper presents the development and implementation of a model-based control algorithm for automated shading and lighting operation, aiming at minimizing energy use while reducing the risk of glare. A detailed validated lighting-glare model is used to compute real-time interior lighting conditions, lighting energy use and DGP, based on the readings of two sensors on every building facade. The model-based operation ensures optimal shade position and light dimming levels that minimize energy use while satisfying glare constraints at each time step. The developed algorithm is demonstrated in a full-scale office space, controlling shades and electric lighting in real-time, using simple sensor readings as inputs. Finally, a comparison between control strategies and control intervals is discussed.

DESIGN RECOMMENDATIONS FOR PERIMETER OFFICE SPACES BASED ON VISUAL PERFORMANCE CRITERIA

Research Assistant: Iason Konstantzos

Principal Investigator: Professor Thanos Tzempelikos

Abstract

Optimal positioning of workstations in perimeter offices is a key factor affecting visual comfort and satisfaction, depending on façade design and control. Visual comfort is related to different factors, such as daylight glare and light adequacy. In addition, connection to the outdoors, delivered through window views, is related to the amount of view as well as view clarity. This study presents a new approach to evaluate office workplaces in terms of overall visual environment. Visual comfort, daylight provision and outside view are used as the three basic criteria. A new index, the Effective Outside View (*EOV*), is introduced to characterize the connection to the outdoors considering the amount and clarity of outside view. In addition, the Visual Comfort Autonomy (*VCA*) is defined as the portion of time when visual comfort criteria, based on vertical illuminance on the eye, are satisfied. The spatial variation of these indices and continuous daylight autonomy are used to evaluate perimeter offices with glass facades and window shades. Detailed simulations, based on a validated daylighting-glare model, are used to evaluate visual conditions for different occupant positions and main view directions. A case study is presented for an open plan office with different façade orientations. Selected glazing and shading properties are used as an example to present results on appropriate seating configurations in order to reduce the risk of glare and maximize daylight use, while maintaining effective outside view. This study, along with future occupant surveys, will help define clear regulations and guidelines for comfortable daylight indoor environments.

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

Research Assistant: Rita C. Jaramillo, Ph.D. Student

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

Sponsor: This research is supported by the National Science Foundation under Grant No. 1329875.

ABSTRACT

This research focuses on supervisory control of large central cooling plants. A large central cooling system consists of several chillers, cooling towers and pumps that supply chilled water to satisfy the cooling requirements of one or more buildings. Optimal supervisory control of such systems involves the determination of the mode of operation and set points that minimize the cost of operation while satisfying cooling and comfort requirements. The optimization problem is complicated because of the presence of both discrete and continuous control variables. Most of the research related to supervisory control of central cooling systems has focused on centralized control approaches. Although these studies have demonstrated the effectiveness of optimal control in reducing operational costs, the results have not been widely implemented. Some of the issues that might prevent a greater penetration of these technologies in the market are the need to have detailed information on the performance profiles of the cooling plant equipment in order to build a model for the optimization process, and the high initial costs associated with site-specific controller design and implementation. Further, once implemented, the plant model and control sequences will need to be updated by experts every time a modification is made to the plant.

This work consists of the adaptation, application and extensive evaluation of a multi-agent control approach that could address the aforementioned issues related to centralized optimal control. The work starts from a multi-agent control simulation framework developed by Cai (2015) for optimization of distributed air-conditioning systems. To adapt the framework to the problem at hand, several tasks will be accomplished: (1) Agents representing the performance of the different devices of the plant will be developed and inserted in the framework. (2) Generalized heuristics will be incorporated in some of the agents to make the approach less computationally intensive. In this context a generalized near-optimal control strategy will be developed for chilled water storage systems. The strategy should work well with the different utility rate structures (i.e. time of use (TOU); TOU and demand charges, and real time pricing). (3) A genetic algorithm will be developed and added to the framework to provide an alternative for finding the global optimal operating point in the presence of non-convex and discontinuous functions. (4) A case study of a real cooling plant with significant complexity will be used to conduct an extensive evaluation of the approaches for different operating conditions. The results in terms of optimality and computational resources will be compared with other benchmarks such as centralized optimization based on mathematical programming techniques and heuristic control schemes. If each hardware component of the plant comes with an integrated agent that represents its behavior, then the proposed multiagent framework could automatically generate the multi-agent structure and control algorithm after some relatively simple pre-configuration steps. This approach will reduce the site-specific engineering and will provide a more economic and easy to configure solutions for central cooling systems including the options of free cooling and cool storage.

A MULTI-AGENT CONTROL BASED DEMAND RESPONSE STRATEGY FOR MULTI-ZONE BUILDINGS

Research Assistant: Jie Cai

Principal Investigator: Professor J. Braun

Abstract

This work presents a multi-agent control approach for optimal demand management of multi-zone buildings. A near-optimal heuristic is proposed for a typical chilled-water air-conditioning (AC) system that can be used to formulate a demand response (DR) problem under a convex form. Then a building multi-agent control framework is utilized to synthesize a multi-agent controller where an alternating direction multiplier method (ADMM) based algorithm is adopted for intra-agent optimization and inter-agent coordination. A 3-zone case study building was used to test the proposed approach and significant cost savings were achieved.

AGENT-BASED SYSTEM IDENTIFICATION FOR DISTRIBUTED CONTROL OF HIGH PERFORMANCE BUILDINGS

Research Assistant: Jaewan Joe

Principal Investigator: Professor P. Karava

Sponsor: CPS: Synergy: National Science Foundation (Grant #1329875)

Abstract

High-performance office building designs that could directly benefit from the implementation of advanced control strategies, through better coordinated and more sophisticated control of energy and comfort delivery systems are gaining significant attention. However, system identification becomes a challenging task for such buildings due to the large number of subsystems and the increased complexity of the integrated building system. Agent-based methods are a special class of distributed approaches where the subsystem solvers are equipped with the capability of collaborating with other subsystem solvers, e.g., exchanging parameters, sharing data, negotiating strategies, etc. By carefully designing the logic of each agent and the coordination strategy among the agents, the collaborative operation of all the agents can lead to the successful attainment of global objectives. However, major challenges in applying the multi-agent framework to model buildings include identifying agents, their function and network structure, and estimating model parameters for both individual agents and their connections.

The primary goal of this project is to develop, for the first time, an agent-based system identification framework for optimal control of high performance buildings. The framework consists of model-structure candidates (sub-models of subsystems) for each agent which are compared considering their prediction error as well as a sensitivity analysis method using the information matrix and correlation coefficient. Then shared parameters among the various sub-models are negotiated while exchanging the information of state trajectory from each agent. Finally, the integrated model is assembled and evaluated with delivered information from sub-model agents. In this study, data-driven models are based on experiments with uncontrolled occupant schedule in the Living Labs at Purdue's Center for High Performance Buildings. The experimental data are collected on the Building Management System (BMS) for a long term period. The proposed agent-based system identification framework is demonstrated using several case studies including the radiant floor system, chilled beam system, and underfloor air distribution system. The proposed framework has the following distinct advantages: (a) efficiency: each agent faces a much smaller-scale problem compared to centralized identification schemes, reducing the required engineering cost; (b) scalability: sub-system models can be developed and integrated in a plug-and-play manner, reducing the required building physics expertise that is associated with the custom design of high performance buildings; (c) robustness: agents are connected via links to form agent networks that can be easily configured and dynamically re-configured and are amenable for designing real-time control algorithms in adaption to the changing conditions and sources of uncertainty. Based on the proposed framework, advanced control solutions for high performance buildings may find their way into the engineering practice.

DEVELOPMENT OF AN INTEGRATED MODEL FOR RETAIL STORES WITH REFRIGERATED CASES FOR CONTROL APPLICATIONS

Research Assistant: Donghun Kim

Principal Investigator: Professor J.E. Braun

Abstract

Retail stores with refrigerated display cases are ubiquitous in much of the developed world. An initial analysis of data from a retail directory indicates that there is approximately 3 billion square feet of buildings that incorporate both air conditioning and refrigeration equipment (big box super-centers, supermarkets, convenience stores, large drug stores, etc.) with approximate electrical energy consumption of 3 TWh per year. Poor coordination between RTUs and refrigeration equipment in convenience stores leads to high energy and demand costs and marginal comfort. The goal of this work is to develop a virtual testbed for an existing convenience store that can assess both energy and comfort performance for these types of applications so that the benefits of integrated control of RTUs and refrigeration systems can be evaluated in terms of energy and comfort and so that appropriate real-time strategies can be developed. The simulation testbed consists of models for a building envelope, reduced-order CFD, RTUs and refrigeration. It is able to capture spatial variations of thermal conditions, which cannot be detected by a fully mixed model, so that electrical peak demand can be realistically simulated. The testbed will be utilized in this project to develop and evaluate advanced control strategies for this application.

AUTOMATION AND DEMONSTRATION OF A PLUG-AND-PLAY (PNP) RTU COORDINATOR

Research Assistant: Donghun Kim

Principal Investigator: Professor J.E. Braun

Abstract

There has been very few advanced control algorithms developed for small/medium commercial buildings due to practical difficulties such as lack of a BMS system, significant disturbances, high sensor costs and high cost of site-specific engineering solutions. The focus of this work is to develop and demonstrate a practical control algorithm for the coordination of multiple roof top units (RTUs). Previously a practical control algorithm for on/off staging of multiple rooftop units (RTUs) was developed and demonstrated using both simulations and experiments for existing buildings. It was shown that significant energy savings (15% HVAC energy) and peak electric demand reduction (30% peak demand savings) compared to the conventional control can be achieved. The goal of the current project is to evaluate the business case for implementation of the RTU Coordinator for a large national chain (Bank of America, BOA) that has more 3300 buildings across the country. Analysis of the buildings led to identification of the 10 most promising sites where demonstrations of the RTU coordinator will be performed. Estimates of 22% energy savings and 15% peak electric demand reduction were obtained for the 10 BOA test sites.

