



**HERRICK**  
**LABORATORIES**  

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**PURDUE UNIVERSITY**<sup>TM</sup>

# **Annual Report**

## **2003-2004**

Ray W. Herrick Laboratories  
School of Mechanical Engineering

## THE RAY W. HERRICK LABORATORIES

*The Ray W. Herrick Laboratories were founded in the mid-1950's as a research laboratory for studying the effects of climate control and for the design of improved climate control equipment. The Labs have grown and evolved into a center where graduate education and engineering research are combined in close partnership with industry in order to develop people and results of great importance. The Herrick Labs goal is to sustain a culture of excellence in an environment of partnership and shared resources.*

*The research programs of the Herrick Labs can be described in four general areas; electro-mechanical systems, noise and vibration control, perception based engineering, and thermal systems. The community at the Herrick Labs, which includes the faculty, staff, students, and sponsors, is focused on results that are both fundamental research discoveries and of practical importance to sponsors.*

*The educational experience at the Herrick Labs combines the traditional training of aspiring researchers with exposure to industrial needs and culture. Students study in a strong peer education environment with active mentoring from faculty and sponsors. Almost 700 Masters and PhD candidates have graduated from the Herrick Labs.*

*The engagement/service programs are highlighted by the well established conference and short course activity sponsored by the Herrick Labs. In addition, technology transfer to sponsors is an integral part of a majority of the research programs. The researchers at the Herrick Labs are also widely published across the spectrum of publications from academic journals to the popular press.*

### MISSION

An institution dedicated to graduate education and engineering research with emphasis on technology transfer to industry.

### VISION

To overcome the barriers between knowledge creation, transfer, and utilization and to become leaders of how graduate education and engineering research are done in partnership with industry.

### GOALS

1. To build upon the research excellence of the *Noise and Vibration Control Research Area* and the *Heating, Ventilation, Air-Conditioning, and Refrigeration Research Area* and grow the reputations of these areas as the top such research programs in the world.
2. Support the emerging research area of *Electro-Mechanical Systems* to enhance its national and international visibility.
3. To develop a proactive evolutionary strategy for the Laboratories to ensure its long-term stability and growth.
4. To improve the educational environment at the Labs so that its graduate students are multi-functional engineers who rate as the top engineering graduates in the country.
5. To continually monitor the technology transfer process by which research results are transferred to sponsors and the engineering community such that the labs will be recognized as *the* premier source of practical cutting edge research in our areas of expertise.
6. To continually grow the research environment at the Labs for the benefit of the students and faculty at the Labs.

## 2003-2004 HIGHLIGHTS

<i>Research</i>	<i>Last year</i>	<i>This year</i>
Research expenditures (academic year)	\$4,190,000	\$3,851,000
Number of sponsors as of September	31	48
Research assistants as of September	52	53
Archival papers published (calendar year)	33	34
Contracts in force for next academic year (7/02)	\$1,145,000	\$544,000
Proposals pending in September (HL share)	\$7,803,307	\$12,288,000

<i>Education</i>		
Graduate students as of September	78	68
MS	23	21
Ph.D.	55	47
Students graduated (calendar year)	19	19
MS	12	14
Ph.D.	7	5
Undergraduate/graduate “research experience” students	16	17
Visiting scholars (academic year)	3	7
Summer interns	3	2
Fellowships	12	10
Grant-in-Aid	1	1
Student Paper Awards	2	3