OPTIMIZATION OF ELECTRICITY MAKE/BUY DECISIONS FOR PURDUE'S WADE POWER PLANT

Research Assistant: Sugirdhalakshmi Ramaraj

Principal Investigators: Professors J.E. Braun and W.T. Horton

Abstract

The Wade power plant at Purdue University produces chilled water, steam and electricity using CCHP (Combined Cooling, Heating and Power) systems to meet the campus cooling, heating and electricity demands. Steam generated from utility boilers is used for power generation, chilled water production, in-plant auxiliary usage and is distributed through a steam tunnel system for campus heating. Chilled water is generated using both steam driven chillers and electric chillers and is delivered through a closed water circulation loop to campus to meet the time-varying cooling demand. The electricity generated using two steam turbine driven generators provide 30-50% of the electricity required to meet campus needs. In addition, there is a diesel engine driven generator for emergency purposes. The remainder of the electricity is purchased from the local electric utility and includes a real-time pricing component that varies with time. Plant primary energy use and costs depend upon decisions regarding generation and purchasing of electricity in response to time varying factors so as to keep the operating cost minimum and meet campus electricity, heating, and cooling demands subject to time-varying prices, loads, and environmental conditions.

The main objective of this project is to develop, demonstrate, and assess a methodology for minimizing the operating cost of the CCHP plant. At each time, the method should find the best combination of electricity production and purchase as well as heating and cooling production in the plant. Given the electrical and thermal (heating and cooling) load behavior of a Purdue campus, the tariff structure for grid-supplied electricity, the price of primary fuel (e.g., natural gas & coal), the operating strategy and characteristics of the CCHP system, and an assumed set of installed CCHP system capacities (e.g., installed capacity of boilers, chillers and generators), classic make-or-buy decision characteristics in response to time varying factors can be analyzed. Cost-efficient operation of the CCHP system is formulated as a Linear Programming (LP) problem based on hourly load forecasts and fuel pricing with a joint characteristic for the energy components to minimize the production and purchase costs of electricity, heating and cooling. The objective function and constraints are defined such that the model is feasible and bounded and it has an optimal solution. The tool will be used to evaluate the benefits of optimal control for the Purdue CCHP plant as a function of different (possibly future) utility rate incentives.

PERFORMANCE OF FINNED HEAT EXCHANGERS AFTER AIRSIDE FOULING & CLEANING

Research Assistant: Harshad Inamdar

Principal Investigator: Professor E. Groll

Abstract

(1) 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.

(2) 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.

(3) 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.

ANALYSIS FOR AIR-CYCLE HEAT PUMPS

Research Assistant: Domenique R. Lumpkin

Principal Investigator: Professor E. Groll

Sponsor: S-RAM Dynamics

Abstract

1. OVERVIEW

The Herrick Laboratories at Purdue University and S-Ram Dynamics planned 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 and ozone depleting potentials. From this, the idea emerged that a full scope of application possibilities for the reverse Brayton cycle (air-cycle) heat pumps have not assessed. Extensive research has been done for space heating in cold-climates and cryogenic cooling applications and often fails in performance compared to standard cycle technology. However, a full range of applications that place the heat pump in the environment that allows it to perform well, within and external to the HVAC&R industry have not been assessed nor has its performance compared to current systems in viable applications.

2. METHODOLOGY

Ideal, open and closed air-cycle heat pump performance models have been developed to conduct parametric studies of the heat pump in various applications. The air-cycle performance compared to existing gas and refrigerant systems in qualifying applications will be conducted. A systematic approach to determine application opportunities that place the air-cycle in an environment to thrive based on its strengths will also be employed. The heat pump's performance in these areas will be established.

3. EXTENDED BENEFITS

The ability to replace HFC systems with a refrigerant system with low global warming and ozone depleting potential can reduce greenhouse gas emissions and resulting environmental and health effects. This work also has the potential to provide enhanced performance in undiscovered applications which expands the HVAC&R industry scope.

ANALYSIS OF PACKAGED AIR CONDITIONING SYSTEM FOR HIGH TEMPERATURE CLIMATES

Research Assistants: Ammar Bahman and Riley Barta
Principal Investigator: Professor E.A. Groll
Sponsors: Adams Communications & Engineering Technology (ACET)

Abstract

This project focuses on enhancing the performance of a transportable Environmental Control Unit (ECU) operated in high temperature climates. The aim of the project is to improve the efficiency of the ECU unit by 10% to 30%, which could result in an annual fuel saving of nearly 3.3M gallons. The ECU project investigates one unit with a capacity of 60,000 Btu/hr (5 tons of refrigeration).

To find a more efficient design for the ECU, the project is divided into several sub-goals for the 60K ECU. 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. Novel compressor technologies will also be implemented in the ECU in order to further reduce power consumption and increase the overall efficiency.

A mid-term goal of this project will be to utilize the results of a previous study performed with a similar 18K and 36K ECUs to implement similar changes on the 60K ECU. The study was based on improvement of refrigerant flow circuitry of the unit's evaporator through interleaved circuitry. The use of both interleaved circuitry and hybrid control systems have been considered for application, however the decrease in power loss that the hybrid system can provide over the interleaved circuitry design is not large enough to justify the increased implementation costs and reduced long-term reliability of the technology. Therefore, interleaved circuitry will be utilized on the 60K ECU. The model for this passive compensation technique showed that the effect of power loss could be reduced to half with interleaved circuitries, and the ECU's current circuitry design shows promise in its potential for improvement.

A long-term goal of the project will be to further improve the system's performance by evaluating the ECU compressor using vapor injection with economizing technology. A previous study on an 18K and 36K ECUs showed a 5.3% larger increase in COP at 55°C using this technique over liquid flooding, therefore vapor injection will be implemented and assessed on the 60K ECU.

In order to attain the overall objectives, ECU 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.

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

Research Assistants: Nicholas Czapla, Harshad Inamdar, and Nicholas Salts

Principal Investigator: Eckhard A. 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 the impeller of the turbine. The rotating impeller 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.

VOLTTRON™ ENABLED RTU AFDD IMPLEMENTATION AND DEMONSTRATION

Research Assistant: Andrew Hjortland

Principal Investigator: Professor J.E. Braun

Abstract

Previous research on automated fault detection and diagnostics (FDD) for HVAC systems has shown promising benefits like earlier detection and more accurate isolation of different faults. While most researchers, equipment manufacturers, and policymakers agree that HVAC system FDD is important and has the potential to reduce significant energy waste due to faulty system operation, widespread adoption of these tools has been slow. An automated fault detection and diagnosis system has been developed for packaged (rooftop) air conditioners based on the VOTTRON™ monitoring and controls framework developed by the Department of Energy. The system implements a virtual-sensor-based FDD methodology capable of isolating common rooftop unit faults such as improper refrigerant charge level, heat exchanger fouling, liquid-line restrictions, and compressor valve leakage. A fault impact evaluation component has also been implemented in order to determine the relative impact that faults have on system performance. This is accomplished using virtual sensor outputs and manufacturers' performance map reference models for performance indices such as cooling capacity and COP. In addition, a service decision-making component is planned that will enable scheduling maintenance when it is most economical in relation to the cost of different service tasks and its on-going operational cost impact. This system has been implemented using low-cost electronics components and will be tested using a 5-ton RTU at Herrick Laboratories. The goal of this research is to produce a field ready FDD tool for RTUs that can be used to show the benefits of FDD in real systems. Ultimately, the software implementation (using Python) and hardware designs of all the systems components will be released under an open source license in an effort to reduce the engineering effort required by equipment manufacturers interested in a complete AFDD solution.

NEAR OPTIMAL RTU SERVICE DECISIONS USING MULTIPLE FAULT IMPACT ISOLATION

Research Assistant: Andrew Hjortland

Principal Investigator: Professor J.E. Braun

Abstract

Automated fault detection and diagnostics (FDD) tools for rooftop unit (RTU) air conditioners enable earlier awareness and facilitate the isolation of faults that may significantly increase utility costs and reduce equipment life over time. While previous research has suggested that FDD may reduce annual US commercial building energy consumption by as much as 30%, building owners and service contractors still face difficult decisions of whether to perform maintenance or let faults persist. These decisions are difficult due to uncertainty associated with estimating the past or future impact faults may have on the system. The problem becomes even more complex when a system develops multiple faults, each simultaneously impacting system performance. In this project, statistical machine learning models used to estimate the relative impacts on capacity, COP, SHR, run-time, and energy consumption of different faults have been developed without requiring more sensors than used for FDD. Using these models, a service decision-making framework has been developed that can be used to make near-optimal service decisions by recommending the subset of service tasks that is most economical. To evaluate its effectiveness, optimal service policies have been determined using dynamic programming for different combinations of faults. While optimizing the maintenance of a single RTU is important, optimizing the maintenance of all RTUs at a building has greater benefit. To this end, future work developing techniques to optimize maintenance of all RTUs at a building will be pursued in order to reduce utility, equipment, and service costs.