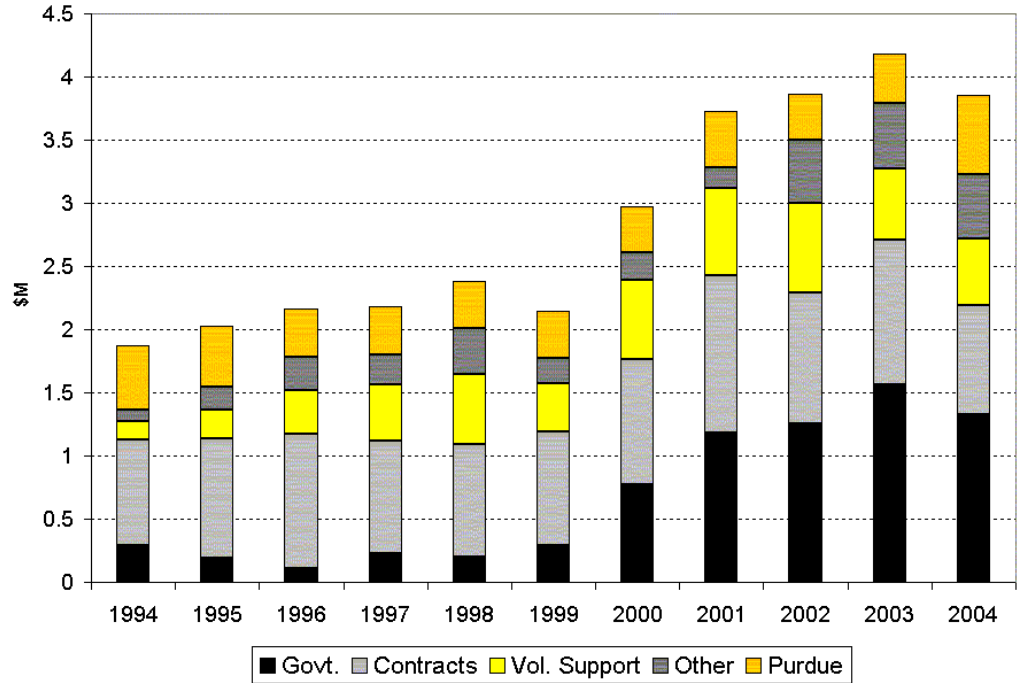
<i>Technology Transfer</i>		
Conferences held	1	3
Conferences planned in the next 2 years	2	3
Short Courses	0	2
HLPP Research Review attendees	25	—
Herrick Labs reports to sponsors	24	26
Conference and journal papers	83	87
Americas Editor and Americas Editorial Office, <b>Journal of Sound and Vibration</b> (Werner Soedel)		
Associate Editors of the <b>International Journal of HVAC&amp;R Research</b> (Jim Braun) and the <b>Noise Control Engineering Journal</b> (Bob Bernhard)		

### Administrative and Support Staff

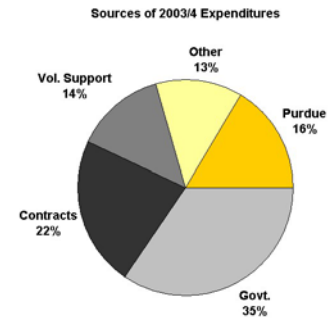
Professor Robert J. Bernhard serves as director of the Ray W. Herrick Laboratories. Judy Hanks is his administrative assistant. The research programs are assisted by the mechanical and electronics shops headed by Fritz Peacock, supervisor of technical services. Ginny Freeman serves as administrative assistant for the Herrick Laboratories’ conferences and short courses. Donna Miller serves as editorial assistant for the *Journal of Sound and Vibration*. Additional support staff includes Jenny Back, account clerk; Linda Tutin, secretary; Gilbert Gordon, electronic shop coordinator; Bob Brown, mechanical shop coordinator and building deputy; and Frankie Lee, mechanical technician.

The Ray W. Herrick Laboratories

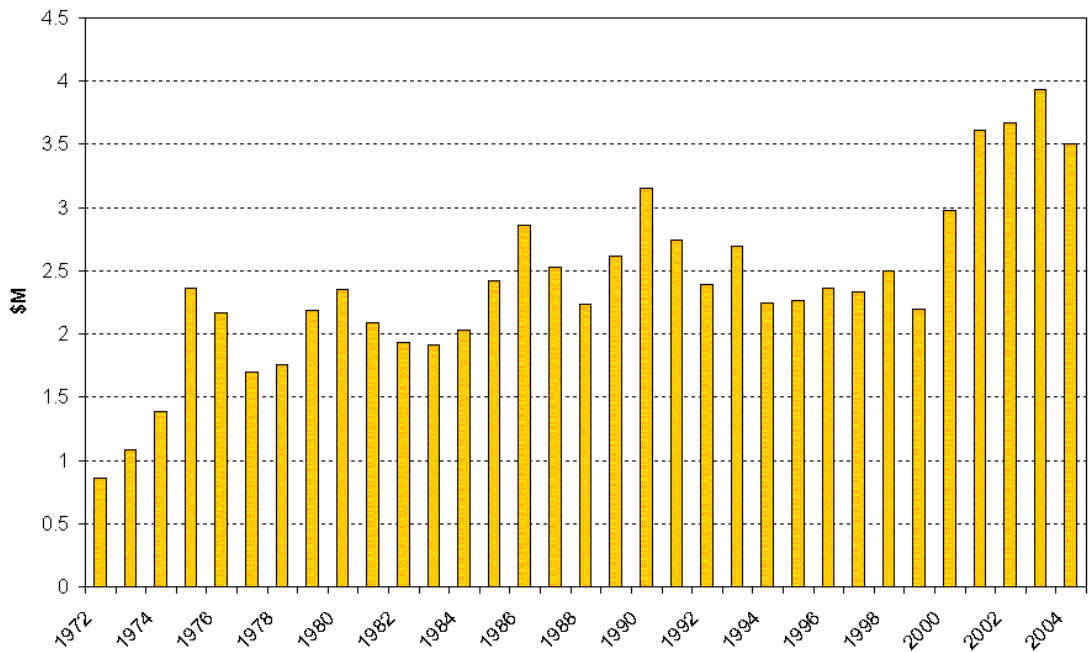
## 2003-2004 EXPENDITURES



Expenditures for the 2003-2004 academic year were down from last year to the level of the previous year. Significant time and energy this past year have been spent on new initiatives for centers and institutes. Awards for 2004-2005 appear to be increasing.

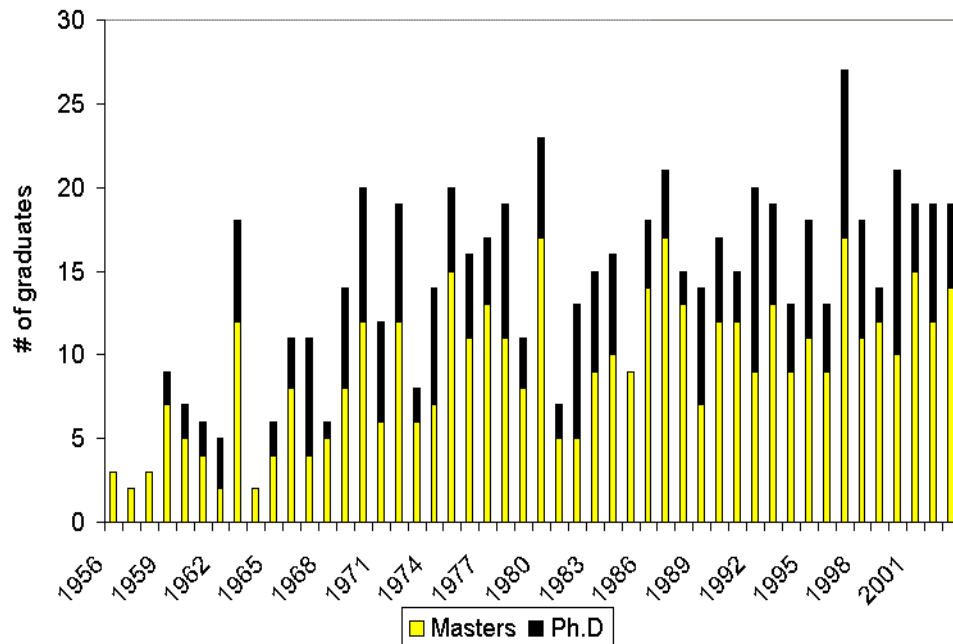


### Expenditures in 2000 dollars



# HERRICK LABS EDUCATION PROGRAMS

The primary educational program at the Herrick Labs is thesis based graduate education. We believe that the experiential learning, the open-ended and integrative nature of thesis based research is outstanding preparation for both academic and industrial careers. To complement the student/advisor relationship, the Labs offer a learning community to the student. This community includes an outstanding cohort of graduate students as well as a staff prepared to support and teach. In many cases, the student's research is sponsored. Sponsor representatives also participate in educational activities with the student. We also have programs where graduate students do internships in industry or government laboratories. In total we believe this is an outstanding educational opportunity for our graduate students.