METHODOLOGY FOR AUTOMATED VIRTUAL CHARGE SENSOR TUNING USING OPEN LABORATORY TESTING

Research Assistants: Akash Patil and Andrew Hjortland

Principal Investigator: J. E. Braun

Abstract

Previous studies have shown that virtual sensors based on low-cost system measurements can replace more expensive or difficult to measure system metrics used in direct-expansion system. Virtual sensors have previously been developed and demonstrated for accurate estimation of the amount of refrigerant charge contained in packaged (rooftop) air conditioners. The virtual charge sensor requires measurements of four surface temperatures and two refrigerant pressures, to determine suction superheat and liquid-line subcooling that are inputs to a model that estimates the charge. The model uses empirical parameters that are determined through regression to laboratory measurements for the system. In the past, extensive psychrometric chamber testing was required at different refrigerant charge levels and ambient conditions to obtain sufficient data for the regression. However, using psychrometric chambers is expensive method for equipment manufacturers and it can be difficult to find available test facilities. The current work focusses on developing an automated open lab training kit for tuning the virtual refrigerant charge level sensor in an open laboratory space. The developed automated training kit algorithm has the ability to modulate the condenser and evaporator fans to simulate the effects of different ambients and automatically change the charge. The charge level is automatically adjusted and monitored using solenoid valves and a digital weighing scale. This approach reduces the human involvement to a great extent and eliminates the need for psychrometric chambers. Software associated with the training kit has been developed using Python. The resulting training kit will be applied in open lab conditions and then results will be compared with results obtained from the psychrometric chamber. Ultimately, the goal of this research is to develop a fully automated virtual training kit to help in reducing upfront engineering costs for manufacturers. Future work will examine this methodology for different RTU configurations (fixed orifice vs TXV expansion device, microchannel vs fin tube condenser).

PARTICLE RESUSPENSION IN BUILDINGS: IMPLICATINS FOR BIOAEROSOL TRANSPORT & HUMAN EXPOSURE

Professor: Brandon E. Boor

Particle resuspension is the process by which settled dust particles detach from a surface and are entrained into the air. It is an important source of biological particles, or bioaerosols, in buildings, including human- and animal-associated bacteria, fungal spores and their fragments, pollen grains, and mite and animal allergens (e.g. dust mite feces). These particles range in size (aerodynamic diameter) from 0.1 to > 30 μm .

Resuspension is typically associated with human activities that induce a disturbance of settled dust deposits, such as walking (footfalls), movements on mattresses and other furniture, and infant crawling. Bioaerosols can detach from our clothing and the shedding of skin cells releases significant quantities of skin-associated bacteria into the air. We can envision ourselves as being surrounded by a cloud of microbes and particles (Pigpen effect). Additionally, impulsive and turbulent airflow in ventilation systems can resuspend particles from ducts, which can accumulate high mass loadings of dust ($\gg 1 \text{ g/m}^2$).

The impact of bioaerosol exposures on human health necessitates that we develop a deeper understanding of the resuspension and transport of biological particles, which can vary considerably in their size, shape, and surface features. This poster presents past and ongoing research related to human-induced particle resuspension from mattresses and carpets and aerodynamic-induced resuspension from monolayer and multilayer particle deposits on ventilation duct surfaces. Lastly, the poster introduces future directions at Herrick Laboratories to advance research on bioaerosol dynamics and resuspension in buildings through application of laser-induced fluorescence (LIF)-based aerosol measurement techniques and quantitative PCR (qPCR).

PREDICTING AIR DISTRIBUTION AND CONTAMINANT TRANSPORT IN AIRCRAFT CABIN WITH A SIMPLIFIED GASPER GEOMETRY

Research Assistant: Ruoyu You

Principal Investigator: Professor Y. Chen

Abstract

Overhead gaspers are prevalently installed in aircraft cabins as a personalized ventilation system. It is crucial to accurately calculate the air distribution and contaminant transport in aircraft cabins with gaspers on using computational fluid dynamics (CFD) in order to improve the design of air distribution system. However, very few studies have investigated the suitable turbulence model to simulation air distribution in cabins with gaspers turned on. This study first conducted experimental measurements of airflow distribution in a mockup of half of a full-scale, one-row, single-aisle aircraft cabin with a gasper on. This investigation then used the measured data to evaluate the performance of computational fluid dynamics (CFD) with the RNG $k-\epsilon$ model and the SST $k-\omega$ model. This study then applied the identified turbulence model to the economy cabin in MD-82 to investigate the contaminant transport in an aircraft cabin with gaspers. The results showed that the SST $k-\omega$ model was more accurate than the RNG $k-\epsilon$ model for predicting the airflow distribution in gasper-induced jet dominant region in an aircraft cabin. For contaminant transport in aircraft cabins, it was found that, large portion of contaminants move up after emission. The contaminants then disperse horizontally in the upper level. Since gasper-induced flow blows downward, it will then carry the contaminant on the upper level down, even to the passengers' breathing zone. Therefore, in real aircraft cabin, turning on gaspers may even increase passengers' exposure to air contaminants.

A FAST MODEL FOR TRANSIENT PARTICLE TRANSPORT SIMULATIONS IN INDOOR ENVIRONMENTS - - THE MARKOV CHAIN MODEL

Research Assistant: Chun Chen

Principal Investigator: Professor Y. Chen

Abstract

INTRODUCTION: Obtaining information about particle dispersion in a room is crucial in reducing the risk of infectious disease transmission to the occupants. As a powerful airflow and contaminant modeling tool, computational fluid dynamics (CFD) has been widely used in predicting transient particle transport in enclosed environments. For particle modelling, Eulerian and Lagrangian are two popular methods. Both methods can obtain detailed information about transient particle concentration distributions. However, they are both considerably time-consuming. Therefore, a new model that not only can obtain detailed information about transient particle concentration distributions like the Eulerian and Lagrangian methods can do, but also runs faster than these two methods is desirable.

METHODS: This study developed a Markov chain model for quickly obtaining the information based on a steady-state flow field calculated by computational fluid dynamics. When solving the particle transport equations, the Markov chain model does not require any iterations in each time step so it can reduce significantly the computing cost. This study used two sets of experimental data of transient particle transport to validate the Markov chain model. This study also applied the validated Markov chain model to predict the person-to-person particle transport in a ventilated room.

RESULTS: The comparison shows that, in general, the trends of the particle concentration distributions predicted by the Markov chain model agreed reasonably well with the experimental data. For the person-to-person particle transport case, the Markov chain model produced similar results as the Lagrangian and Eulerian model did, while the speed of calculation increased by 8.0 and 6.3 times, respectively.

CONCLUSIONS: The proposed Markov chain model can be used for predicting detailed information about transient particle transport in enclosed environments, with less computing cost as compared the Eulerian and Lagrangian models.

IMPLEMENTATION OF A FAST FLUID DYNAMICS MODEL IN OPENFOAM FOR SIMULATING INDOOR AIRFLOW

Research Assistants: Wei Liu, Mingang Jin, Chun Chen, and Ruoyu You

Principal Investigator: Professor Y. Chen

Abstract

This study implemented FFD in OpenFOAM and used a local searching method that made the FFD solver applicable to unstructured meshes. Because the split scheme used in FFD is not conservative, this investigation developed a combined scheme that used split scheme for the continuity and momentum equations and iterative scheme for scalar equations. The combined scheme ensures conservation of the scalars. This investigation used two two-dimensional cases and one three-dimensional case, with experimental data, to test the FFD solver. The predicted results were similar with different types of meshes and numerical schemes and agreed in general with the experimental data.

Keywords: Structured mesh; unstructured mesh; split scheme; iterative scheme; semi-Lagrangian.

AN ORDERED PROBABILITY MODEL FOR OUTDOOR THERMAL COMFORT

Research Assistant: Dayi Lai

Principal Investigator: Professor Y. Chen

Abstract

Outdoor thermal comfort of urban spaces is gaining increasing research attention because it is associated with the quality of life in cities. Traditional models can only give a single value prediction of the occupant thermal condition. This paper applied the econometric and statistics method and developed an ordered probability model for outdoor thermal comfort by using 1549 observations obtained from 11 field surveys in Tianjin, China. This model is able to calculate the thermal sensation vote (*TSV*) distribution and can thus provide more information than traditional models. Air temperature (T_a), global solar radiation (G), wind speed (V_a), the metabolic rate of occupants (*MET*), clothing (*CLO*) and the hot day indicator (*HOT*) were found to significantly affect the *TSV* distribution. The model performance test shows that the averaged difference between the predicted and sampled probability for different *TSV* categories was 2.61%. This model provides a new and more informative tool when studying outdoor thermal comfort.

Keywords: Outdoor thermal comfort, ordered probability model, thermal sensation distribution

THE ULTRASONIC EXCITATION OF THERMAL RESPONSES WITHIN ENERGETIC MATERIALS

Research Assistants: Jacob K. Miller, Jesus O. Mares, Zane A. Roberts, Ibrahim E. Gunduz,
and Steven F. Son

Principal Investigator: Professor J.F. Rhoads

Abstract

Despite the significant amount of research related to improvised explosive devices (IEDs) 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, this project aims 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. A heat point source model was used to estimate heating rates and temperatures at the particle locations in this frequency region, with correlation noted between particle morphology and thermal response. Ammonium perchlorate (AP) particles recrystallized in the laboratory, with sharp crystal facets, exhibited a greater likelihood of significant heat generation than more spherical crystals received directly from a propellant supply company. At elevated excitation parameters near the transducer resonance frequency embedded particles of AP and cyclotetramethylene-tetranitramine (HMX) were driven to chemical decomposition, illustrating the effectiveness of this type of excitation.