## Fellowships, Scholarships and Student Awards

### *Fellowships:*

- Patrick Cunningham** received the SAE Doctoral Scholars Award
- Miguel Jovane** received the William E. Fontaine Memorial Fellowship
- Jennifer Gosselin** received the Lozar Fellowship
- Jason Hugenoeth** received the ASHRAE Fellowship
- Timothy Johnson** received the Lozar Fellowship
- Chenzhou Lian** received the Willis Carrier/ASHRAE Fellowship
- Joshua McKinsey** received the GEM Fellowship
- Insu Paek** received the Purdue University Special Initiative Program
- Suwat Trutassanawin** received the ASHRAE Fellowship
- Jonathan White** received the Lozar Fellowship

### *Awards*

- Paul Deignan** received the Best Presenter in Session Award at the 2004 American Control Conference
- Mert Geveci** received the Magoon Award for Excellence in Teaching from the School of Mechanical Engineering, Purdue University
- Kyoung-Ho Lee** received a Best Student Paper Award from the International Building Performance Association
- Kiho Yum** received a 2004 INCE Student Paper Prize Competition award

*The Ray W. Herrick Laboratories*

## Herrick Labs Faculty Research Interests

**Douglas E. Adams**, assistant professor of mechanical engineering. Experimental nonlinear structural dynamics and system identification, diagnostics and prognostics for mechanical systems, integrated vehicle/structural health monitoring, system-level modeling of vehicle systems (compressors, suspensions, exhausts, mounts), nonlinear dynamics in mechanical design, signal processing and data interrogation and novel experimental techniques.

**Anil K. Bajaj**, professor of mechanical engineering. Nonlinear oscillations in structures, chaotic dynamics, stability analysis, flow-induced vibrations, perturbation techniques, mistuned structures, and localization of modes, drum and disk brake squeal-friction induced vibrations, modeling of carseat-occupant dynamics, and modeling and identification of polyurethane foam properties.

**Robert J. Bernhard**, professor of mechanical engineering, director of Ray W. Herrick Laboratories, and co-director of The Institute for Safe, Quiet, and Durable Highways. Acoustics, noise and vibration control, and numerical methods.

**J. Stuart Bolton**, professor of mechanical engineering. Acoustics, numerical models of porous noise control materials, optimal design of noise control materials and treatments (barrier and sound absorption), measurement of physical properties of noise control materials, smart materials, theoretical and experimental analysis of tire vibration and sound radiation, multi-reference nearfield acoustical holography, outdoor sound propagation, visualization of motor vehicle passby sound radiation, and machinery noise source identification.

**James E. Braun**, professor of mechanical engineering. Thermal systems measurements, modeling, analysis, design optimization, and control optimization with applications to air conditioning and refrigeration equipment and systems.

**Qingyan (Yan) Chen**, professor of mechanical engineering. Indoor and outdoor airflow modeling by computational fluid dynamics and measurements, protection of buildings from chemical/biological warfare agent attacks, building ventilation systems, indoor air quality, building energy analysis.

**George T.-C. Chiu**, associate professor of mechanical engineering. Dynamic systems, measurements and control, modeling and control of digital printing and imaging systems, mechatronics, network/wireless remote control, noise and vibration control, electro-hydraulic control, human-machine interface, and MEMS.

**Patricia Davies**, professor of mechanical engineering. Signal processing and data analysis applied to mechanical systems, condition monitoring, vibration measurement, sound quality and perception-based engineering, nonlinear system identification, modeling of car seat-occupant dynamics and modeling and identification of polyurethane foam properties.

**Eckhard A. Groll**, associate professor of mechanical engineering. Thermal sciences as applied to advanced HVAC&R systems and their working fluids: alternative refrigeration technologies, vapor compression systems performance evaluations, natural refrigerants, analysis and optimization of individual components, such as compressors and heat exchangers.

**Charles M. Krousgrill**, professor of mechanical engineering. Non-linear oscillation, elastic stability, dynamics, vibrations, rotor dynamics, chaos, automotive brake squeal/vibration, and vibration in gearing systems.

**Monika Ivantysynova**, MAHA Professor of Fluid Power Systems. Fluid power systems and components measurements, modeling, analysis, design optimization, and control optimization with applications to off-road vehicles, airplanes, cars, robots and other drive systems.

**Peter H. Meckl**, associate professor of mechanical engineering. Motion and vibration control of high-performance machines, adaptive control, virtual sensing, and diagnostics. Applications to manufacturing devices, robotics, and automotive engines.

**Luc G. Mongeau**, professor of mechanical engineering. Flow-induced sound and vibration, thermo-acoustics, turbomachinery noise, aerodynamic noise of road vehicles, highway noise, and voice production.

**Werner Soedel**, professor of mechanical engineering and Herrick Professor of Engineering. Vibrations and dynamics of elastic systems, plate and shell vibrations, including gases and fluids, stress analysis, acoustics, simulation of machinery dynamics, and fluid machinery. Examples of applications: compressors, tires, valve flutter, suspensions, and mufflers.

**David R. Tree**, professor of mechanical engineering. Applied aspects of thermodynamics, fluid mechanics, and heat transfer to thermal systems and fundamental nature of heat transfer in heat exchangers.

**Bin Yao**, associate professor of mechanical engineering. Design and coordinated control of intelligent and high performance electro-mechanical/hydraulic systems; mechatronics; robotics; automotive control; optimal adaptive and robust controls; nonlinear observer design and neural networks for virtual sensing, modeling, fault detection, diagnostics, and adaptive fault-tolerant control; data fusion.

# MAJOR RESEARCH FACILITIES

## Thermal Systems Research Area

- Two 7000 ft<sup>3</sup> psychrometric rooms with –10° to 130°F temperature range
- Two room indoor air quality (IAQ) laboratory
- Psychrometric wind tunnel with dust injection system
- Large HVAC equipment lab with 90 ton centrifugal chiller
- Two computer controlled compressor load stands for small compressors
- Many bench test facilities and special experimental setups

## Noise and Vibration Research Area

- 25 by 20 by 18 ft reverberation room
- Anechoic room with useful volume 12 by 12 by 12 ft
- Hemi anechoic room with useful volume 41 by 27 by 18 ft
- 8 by 8 ft audiometric room
- Acoustical materials laboratory
- Two wheel chassis dynamometer with 67 in. rollers
- Anechoic wind tunnel with 18 by 24 in. test section and flow velocity up 120 mph
- Three 1000 lb<sub>f</sub> hydraulic shakers with 6 in. stroke
- Two 4000 lb<sub>f</sub> electromagnetic shakers
- 64 microphone acoustical holography array and 80 channel data acquisition system

## Perception Based Engineering

- 8 by 8 ft audiometric room
- Printer image quality facilities
- Binaural measurement system and sound quality estimation software
- Steering wheel vibration perception facility
- Two room indoor air quality (IAQ) laboratory
- Thermal comfort
- Perception Based Engineering Lab (*future*) (combined thermal, acoustic, motion, and visual perceptions)

## Electro-mechanical Systems Research Area

- 1500 psi 3-axis electro-hydraulic robot
- Four post experimental electro-hydraulic lift system
- Diesel engine control load stand with eddy current dynamometer, EGR, and exhaust after-treatment with transient emissions analyzers
- Gasoline engine control load stand with eddy current dynamometer and transient emissions analyzer
- Prognostics modeling and simulation facility
- Thermal/acoustic test facility
- Environmetrics material conditioning chamber
- MTS static/dynamic/fatigue test apparatus
- Large inventory of vibration and acoustics sensors and actuators

Ray W. Herrick Laboratories

## HERRICK LABS STUDENTS

<b>Student</b>	<b>Advisor</b>	<b>Thesis Subject</b>
Gazi Naser Ali	Allebach/Chiu	Banding characterization and reduction for laser printers
Rachael Anderson	Davies	Effects of age on speech intelligibility/sound quality perception
Vince Badagnani	Mongeau/Bolton	Electronic cooling fan noise
Stefan Bertsch	Groll	Unitary equipment testing
Nasir Bilal	Adams	Prediction uncertainty in compressor modeling and simulation
Arthur Blanc	Bernhard	Numerical model validation
David Bouffard	Groll/Hutzel	Thermal systems
Hung-Ming Cheng	Chiu	Finite word length controller implementation-limitation on sampling rate
Rudy Chervil	Braun	Heating, ventilating and air conditioning research
Yong Cho Thung	Bolton	Spherical/acoustical holography
Jack Chuanasa	Yao	Accurate parameter estimation and control of hydraulic cylinders
Douglas Cook	Mongeau/Frankel	Fluid structure interactions
Patrick Cunningham	Meckl	Diagnostics of diesel particulate filters
Paul Deignan	Meckl/King	Virtual sensor development for automotive engines
Don Gallant	Davies/Bajaj	Sound quality of temporally varying tonal sounds
Phanindra Garimella	Yao	Observer based integrated direct/indirect adaptive robust control of electro-hydraulic systems
Mert Geveci	Bernhard	Diagnostics and control
Jennifer Gosselin	Chen	Building energy conservation
Muhammad Haroon	Adams	System identification of tire-suspension interactions
Lei He	Bolton	Acoustic arrays
Kwan Woo Hong	Bolton	Acoustics
Jason Hugenroth	Groll/Braun/King	Erickson cycle technology
Grant Ingram	Chiu/Franckek	Engine emissions
Janette Jaques	Adams	Squeak and rattle work
Hao Jiang	Adams	Acoustics and vibrations
Tim Johnson	Adams	Diagnostics and prognostics for rolling tires
Alok Joshi	Meckl	Diagnostics of engines
Raymond Joshua	Adams	Flutter mechanics/ aeroelasticity
Miguel Jovane	Braun/Groll	Modeling of rotary compressors
Harold Kess	Adams	Vibration-based structural health monitoring
Jeong-Woo Kim	Bolton	Acoustics and vibration
Jong Ryel Kim	Davies	Artificial neural network modeling of annoyance
Jun-Hyeung Kim	Groll	Capacity control of positive displacement compressors
Uije Kim	Mongeau/Krousgrill	Friction-generated sound and vibration
Ted Kostek	Meckl/Franckek	Diagnostics of automotive catalytic converters
Jaeho Kwak	Yao/Bajaj	Advanced control of future vehicles