OPTIMIZATION OF ACOUSTIC WAVE TRANSMISSION INTO ELASTIC AND VISCOELASTIC MATERIALS

Research Assistant: Daniel C. Woods
Principal Investigator: Professor J.S. Bolton and J.F. Rhoads
Sponsor: Office of Naval Research

Abstract

Stress and energy transmission by airborne sound into solid materials is of interest in a wide range of applications, but is generally limited by the high impedance-differences between air and typical solids. The present work is focused on tuning the parameters of incident acoustic waves to maximize the transmission into representative solid materials. In particular, both homogeneous and inhomogeneous plane waves in air, and both elastic (i.e., lossless) and viscoelastic solid materials are being considered. General plane waves in air can be closely approximated over a given region of space by using, for example, phased arrays of sources. As such, the parameters of the incident wave, including the incidence angle, spatial decay characteristics (i.e., degree of inhomogeneity), and frequency, can be varied. By varying these incident wave parameters, significant transmission increases can be achieved. In the context of low-frequency acoustic waves (which can be transmitted over large distances), this optimization reveals a pathway to increased stand-off transmission and, for dissipative materials, increased stand-off heating.

Models for the fluid-structure interaction in the presence of (as well as in the absence of) material dissipation are being developed that allow for both homogeneous and inhomogeneous incident waves. The incident wave parameters which yield the minimum values of the reflection coefficient magnitude were sought, since the energy transmission is maximized when the fraction of energy reflected is minimized. In the case of inhomogeneous plane waves in lossless media, the planes of constant amplitude are perpendicular to the planes of constant phase, so the wave amplitude decays normal to the propagation direction. In contrast, for viscoelastic media, the planes of constant amplitude and the planes of constant phase for inhomogeneous waves are offset by the degree of inhomogeneity, which is less than 90° ; this angle, along with the material properties, sets the rate of spatial decay. In this study, the spatial decay rate was varied along with the incidence angle to minimize the magnitude of the reflection coefficient.

The results for the elastic interface reveal, for a given frequency and set of material properties, a unique combination of the incidence angle and incident wave decay rate which yields zero reflection, and consequently substantial transmission increases, at the interface. For the viscoelastic interface, the minimum in the reflection coefficient remains nonzero, but the reduction is evident over a larger range of incidence angles (compared to the elastic case), and so provides a wider domain over which considerable transmission increases are predicted. The results also reveal that with sufficient dissipation levels in the solid material, homogeneous incident waves may yield lower reflection values than inhomogeneous waves, since the high dissipation levels necessitate transmitted waves with large degrees of inhomogeneity even when the incident wave is homogeneous.

IDENTIFICATION OF LOW FREQUENCY DYNAMIC BEHAVIOR OF SURROGATE EXPLOSIVE MATERIALS

Research Assistant: Jelena Paripovic
Principal Investigator: Professor P. 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 are indicative of 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 surrogate cylindrical samples composed of HTPB binder embedded with ammonium chloride crystals which is similar in structure to materials used in 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 hereditary viscoelastic term improves the prediction of the system frequency response function. Increasing the order of the relaxation kernel from one to two for a single base excitation experimental data set improves the fit 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. Applying this identification approach but using data from multiple experiments in the model fit (5g, 7.5g, and 10g base excitation), the model predictions worsen. It is hypothesized a higher order relaxation kernel is needed to fully characterize the response behavior. The identification procedure has been adapted to include Prony analysis to estimate the coefficients of the viscoelastic kernel in either the time or frequency domain. Increasing the viscoelastic model order above two improves the fit near resonance for both the 0% and 50% test samples when using multiple data sets in the estimation. The models developed and estimated material properties are being shared with researchers who are studying other systems that incorporate these surrogate materials. These types of viscoelastic models can be used to characterize a wide variety of materials including rubber-like materials, foams and human tissue.

POINT EXCITATION OF A COUPLED STRUCTURAL-ACOUSTICAL TIRE MODEL WITH EXPERIMENTAL VERIFICATION

Research Assistant: Rui Cao

Principal Investigator: Professor J.S. Bolton

Abstract

The acoustical modes that exist within a tire's interior cavity have an important influence on tire noise, particularly structure-borne noise. The first circumferential mode is most commonly considered: it occurs when the average circumference of the tire interior cavity is approximately one wavelength. However, that mode is just the first of a family of circumferential and depth modes, the latter of which, in particular, are rarely considered, but which were the primary focus here. A modal expansion method was utilized to solve for the point excitation of a fully-coupled, ring-like structural-acoustical tire model. From that model, the dispersion features associated with acoustical depth modes, which typically first appear between 1700 and 1800 Hz, were identified, and their existence was verified by making detailed measurements on tires.

REDUCED ORDER SIMULATION IN ROOM ACOUSTICS

Research Assistant: Yangfan Liu

Principal Investigator: Professor J.S. Bolton

Abstract

The use of Equivalent Source Models (ESM) has recently been extended, with appropriate modifications, from its original application in acoustical holography to room acoustics simulations. This approach can serve as an alternative that is less computationally intensive than Boundary Element Models and which is more flexible than traditional ray-tracing models in terms of dealing with non-compact sources and lower frequencies where the ray approximation is no longer accurate. Such room acoustics ESMs are based on the assumption that the room component of the total sound field can be represented by a number of equivalent sources of certain types, and that the total sound field can be predicted, with given free-space source information, by estimating the strengths of these equivalent sources based on a least-square match of the impedance boundary conditions on both the source and the room surfaces. However, to-date, the room acoustics ESMs have only been formulated and validated for two-dimensional cases. In the current work, the ESM formulation has been extended to three dimensions by replacing the two-dimensional equivalent sources with their three-dimensional counterparts, and its application in realistic three-dimensional room environments has been validated by successfully comparing the ESM and Boundary Element predictions.

A TUNABLE SIGNAL INTERFERENCE TOPOLOGY USING AN ELECTROMECHANICAL RESONATOR

Research Assistant: Bryce A. Geesey
Principal Investigator: Professor J. Rhoads

Abstract

As communication and signal processing technologies progress, often the goal is to achieve improved levels of frequency selectivity. Although high frequency studies are continually increasing the upper bound of the available frequency spectrum, there is a considerable demand for creating higher-order filters to better utilize those parts of the spectrum currently in use, while improving signal integrity and noise rejection. Frequency selectivity is a topic that spans multiple disciplines, from telecommunications to acoustics and beyond.

Most higher-order electrical filters utilize complex arrays of passive and active components, but these filters tend to have significant insertion losses and delays when implemented at high frequencies. One existing approach to improve filter selectivity with low losses involves signal interference techniques, where an input signal is split into two paths, each with different magnitude and phase characteristics, which are then recombined at the output. By essentially combining a signal with a phase-shifted copy of itself, the resulting outputs of these filters can demonstrate fully constructive interference (doubled amplitude), fully destructive interference (zero amplitude), or an arrangement of constructive and destructive effects, around a designed frequency. Related research efforts in this area have proven the effectiveness of this design as a bandpass filter at ultra-wideband frequencies (typically a few GHz) using a simple microstrip implementation.

However, this technology is not easily down-scaled because microstrip phase shifting in the very-high frequency (VHF) band and below may require a meter or more of copper trace length (in FR-4 printed circuit boards) to achieve similar signal offsets. For this reason high quality factor mechanical resonators are proposed for increasing the filter roll-off at lower frequencies while using analog components for phase shifting and amplifying an input signal. This study lays the groundwork for a new signal interference filter at VHF frequencies with tunable parameters.

The proposed design is tested around 50 MHz using a bulk-mode piezoelectric crystal resonator and other analog electrical components on a printed circuit board layout. Preliminary results for this study show the expected constructive interference when the resonator and phase-shifted signals are in-phase, and destructive interference results when the two signals are phased 180 degrees apart. These two results can be easily adjusted, or “tuned”, by varying the parameters of the phase-shifting components of the circuit.

In future study, this initial proof-of-concept will be applied to arrays of two or more resonators, and the theory may be downscaled further in the frequency domain to design an acoustic or fluid dynamics equivalent. In conclusion, the authors hope to improve upon the design of signal interference filters by lowering their usable frequency ranges and leveraging the high quality factor benefits of mechanical components.

TRACE ENERGETIC VAPOR DETECTION VIA NONLINEAR RESONANT SENSORS

Research Assistant: Nikhil Bajaj

Principal Investigator: Professor G. Chiu and J. Rhoads

Abstract

The detection of energetic materials is a significant safety and security challenge. To date, methods of detecting energetic materials have been highly setting-dependent, and tend to rely on expensive equipment that is not portable or practical. In many instances, the systems in place to detect energetic material vapors that would indicate a hazard are not actually sensitive enough to do so, as many dangerous materials have low vapor pressures at ambient conditions. In order to address these challenges, the present work investigates the development of a low-cost, highly-sensitive sensor platform referred to as PIMS (Portable, Integrated, Microscale Sensors). These PIMS devices are comprised of electronics for sensing and driving a microscale resonator into nonlinear behavior, in order to take advantage of sensitive bifurcations that can detect small changes in mass and indicate this with a large change in response amplitude.

The device is built by using analog multiplier and operational amplifiers to feed back a signal representing the current state of the device cubed back into the drive signal. This cubic feedback (with adjustment gains) allows the system to take a low cost device with a highly linear response and cause it to exhibit a response similar to that of a Duffing resonator.