## HERRICK LABS STUDENTS (Cont.)

Josephine Lau	Chen	Indoor air quality
Kyoung Ho Lee	Braun	Control of building thermal storage
Kyoung Hoon Lee	Davies	Perception of tones in large machinery noise
Moohyung Lee	Bolton/Mongeau	Acoustical holography of jet noise
Daqing Li	Groll	Transcritical CO <sub>2</sub> cycles with ejectors
Chenzhou Lian	Chen	Indoor air quality
Ji Min Lim	Bolton	SEA modeling of compressors
Feng Liu	Chiu	Xerographic process control
Song Liu	Yao	Optimal energy-saving control of electro-hydraulic systems using programmable valves
Pravara Mantha	Mongeau	Fluid structure interactions in the human larynx
Joshua McKinsey	Chiu	Force feedback of electro-hydraulic manipulators
Jackie Mohrfeld	Meckl/Franck	Practically zero emissions vehicles
James Mynderse	Chiu	Vibration quality
In-su Paek	Mongeau/Braun	Thermoacoustic refrigeration
Jong Beom Park	Mongeau	Voice production
Tarun Puri	Davies	Foam and car seat dynamics
Abhijit Sathe	Groll	Miniature-scale diaphragm compressors for electronics cooling
Bo Shen	Groll/Braun	Improving accuracy and capabilities to model unitary equipment
Shankar Sundararaman	Adams	Damage prognosis in heterogeneous structures
Will Thornton	Bernhard	Tire/pavement interaction noise
Kenji Totsuka	Chiu	Electrophotographic process control
Suwat Trutassanawin	Groll	Miniature vapor compression systems for electronic cooling applications
Liangzhu Wang	Chen	Detailed multi-zone air flow simulation
Jonathan White	Adams	Structural diagnostics
Rich Widdle	Davies/Bajaj	Micro/macrosopic modeling and measurement of foam properties
Tae Wook Yoo	Bolton	Numerical acoustics
Tao Yu	Bolton	Tire noise
Kiho Yum	Bolton	Sound radiation from tires
Tengfei Zhang	Chen	Indoor air quality
Zhao Zhang	Chen	Indoor air quality
Zhipeng Zhong	Braun	Night ventilation pre-cooling
Xiaotang, Zhou	Braun	Transient modeling of cooling coils

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## **HERRICK LABS TECHNOLOGY TRANSFER PROGRAMS**

*The Herrick Labs technology transfer programs are well established and include an array of proprietary research, educational outreach, and publications.*

### **2004 PURDUE CONFERENCES**

The 17<sup>th</sup> International Compressor Engineering Conference and the 10<sup>th</sup> International Refrigeration and Air Conditioning Conferences took place July 12-15, 2004 on the campus of Purdue University in West Lafayette, Indiana. Approximately 500 attendees from 30 different countries attended the conferences. The Compressor Conference included sessions on specific compressor technologies (reciprocating, rolling piston, scroll, screw, centrifugal, and linear compressors) and issues related to compressor design and reliability (noise control, vibrations, gas pulsations, lubrication, wear, valves). In addition, there were several sessions that focused on new and existing applications of compressor technologies, including uses in transcritical carbon-dioxide cooling cycles and automotive air conditioning. The Refrigeration and Air Conditioning Conference covered a wide range of topics, including advanced refrigeration and air conditioning technologies (e.g., transcritical carbon-dioxide cycles), heat transfer/exchanger issues, modeling (steady-state and transient), automated fault detection and diagnosis, electronics cooling, and lubrication and noise issues. A total of 215 papers were published in the combined CD-ROM proceedings.