There are three distinct challenges with this strategy for detection of energetic materials: the sensing device (developed as discussed above), the delivery of samples to the sensor, and the chemistry with which the sensor is functionalized in order to gain specificity to detection targets.

The sensor has been tested with water vapor to confirm its functionality. Current work is focusing on which resonator geometries have high sensitivity, as well as exploring various detection chemistries and improving the delivery of air samples (containing trace vapors) to the sensor.

PIEZOELECTRIC PRINTING OF NANOTHERMITES ON SILICON SUBSTRATES

Research Assistants: Trevor Fleck, Allison Murray, and Whitney Novotny

Principal Investigator: Professor J. Rhoads

Abstract

There exists a pressing operational need to secure and control access to high-valued electromechanical systems, and in some cases render them inoperable. Developing a reliable method for depositing energetic materials will allow for the near-seamless integration of electromechanical systems and energetic material, and, in turn, provide the pathway for security and selective destruction that is needed. In this work, piezoelectric inkjet printing was used to selectively deposit energetic materials. Nano thermites, comprising of nanoscale aluminum and nanoscale copper oxide suspended in dimethyl-formamide (DMF), were printed onto silicon wafers, which enabled both thermal and thrust measurements of the decomposing energetic material. Various solids loadings as well as drop characterization were studied in order to optimize printing characteristics. Going forward, future studies will focus on the plausibility of inkjet printing other energetic materials for the purposes of the degradation of electromechanical systems.

ADVANCED MESHING TOOLS FOR TOMOGRAPHIC INVERSE PROBLEMS

Research Assistant: Jie Yang

Principal Investigator: Professor F. Semperlotti

Abstract

Tomography is a noninvasive technique for real time reconstruction and visualization of the interior properties of a continuum body. Tomographic problems are typically governed by multiple spatial and temporal scales that strongly affect the sensitivity and resolution of nonlinear inverse problem. Efficient computational tools able to resolve and extract features defined on these different scales are needed. Adaptive mesh refinement can provide an interesting approach to this class of problems by drastically increasing the global accuracy at a greatly reduced computational cost. This poster explores the use of a specific class of adaptive meshing technology, namely the Wavelet Adaptive Mesh Refinement (WAMR), which is a multiresolution analysis tool able to effectively deal with highly localized features. This poster presents the WAMR algorithm and a numerical study to assess the performance in terms of computational time and accuracy. Then, WAMR is implemented into Electrical Impedance Tomography (EIT) and numerical results are used show the significant improvement in computational efficiency and quality of the reconstructed image.

STRUCTURAL DAMAGE DETECTION VIA IMPEDIOGRAPHY

Research Assistant: Liuxian Zhao

Principal Investigator: Professor F. Semperlotti

Abstract

We investigate the use of impediographic tomographic to achieve high sensitivity and high resolution damage identification in metallic structures. The impediographic approach exploits the coupled piezo-resistive and electrostatic response of the host structure to generate high sensitivity and high resolution maps of its internal electrical conductivity. Focused acoustic waves are used to generate localized electrical conductivity perturbations that allow drastic improvement in the conditioning of the inverse problem by enriching the dataset of input data used for the inverse reconstruction problem. The localized acoustic perturbation is obtained by exploiting the concept of Frequency Selective Structures (FSS) in which intentional mistuning of periodically distributed structural features (e.g. thin notches) enables self-focusing and vibration localization by using a single ultrasonic transducer.

The poster presents a numerical study investigating the performance of impediography as damage identification approach for metallic structures. The inverse tomographic problem is solved by an iterative Levenberg-Marquardt (LM) method. Numerical results show that the LM approach performs well in terms of damage identification, localization, and sizing, and it is able to handle incomplete data. Results support the conclusion that the FSS-based impediography provides a viable and effective way for high resolution damage identification. Experimental validation of the FSS design is also presented.

SPATIAL LOCALIZATION OF COMBUSTION AND MECHANICAL NOISE SOURCES IN A DIESEL ENGINE

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

Abstract

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

MODELING VEHICLE NOISE CONTROL TREATMENTS

Research Assistant: Hyun Jun Shin
Principal Investigator: Professor J.S. Bolton

Abstract

Concerns about creating a quiet environment for drivers and passengers have been prominent for several decades. Thus, thick and heavy multi-layered materials have been implemented to reduce vehicle interior noise levels. However, automobile companies not only require quietness but also light weight for many reasons. Therefore, the investigation of lighter materials with excellent acoustical performance is currently a significant concern for acoustic engineers in the automobile industry. To resolve this issue, materials with lower surface density and higher in sound barrier performance are required. Thus, the present research is focused on finding lightweight acoustic treatments which are compatible with conventional sound absorbing materials currently being used in automotive applications. Multi-layered materials are designed to serve as both sound barriers and absorbers. Barriers are typically heavier to prevent the outside noise sources from transmitting into the vehicle. On the other hand, sound absorbers, much lighter in weight compared to barriers, are used to absorb the sound field within the vehicle. Thus, there is also an issue related to balancing the usage of sound absorber and barriers to optimize the weight and acoustic performance. To find the optimum light weight treatments for a vehicle, the following work is being performed. First, transmission losses and absorption coefficients are measured using a standing wave tube to assess the acoustic performance of conventional sound absorbing materials. Then, to quantify the behavior of the sound inside of a vehicle, a simple acoustic model is developed using transfer matrix method (TMM); this model gives an estimate of the space averaged sound level within a vehicle as a function of frequency for a specified input spectrum, and the model may incorporate complete treatment transfer matrices that are either measured or predicted. Lastly, Alphacell software is used to simulate the different combinations of multi-layered materials with an emphasis on finding combinations that balance barrier and absorption performance while at the same time being of reduced weight when compared with existing treatments.

OPTIMIZATION OF MULTI-LAYER MICROPERFORATED SYSTEMS AS A FUNCTIONAL ABSORBER AND A DUCT LINER

Research Assistant: Nicholas Kim

Principal Investigator: Professor J.S. 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 performance of microperforated panels can be controlled by panel thickness, diameter of the holes, surface porosity, mass per unit area, and air backing 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 results 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 and duct liners are considered, and the focus is on the speech interference range (500 to 4000 kHz). The MPP treatment is assumed to be locally reacting in the normal direction, and 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 $5N-1$ parameters 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.

DESIGN OF MULTI-CHAMBER SILENCERS WITH MICROPERFORATED ELEMENTS CONSIDERING FLOW EFFECTS

Research Assistant: Seungkyu Lee
Principal Investigator: Professor J. S. Bolton
Sponsor: 3M Company

Abstract

An acoustic silencer is known to provide a good noise reduction solution in duct systems. However, the loss of flow performance resulting from an increase in flow resistance is an inevitable result of the expanded section of a typical silencer. Therefore the objective in this study was to design an acoustic silencer with good noise attenuation performance over the speech interference range (500-4000 Hz) while also considering the flow performance. Here, both Finite Element Modeling (FEM) simulation and experimental methods were used to design an acoustic silencer. First, the flow effect inside the duct was considered experimentally, and a FEM model of the silencer with microperforated elements and with flow effects was developed. The model was shown to work well for the relatively low flow speeds typical of HVAC systems. A series of design studies were performed using the finite element model. In the final design, extended inlet and outlet sections were used to eliminate minima in the transmission loss, and duct liners made from microperforated films were also included: the latter elements, in particular, were used both to provide dissipation and improve the flow performance of the silencer by reducing the pressure drop due to the expanded region.

A PREDICTION OF SOUND FIELD GENERATED BY AN EN-ROUTE AIRCRAFT IN AN ATMOSPHERE WITH TEMPERATURE GRADIENTS

Research Assistant: Yiming Wang

Principal Investigator: Professor K.M. 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.

DYNAMIC MODELING OF GEARS FOR REDUCTION OF NVH NOISE IN AUTOMOBILE

Graduate Student: Eeshan Mitra

Advisors: Kai Ming Li, Henry Zhang and Charles M Krousgrill

Abstract

Periodic time varying loads resulting from meshing of gear teeth are a primary source of noise and vibration (NVH) emanating from planetary gear trains. The frequency response function for such a multibody system helps develop an understanding of noise generation for a given set of operating conditions. One approach to model the contact between pairs of gear teeth is to replace them with springs having time varying stiffness. The stiffness can be determined accurately with the help of a finite element solver as one set of teeth mesh and leave contact in one pitch angle. This study endeavors to develop a correlation between the proximity of operating speed and frequency to resonances of the system, and samples of noise from experimental data. Time varying stiffness serves as an example of a problem having parametric excitations. Additionally, this problem is also complicated by backlash and transmission error which make the problem nonlinear in nature. Having incorporated the aforementioned aspects into the model, an approach to solve for the response of this cyclic symmetric system would be to solve Mathieu's or Hill's equation for multi degree of freedom systems. The study will present some preliminary results for the vibration of pinion gear interacting with four nested planetary gears.

CALCULATION OF THE TIME-VARYING MESH STIFFNESS OF PLANETARY GEAR SETS WITH 2D & 3D FE MODELS

Research Assistant: Darioush Kevian Esfahani

Principal Investigator: Kai Ming Li

Advisors: Henry Zhang and Charles M Krousgrill

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Purdue University, 177 S. Russell St., West Lafayette, IN 47907-2099

Abstract

The torsional mesh stiffness is one of the most important characteristics of gears. It is a periodic function caused by the change in the number of tooth-contact pairs and their contact positions. It is one of the main sources of noise, vibration and harshness (NVH) for a gear transmission system in automobiles. This poster presents the development of detailed finite element models which can be used to calculate the torsional mesh stiffness of a transmission gear set. Typically, a two-dimensional model is well suited to simulate a variety of different gear pairs in a short period of time. The more complex three-dimensional model features more options in terms of investigating tooth face modifications for further studies to reduce noise and vibration. The torsional mesh stiffness presented for each gear is based on the individual stiffness of the three main components – the gear transmission body, teeth of the coupling gears and their contact positions. The results from both the two- and three-dimensional finite element models are validated by comparing with the results obtained by using the potential energy method.

SIMULATIONS OF NESTED PLANETARY GEAR SETS IN ROMAX FOR ELIMINATION OF NVH SOURCES

Research Assistant: Cong Liao

Principal Investigator: Kai Ming Li

Advisors: Henry Zhang and Charles M Krousgrill

Ray W. Herrick Laboratory, School of Mechanical Engineering,
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Abstract

The sources of noise and vibration (NVH) in a gear train consists of many inter-related elements such as gear meshing dynamics, manufacturing and assembly errors, excitation of gear housing and resonance of other parts in the transmission. These NVH sources are coupled in the gear train with the nested planetary gear sets. Modeling and simulating of the gear train provide an access to control macro and micro parameters of the gear tooth. It is also helpful to improve the designs of shaft and bearing of the transmission plant. A set of four planetary gears, two of them are nested offering multiple speed ratios. The planetary gear sets, clutches and bearing are modeled in the present study by using proprietary software - ROMAX. Numerical simulations are conducted with varying drive speeds in order to obtain transmission errors, misalignment variations, proportions of tooth contact, distribution of tooth loading and excitation harmonics of gear teeth. Tooth profiles are optimized for compensating design errors and, possibly, reducing the gear meshing vibration. With an improved tooth profile, the reduction of gear train's NVH are then assessed.

SOUND QUALITY OF HVAC&R EQUIPMENT

Research Assistant: Weonchan Sung
Principal Investigators: Professors P Davies, J.S. Bolton
Sponsor: UTC/Carrier
Collaborator: Asad M. Sardar, Robert Chopko

Abstract

Some HVAC&R (Heating, Ventilating, Air-Conditioning, and Refrigerating) machinery can produce noise that is irritating to people, which includes people inside building and homes. HVAC&R noise is composed of broadband noise and periodic components related to rotation rates of fans and compressors. Most metrics that are used today to predict HVAC&R noise are just functions of a level measure and a tonalness measure but models incorporating both, e.g. ANSI/AHRI Standard 1140-2012, are not widely used. The goal of this research is to develop better metrics for HVAC&R machinery noise that can be used in HVAC&R system design. It is not clear whether it is appropriate to use one model for all market sectors (residential, light commercial and truck), so initially subjective tests will be run with sounds from all three. A series of subjective tests will be conducted to determine what sound attributes are noticed and the role that they play in peoples' perception of HVAC&R sound quality. Existing metrics will be examined to see how well they predict strengths of perceived sound attributes, and deficiencies, if any, will be identified. A database of sounds has been assembled and additional measurements have been conducted. A metric analysis has also been performed. To construct a sound quality model we need to be able to vary important attributes independently, and so the initial work has been focused on analyzing the sounds and breaking them into components. The components can be manipulated to strengthen or weaken sound attributes and new sounds can be constructed. Sound attributes include tonality, level, frequency modulation and amplitude modulation. The next step will be to conduct the first subjective test where people will listen to sounds and describe them. This approach to sound quality model development can be applied to other machinery, thus giving product designers people sensitive metrics to enable them to tailor machine/system design.

CHARACTERIZATION OF NEXT-GENERATION CAR SOUNDS

Research Assistant: Youyi Bi

Principal Investigators: Professors T. Reid & P. Davies

Abstract

The goals of this study are to understand future car owners' preferences for sounds made by cars and how willing they are to consider very different sounds to those currently heard. Of interest also, is how visual input and context affects people's preferences of sounds. A pilot study has been designed to determine sound preferences when people are presented with the current sound, very different sounds, and something in between the two. Another goal of this test is to gather descriptions of sounds to understand which sound attributes subjects are noticing so that we can form hypotheses on the inputs to their decision models. Sounds are presented with and without visual information and the results will be compared. Intentional sounds (e.g., turn indicators) and consequential sounds (e.g., car doors latching) are considered in four different contexts. Both automobile and other contexts are considered. Currently we are finalizing the sounds to be used in the tests. The very different sounds are inspired by music preferences of the millennial generation. These and the original sounds are being modeled and manipulated to generate the 18 sounds for this test. Once this is completed the first test will commence (IRB# 1504016034). From the results of this test, we will design more detailed tests to test potential preference decision models.

HUMAN RESPONSE TO SUPERSONIC AIRCRAFT NOISE WHEN HEARD INDOORS

Research Assistant: Daniel J. Carr
Principal Investigator: 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 expressed interest in 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 laboratory testing to evaluate people's responses must occur. To guide aircraft design, objective measures that predict human response to modified sonic boom waveforms and other impulsive sounds are needed. The current research phase is focused on understanding how people will react to booms when heard inside, and must therefore include considerations of house type and the indoor acoustic environment. 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 of vibration, and subjects sat in a small living room environment. A second test was conducted in a sound booth at Purdue University, using similar sounds played back over earphones. The sounds in this test contained less very-low-frequency energy due to limitations in the playback, and the laboratory setting is a less natural environment. For the purpose of comparison, and to improve the robustness of the human response prediction models, both sonic booms and other more familiar transient sounds were used in the tests. In the Purdue test, binaural simulations of the interior sounds were included to compare responses to those sounds with responses to playback of binaural recordings taken in the IER. Major conclusions of this research are that subject responses are highly correlated between the two tests, and that annoyance models including Loudness, maximum Loudness Derivative, Duration, and Heaviness terms predict annoyance accurately.

INFLUENCES OF WIND ON AUTOMOTIVE INTERIOR SOUND QUALITY

Research Assistant: Daniel J. Carr, Sara Huelsman (Purdue SURF student, University of Hartford)

Principal Investigator: Professor P. Davies

Collaborators: Adam Karlin, William Gulker, Ford Motor Company

Sponsor: Ford Motor Company

ABSTRACT

Wind noise constitutes a significant portion of the noise heard by people inside their automobiles, and may reduce human comfort by causing fatigue and interfering with conversation. Loudness metrics are generally accurate in predicting annoyance to wind noise, but there are circumstances in which other factors have significant effect. Thus, there is a need for more detailed investigation of how wind noise affects acoustic comfort, and of the principal noise characteristics that should be considered in addition to Loudness. Measures of Articulation Index (the degree to which a sound interferes with conversation) are also believed to be important. However, it is suspected that these criteria alone are insufficient, and that a more accurate predictor of human response is needed. This predictor can then be used by car designers to check the wind noise of new or proposed vehicles. The present research entails investigation of sounds recorded in a wind tunnel. These sounds were recorded in a variety of cars placed at different angles to the wind, and at multiple wind speeds. Recordings were made at four separate locations in each car using Aachen heads. A small number of metrics have been generated, and statistics of these metrics are being assembled into a database for easy reference. Additional metrics generated include Sharpness, Roughness, Fluctuation Strength, and Tonality; and the statistics generated include quantities of each exceeded 5 and 10 percent of the time. Another metric, which will be used to characterize spectral balance, is based on 12th-octave band analysis of the sounds and their relationship to a desired spectral energy distribution. Loudness, Roughness, and Articulation Index are highly correlated with each other ($R^2 > 0.9$). The remaining metrics are less highly correlated, which is good for model-building. However, it is not certain that louder sounds are necessarily rougher or cause greater interference with conversation. For the purpose of future subjective testing, the existing wind noise recordings will be pre-processed to determine whether these three metrics may be de-correlated.

EXTREME DIRECTIONAL WAVE PROPAGATION IN NONLINEAR METAMATERIALS: EXTREME DAMPING, ENERGY HARVESTING AND MECHANICAL DIODES

Principal Investigator: Professor A. Arrieta

Abstract

Metamaterials are engineered materials featuring unconventional effective properties, such as negative Poisson's ratio or negative effective dynamic mass. To date, most research in mechanical (acoustic) metamaterials has concentrated on exploiting linear behaviour. *Nonlinear metamaterials offer great opportunities to expand the attainable properties* of such engineered material systems. One example is the realization of mechanical diodes, allowing mechanical energy to be propagated only in a desired direction. *Lattices formed with multi-stable unit cells exhibit the characteristics required to obtain extreme wave propagation anisotropy and extreme energy localization. Multi-stability allows a structure to adapt several statically stable configurations*, each of which is associated to a minimum in the strain energy potential of the system. A state of induced internal strains, typically as a result of asymmetric strain distribution through the thickness, governs the multi-stable behaviour. The nature of this nonlinear phenomenon is *material independent phenomenon*, thus applicable in a large class of structures over a wide range of scales. Tailoring the *asymmetry in the strain potential of the multi-stable unit cells allows for designing the desired effective materials characteristics*, such as the propagation anisotropy and localization of energy. Physical realization of this type of lattices would enable the production of a new class of nonlinear metamaterials offering a broad range of interesting applications including mechanical diodes, extreme damping/perturbation rejection, highly concentrated waves for imaging and extreme energy harvesting exploiting the high localization of energy.