Two short courses have been conducted prior to the 2004 conferences: 1) Design Analysis and Applications of Centrifugal Compressors and 2) Simulation Tools for Vapor Compression System and Component Analysis. Approximately 70 people participated in these short courses.

### **2006 PURDUE CONFERENCES**

#### **18<sup>th</sup> INTERNATIONAL COMPRESSOR ENGINEERING CONFERENCE AT PURDUE**

#### **11<sup>th</sup> INTERNATIONAL REFRIGERATION AND AIR CONDITIONING CONFERENCE AT PURDUE**

**Conferences – July 17-20, 2006  
Short Courses – July 15-16, 2006**

**Contact:** Virginia D. Freeman, Conference Secretary  
Purdue University  
140 S. Intramural Drive  
West Lafayette, IN 47907-2031, USA  
Telephone: (765) 494-6078; FAX: (765) 494-0787  
E-Mail: herlconf@ecn.purdue.edu  
web page: <http://www.ecn.purdue.edu/Herrick/event/>

## 2003 Herrick Labs Graduates

<b>Anders, Jonathan</b>	MSME	<i>An Instrumental Variable Approach to Nonlinear Model-based Adaptive Control of Engine Speed</i>
<b>Buhr, Craig</b>	Ph.D.	<i>Active Control of Rotating Stall in Compressors</i>
<b>Duraiswamy, Shivkumar</b>	MSME	<i>Nonlinear Adaptive Nonsmooth Dynamic Surface Control of Electro-Hydraulic Systems</i>
<b>Haroon, Muhammad</b>	MSME	<i>Nonlinear System Identification of a Tire-Vehicle Suspension System Using Response Transmissibility</i>
<b>Hubacher, Beat</b>	MSME	<i>Experimental and Theoretical Performance Analysis of Carbon Dioxide Compressors</i>
<b>Ippili, Rajani</b>	MSE	<i>System Identification of Quasi-Static Foam Behavior and Its Application in the Prediction of Static Equilibrium Position of a Car Seat Occupant</i>
<b>Kankatala, Veerabhadra</b>	MSME	<i>Non-thesis. Friction Based Vibrations</i>
<b>Kim, Yong Joe</b>	Ph.D.	<i>Visualization of Tire Vibration and Sound Radiation and Modeling of Tire Vibration with an Emphasis on Wave Propagation</i>
<b>Martin, Brett G.</b>	MSME	<i>The Use of Information Theory in Input Space Selection for Modeling and Diagnostic Applications</i>
<b>Mercer, Kevin B.</b>	MSME	<i>Modeling and Testing Strategies for Evaluating Ventilation Load Reduction Technologies</i>
<b>Merrill, Kyle</b>	MSME	<i>Perturbation Observer Design and Cylinder Piston Velocity Estimation for Electro-Hydraulic Systems</i>
<b>Nataraju, Madhura</b>	MSME	<i>A Transitional Nonlinear Dynamic Approach for Modeling and Simulating Damage Evolution in a Cantilevered Structure</i>
<b>Osburn, Andrew W.</b>	Ph.D.	<i>Performance Enhancement of Internal Combustion Engines Using Crank-Angle Domain Control</i>
<b>Ponnambalam, Tharanivel V.</b>	MSME	<i>Numerical Investigation of Heat Transfer and Streaming Due to High Amplitude Standing Waves in Cylindrical Tubes</i>
<b>Song, Jinho</b>	Ph.D.	<i>Nonfibrous Sound Absorbing Materials</i>
<b>Suh, Sanghoon</b>	Ph.D.	<i>Comparison of the Performance of Absorbing and Rigid-Edged Barriers by Using Experimental and Numerical Methods</i>
<b>Sundararaman, Shankar</b>	MSME	<i>Structural Diagnostics Through Beamforming of Phased Arrays: Characterizing Damage in Steel and Composite Plates</i>
<b>Yoo, Taewook</b>	MSME	<i>The Performance of Sound Barriers with Jagged Edges</i>

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