MORPHING, TIME-DEPENDENT STIFFNESS AND SHAPE PROGRAMMABLE ADAPTABLE SYSTEMS BASED ON STRUCTURAL MULTI-STABILITY

Principal Investigator: Professor A. Arrieta

Abstract

Engineering structures exhibit limited capacity, if any, for shape adaptation. On the contrary, *inherent shape adaptability* is a prevalent characteristic in nature exemplified by the broad range of manoeuvres enabled by the geometry adaptability of wings exhibited by birds and bats. Furthermore, exploitation of the large deformations warranted by shape adaptability allows plants to achieve rare functionalities, such as insect hunting achieved by the well-known Venus Flytrap. Inspired by nature's designs, the focus of this research is the realisation of engineering systems exhibiting inherent shape adaptability. In particular, our investigations focus on generating *intrinsic shape adaptability programmed into the system during manufacturing*. These concepts are explored and applied in a diversity of applications. Starting with morphing wings, in which the conformal variation of the wing geometry allows for tailoring the aerodynamic response to fulfil optimally multiple mission objectives with a single aircraft system. Morphing capabilities are further expanded by designing elements exhibiting the ability to adopt several stable geometries, a property known as *structural multi-stability*. Embedding these components within distributed compliance structures enables the *selective modification of the structural behaviour of the systems*. This *time-varying stiffness characteristics are utilised to selectively activate morphing modes*, while maintaining high stiffness in the directions of loading. Ultimately by exploiting structural multi-stability, our aim is to program into the structure of engineering systems the capability to exhibit large intrinsic shape adaptation. The multiple attainable geometries are designed to fulfil a series of functions. Moreover, *the work and motion as a result of the adaptation* between the available stable configurations *are utilised to generate further functionality*.

APPLICATIONS OF COMPUTER VISION IN STRUCTURAL HEALTH MONITORING

Research Assistants: Jongseong Choi and Chul Min Yuem

Principal Investigator: Shirley J. Dyke

Abstract

This work explores two applications of computer vision work in structural health monitoring that are visual inspection of cracks on bridge and mobile bridge inspection. Visual inspection of bridges is customarily used to identify and evaluate faults. However, current procedures followed by human inspectors demand long inspection times to examine large and difficult to access bridges. Also, highly relying on an inspector's subjective or empirical knowledge induces false evaluation. To address these limitations, a vision-based visual inspection technique is proposed by automatically processing and analyzing a large volume of collected images. Images used in this technique are captured without controlling angles and positions of cameras and no need for preliminary calibration. As a pilot study, cracks near bolts on a steel structure are identified from images. Using images from many different angles and prior knowledge of the typical appearance and characteristics of this class of faults, the proposed technique can successfully detect cracks near bolts. As second application, mobile bridges have been widely used for a broad range of applications including military or disaster restoration. Because the bridge is rapidly deployed under a variety of boundary and environmental conditions, and has irregular usage patterns, a detailed record of usage history is crucial for ensuring structural safety. Current procedures only approximate the number of vehicle crossings with a passive indicator, limiting the usefulness and accuracy. To address the limitations to this approach, and collect more granular information regarding usage, a new acceleration based vehicle classification technique is proposed to automatically identify the class of each vehicle. The proposed technique is based on the premise that each class of vehicles produces distinctive dynamic patterns while crossing this mobile bridge and those patterns can be extracted from the acceleration responses. Measured acceleration signals are converted to time-frequency images to extract 2D visual patterns. Object recognition techniques that originate from computer vision methods are repurposed to uniquely extract and classify those patterns. The effectiveness of the proposed technique is successfully demonstrated using laboratory and full-scale bridges by simulating various real scenarios.

FAULT TOLERANCE STUDY OF WIRELESS STRUCTURAL CONTROL SYSTEM

Research Assistant: Zhuoxiong (Charlie) Sun
Principal Investigator: Professor S. Dyke
Sponsor: National Science Foundation

Abstract

Over the last decade, wireless structural control systems have received increasingly attention in the civil engineering community. As an alternative approach to protect structures from undesired dynamic loading, wireless structural control systems are convenient and flexible to install and cost-effective compared to their wired counterpart. Although wireless control systems (WCSs) are attractive, there are existing challenges associated with them such as network-induced time delay, potential sensor data loss and sensor failure. These challenges inhibit the adoption of WCSs in real structures. In this work, fault tolerance of the wireless control system is investigated to consider the faulty conditions including sensor data loss and sensor failure. The relative importance of sensor location is evaluated. In addition, a switching estimator is proposed for WCSs. In this method, the switching gains are pre-calculated to enable real-time implementation. The proposed method is verified through numerical simulation considering multiple sensor data loss and sensor failure cases. Furthermore, the estimation switching method is incorporated in a closed loop WCS in the experimental study. The results show the effectiveness of this method with the impact of sensor data loss and sensor failure.

TRANSIENT CONTROL OF A DIESEL ENGINE EQUIPPED WITH VARIABLE VALVE ACTUATION

Research Assistants: Dheeraj Gosala, Aswin Ramesh, Alexander Taylor, Soumya Nayyar, Cody Allen, Xueting (Sylvia) Lu, Matthew VanVoorhis, Kalen Vos, and Mrunal Joshi

Principal Investigator: Professor G. Shaver

Sponsors: Cummins Inc. and Eaton Corporation

Abstract

Variable Valve Actuation (VVA) in IC Engines has displayed great potential in improving fuel economy while also satisfying the increasingly stringent emission norms. To evaluate the impact of this technology, extensive work has been done on a Cummins ISB 6.7 liter 6 cylinder engine equipped with an electro-hydraulic fully flexible valve actuation system. Steady state testing of the engine at different operating conditions has shown notable improvement in fuel efficiency at idle and has also shown potential in improving aftertreatment thermal management. However, diesel engines in automotive and heavy duty applications seldom remain in steady state conditions and are subject to transients. In order to develop a true assessment of the benefits of VVA in automotive/ heavy duty applications, transient testing is required. The presence of VVA requires additional control of air and fuel handling systems which cannot be handled by the Engine Control Module (ECM). While the VVA system is being controlled by dSPACE microcontroller and the air and fuel handling systems by the ECM, it is crucial to achieve time synchronization between them. This work focuses on developing an additional layer of control to enable transient operation of the engine. The ECM is equipped with a GSI link that enables monitoring and modification of various ECM parameters on a cycle-to-cycle basis. The Fuel System Interface (FSI) module on the ECM allows for cylinder specific fueling control while air handling parameters are read off lookup tables. By making appropriate modifications to these tables and overriding fueling values into FSI, automatic transient control of the engine over the drivecycle can be achieved.

HEV DESIGN OPTIMIZATION: INCORPORATING BATTERY DEGRADATION IN ITS ECONOMIC ANALYSIS

Research Assistants: Vaidehi Hoshing

Principal Investigator: Professor G. Shaver

Abstract

The optimal design of hybrid electric vehicle powertrains from a systems perspective is critical to realize the maximum benefits of hybridization for a given application, especially in the heavy-duty vehicle space due to the large number of unique applications. This poster presents a novel framework that enables parametric design optimization of hybrid electric vehicles while accounting for the degradation of the electric battery and its impact over the lifecycle of the vehicle. This framework captures the impact of battery degradation on fuel consumption and battery replacement over the vehicle life by integrating a battery model capable of predicting degradation, and degraded performance, into the drivecycle simulation. These results are incorporated into a lifecycle economic analysis that enables the use of specific economic metrics (including net present value, payback period, and internal rate of return) as optimization objectives. To demonstrate the framework, the electric motor and battery sizes are optimized for a North American transit bus application. The results show that the optimal component sizes depend on the metric of interest, i.e. different optimum parameter sets are obtained when the objective is different. Further, these optimum parameter sets are different if the objective is simply the “day 1” fuel consumption. For example, while optimizing for fuel consumption leads to selection of the largest available battery pack and electric motor, optimizing for payback period leads to the selection of a smaller battery pack. Lastly it was also observed that the fuel consumption increases by up to 10% from “day 1” to End-of-Life of the battery. These results highlight the utility of the proposed framework in enabling better design decisions as compared to methods that do not capture the evolution of vehicle performance and fuel consumption as the battery degrades.

INCORPORATION OF A CAMLESS DIESEL ENGINE IN THE CUMMINS POWER LABORATORY AT HERRICK LABS

Research Assistant: Alexander Taylor, Aswin Ramesh, Soumya Nayyar, Cody Allen,
Dheeraj Gosala, Xueting (Sylvia) Lu, Kalen Vos, Mrunal Joshi,
And Matthew VanVoorhis

Principal Investigator: Professor G. Shaver

Sponsors: Cummins Inc. and Eaton Corporation

Abstract

To continue performing meaningful emissions and fuel improvement studies on a camless 6.7L Cummins ISB diesel engine equipped with Variable Valve Actuation (VVA), an AC dynamometer was needed. The existing eddy current dynamometer was able to provide a torque load on the engine for steady-state testing, but could not allow for engine motoring or running drive profiles. In order to perform EPA Federal Test Procedure (FTP) drive cycle testing, an improvement over the existing eddy current dynamometer was needed. With additional lab space in the new Herrick Labs building to grow into, a PowerTest variable frequency drive AC dynamometer was installed in Test Cell #1. The existing engine setup in the old Herrick Labs was then moved over to Test Cell #1 and its operation and capability had to be verified. At the time of this writing, four FTP-72 tests and one HD FTP test have been performed in the new test cell. As the experimental engine speed and torque will never perfectly match the input drive cycle, regulation exists (EPA Title 40 CFR 1065.512) which dictates statistical measures by which the experiment is allowed to deviate. Analysis was performed on the completed FTP-72 and HD FTP tests and the results met the EPA standards. Additional HD FTP drive cycles will need to be performed to confirm repeatability of meeting the criteria of 40 CFR 1065.514. With the expanded capability of the new test cell, fuel economy and emissions improvements can now be studied over drive cycles which simulate real world driving.

IMPROVING DIESEL ENGINE EFFICIENCY AND EMISSIONS CONTROL USING VARIABLE VALVE ACTUATION

Research Assistants: Aswin Ramesh, Soumya Nayyar, Cody Allen, Dheeraj Gosala, Xueting (Sylvia) Lu, Alexander Taylor, Kalen Vos, Mrunal Joshi, Matthew VanVoorhis

Principal Investigator: Professor G. Shaver

Sponsors: Cummins Inc. and Eaton Corporation

Abstract

To meet consumer demands for improved fuel economy while also satisfying stringent emission regulations, many engine manufacturers are investigating the benefits of variable valve actuation systems. This study focuses on the quantification of the effects of variable valve actuation (VVA) in order to improve aftertreatment thermal management and engine efficiency. VVA strategies currently being studied include cylinder deactivation, Miller cycling, reverse breathing, rebreathing, and valve timing optimization. Characterization of these strategies are 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.) connected to a Power Test AC dynamometer. A unique capability of this multi-cylinder test bed is that it is outfitted with a fully-flexible electro-hydraulic VVA system that enables cylinder-independent and cycle-to-cycle control of both the intake and exhaust valves. This allows for optimized valve timings at given loading conditions. 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 of emissions, fuel economy, or both are possible. Another VVA strategy being studied is cylinder deactivation (CDA). In a standard drive cycle, the engine operates at part load conditions for significant portions of time during which not all cylinders are needed to provide the required power. During these conditions, CDA can be implemented by deactivating a certain amount of cylinders. CDA has shown fuel economy benefits as well as an increase of tailpipe temperatures, which can lead to aftertreatment performance improvements. The AC dynamometer allows for direct quantification of the benefits of CDA and other VVA strategies over standard transient drive cycles. Advancing the knowledge of VVA strategies can help improve the performance, emissions, and operating costs of diesel engines.

MODELLING AND CONTROL OF A HYBRID DIESEL VEHICLE

Research Assistant: Rohinish Gupta

Principal Investigator: Professor P. Meckl

Abstract

To develop a control strategy for a vehicle, the most important factors are to minimize the cost in terms of time, resources and availability of a risk free test environment to test new strategies.

This poster presents the strategy for developing control based models for a plug-in hybrid vehicle. The resulting model will allow the team to work on improving the supervisory control strategy for the vehicle and minimize the required experimentation completing most of the development and calibration work before testing on the vehicle.

MODELLING AND CONTROL OF UREA-SCR DOSING FOR A DIESEL ELECTRIC HYBRID CAR

Research Assistant: Kaushal Kamal Jain, *MSME 2017, Purdue University*

Principal Investigator: Dr. P. Meckl, *Assistant Head & Professor, Mechanical Engineering, Purdue University*

ABSTRACT

In order to meet increasingly stringent NO_x emission regulations, Urea-SCR (Selective Catalytic Reduction) is an essential component of the diesel engine after treatment system [1], [2]. The Urea-SCR system employs ammonia (NH₃) to reduce NO_x into molecular nitrogen (N₂) and water (H₂O) in presence of abundant O₂. Since it is difficult and dangerous to store NH₃, Diesel Exhaust Fluid (DEF or AdBlue, a mixture of 32.2% urea and 67.8% ionized water) is injected into the Urea-SCR system. The water gets evaporated and the urea is converted into NH₃ through pyrolysis and hydrolysis.

The variation in the amount of NO_x emissions with the change in engine load and speed calls for a control system which would regulate the DEF injection in order to maximize the NO_x conversion (or reduction) efficiency and minimize the NH₃ slip. As part of his Master's thesis, J. Hiremath designed Stoichiometric Control Strategy for temperatures less than 350°C and NH₃ Feedback Control Strategies for higher temperatures. These strategies assumed 100% conversion from urea to NH₃ and didn't consider the estimates of NH₃ storage on the catalyst [1]. These were tested on the EcoCar 2 platform at Purdue University.

For temperatures less than 350°C, the results in [1] showed that even when the amount of DEF injected was more than the stoichiometric requirements, the NO_x conversion efficiency was very poor implying that only a fraction of NH₃ was used for NO_x reduction. The remaining amount either contributes to NH₃ slip or get adsorbed in the catalyst. At higher temperatures, NH₃ slip was observed even for zero DEF injection. This was due to the NH₃ desorption from the catalyst at higher temperatures. These results show that NH₃ storage dynamics plays an important role in affecting the NO_x conversion efficiency and NH₃ slip.

Hence, the goal of this research is to develop a NH₃ storage model using the measurement and computational resources available at Purdue University and improve the existing control strategies.

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FUEL TYPE DETERMINATION USING FUEL SYSTEM PARAMETERS

Research Assistant: Mukta Kulkarni
Principal Investigator: Professor P. Meckl
Sponsored By: Cummins Fuel Systems, Columbus, IN

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 fueling, 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 explore techniques to independently estimate these critical parameters and perform a statistical analysis of the combined fuel determination strategy. Quantification of the level of uncertainty associated with fuel determination will be done when combinations of the critical parameters are used to identify 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).

MIMO CONTROL DESIGN AMENABLE MODELING OF A NATURAL GAS ENGINE

Research Assistant: Chaitanya Panuganti
Principal Investigator: Professor G. Shaver
Sponsor: Caterpillar Inc.

Abstract

To meet increasingly stringent government regulations on emissions, engine manufacturers can optimize the control strategies of various sub-systems in the engine architecture. This includes systems such as air-handling and fueling. Multi-input multi-output (MIMO) control strategies are an appealing choice because they account for the coupling and nonlinearity that is often present in systems such as an air-handling system of a natural gas engine. The presence of architectural features such as turbochargers, wastegate valves, exhaust gas recirculation, etc. creates an air-path system with highly coupled physics. In order to apply MIMO control strategies, a control-amenable model must first be obtained by means of physically based modeling or system identification. This study explores a physically based modeling approach to obtain a linear state-space model for a natural gas engine. This modeling approach starts with first-principles to obtain dynamic equations for explicitly defined states and state variables. This physically based approach provides an explicit way to obtain functions of various expressions, such as mass flows or power terms, as functions of the pre-determined state variables. Individual expressions that are functions of state variables are then linearized based on truth reference data from the engine. Linearization concludes by performing a Taylor-Series expansion about an equilibrium point and thus obtaining a linear system model that is amenable for MIMO control strategies. A key characteristic of the approach is the iterative nature. This means making incremental changes and then validating each incremental change by simulating the state space model and comparing it with reference data for the engine. A systematic modeling approach, like the one taken in this study for a natural gas engine, is a useful way of obtaining a physically based engine model that is compatible with MIMO controller design.

A MATHEMATICAL FRAMEWORK FOR INCREASING TRUST IN HUMAN MACHINE INTERACTIONS

Research Assistant: Kumar Akash

Principal Investigator: Professor N. Jain

Abstract

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

ADVANCED CASTER ROLL GAP CONTROL

Research Assistant: Rian Browne

Principal Investigator: Professor N. Jain

Abstract

According to the World Steel Association, in 2014, 1.7 billion tons of steel were produced worldwide; the United States alone produced 240 thousand tons of crude steel each day. Steel strip is used in applications ranging from building construction to automobile manufacturing. Twin roller casting produces steel strips by pouring steel directly onto rollers and compressing it to a thickness near the final gauge, whereas traditional casting uses a mold to form a steel slab that is later rolled to the desired thickness. The twin roller method is 9 times more energy efficient and 7000 times faster than thick slab casting. However, achieving precise physical properties along the length of the strip poses a challenging engineering problem due to the highly coupled nature of the thermal and mechanical dynamics. A model of the coupled dynamics can yield insights into the appropriate control architecture and methodology that will overcome performance limitations levied by system characteristics such as time delays and unmeasurable variables. The development of a control methodology for highly-coupled and high frequency thermal and mechanical dynamics will not only improve the quality of the steel produced by the twin roll casting process but will also translate to other materials processing and manufacturing applications.

MICRO AERIAL VEHICLES

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

Principal Investigator: Professor David Cappelleri

This research is focused on developing individual robots and teams of robots that are capable of advanced physical interactions with the environment.

In aerial robotics, two new vehicle configurations are introduced: the Omnicopter, and the BoomCopter. Different from traditional underactuated MAVs, the Omnicopter employs a tilt-rotor mechanism (composed of three ducted fans and three servo motors) and is over-actuated. The characteristic of over-actuation enables the Omnicopter's position dynamics to be decoupled from its attitude dynamics. This allows the Omnicopter to perform maneuvers that traditional multicopters are unable to perform. Similarly, the BoomCopter, which is based on a standard three-rotor frame, makes use of an additional propeller mechanism (3D-printed), which rotates around the rear boom. This propeller provides transverse thrust, allowing the BoomCopter to travel at high speeds, or to apply horizontal forces on an object such as a door. These two new aerial vehicle configurations show great promise in advancing the field of aerial manipulation research.

On the ground, TurtleBots (from Clearpath Robotics) and the AgBug (an original centimeter scale robot) are being combined with custom and open-source hardware and software to enable collaboration among heterogeneous teams of ground and aerial robots. The software developed in the lab builds on the Robot Operating System (ROS) framework, and allows multiple robots to share information and work together in both indoor and outdoor wireless networks.