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ADP012099

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TITLE: Army Research Office and Air Force Office of Scientific Research. Contractors' Meeting in Chemical Propulsion [2001] Held in the University of Southern California on June 18-19, 2001

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Intelligent Turbine Engines

Grant Number DAAH04-96-1-0008

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SUMMARY/OVERVIEW:

This program focuses on the fundamental and practical issues that hinder development of intelligent control systems for improving the performance of turbine engines, such as rotorcraft turboshaft engines. Our approach to the development of an intelligent control system has focused on advances in the basic understanding of engine processes through experiments and advanced computational models, refinement of appropriate sensor and actuator technologies, and development of practical control strategies for control of steady-state and transient performance. Substantial advances have been made on: unsteady modeling of compressor and combustor flows, control strategies for compressor surge and stall; combustor control using synthetic jets and smart fuel injectors; model-based, fuzzy logic and neural network control approaches; and MEMS and optical sensors able to operate in high temperature environments. In this report, we highlight advances in simulations, control theory, and compressor control (since last year's report focused on sensor and actuator technologies).

TECHNICAL DISCUSSION:

COMBUSTOR CONTROL

The work described below involves efforts toward improved understanding and design of controllable combustor modeling and simulation, and investigation of new control hardware and architectures for combustor control.

TWO-PHASE LES

A generalized Large-Eddy Simulation (LES) methodology has been developed to simulate premixed and non-premixed gas-phase and two-phase combustion in complex flows such as those typically encountered in gas-turbine combustors. The LES methodology uses a new subgrid-based scalar mixing and combustion model. The unique feature of the model is that scalar mixing and the reaction-diffusion processes in the subgrid domain are simulated inside every LES cell. This more fundamental treatment allows the study and analysis of the physics involved in the interaction between the flame, gas-phase, and liquid flow dynamics. Earlier studies under this MURI validated and demonstrated the method's ability to accurately capture Le, Sc, Re, Ka and Da number effects without requiring any explicit or *ad hoc* adjustments to the model.

Results have been obtained for a number of configuration, including a lean premixed combustor with swirl stabilization (Fig. 1). The results showed that the swirl stabilization reduced the magnitude of the amplitude of the pressure oscillation and that the dominant mode shape was the three-quarter acoustic mode of the combustor. It was also found that heat release plays a similar role in determining the stability of the combustion. The effects of swirl and heat release on the 'Vortex-Breakdown' phenomenon are currently under study. In two-phase systems, significant modification to the high shear regions due to vaporization of droplets is observed. Droplets with stokes number of the order of one, are seen to concentrate preferentially in regions of low vorticity and when they vaporize, the gaseous fuel gets entrained into regions of high vorticity. This process plays a major role in fuel-air mixing and combustion processes in two-phase systems. On the other hand, it was also observed that the heavier particles, with a higher inertia do not show a tendency to collect in low-vorticity regions. This emphasizes the existence of an optimum ratio of particle time constant to fluid time scale such that particles show preferential accumulation. The effect of the mass loading ratio, droplet vaporization rate, and Stokes number on mixing and combustion are currently being studied.

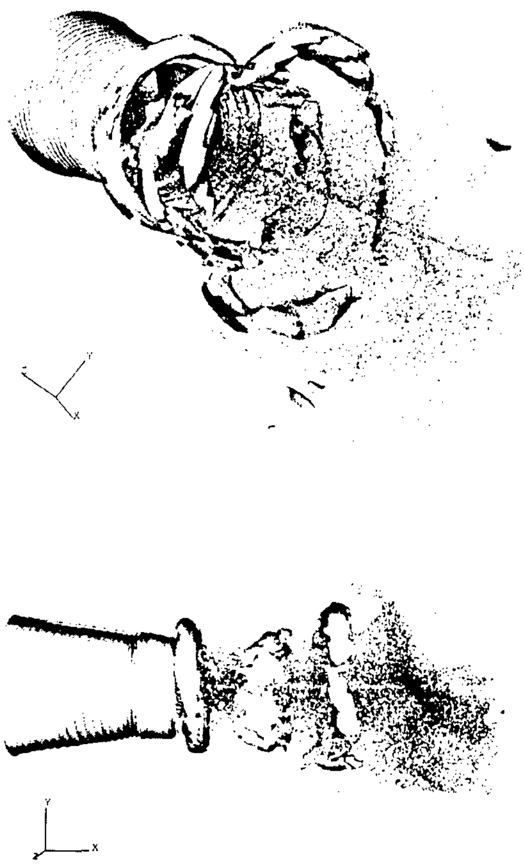

Figure 1. Perspective (top) and side (bottom) views of instantaneous isovorticity and droplet distributions in LM6000 combustor, nonreacting.

HARDWARE NEURAL NETWORKS

We have demonstrated a single chip learning neural network that can learn (from a zero weight state) to control an simulated combustion instability. Two features differentiate this work from similar work. First, the chip operates in real-time on an analog system. The chips inputs and outputs are analog, and are not clocked or gated in any way. Thus once the chip has learnt to control the combustor, changes in the analog inputs result in controls in less than a microsecond. Second, the learning algorithm used requires no knowledge of the system to be controlled. It need only be fed an error signal (in this case differential pressure) to begin seeking weights that minimize the error.

HYBRID RESETTING CONTROLLERS

A new class of controllers, called hybrid resetting controllers, has been developed for control of combustion instabilities. The key idea of hybrid resetting control is to achieve enhanced energy dissipation between interconnected systems. Specifically, if a dissipative or lossless plant is at a high energy level, and a dissipative feedback controller at a low energy level is attached to it, then energy will generally tend to flow from the plant into the controller, decreasing the plant energy and increasing the controller energy. Of course, emulated energy, and not physical energy, is accumulated by the controller. Conversely, if the attached controller is at a high energy level and the plant is at a low energy level, then energy can flow from the controller to the plant, since a controller can generate real, physical energy to effect the required energy flow. Hence, if and when the controller states coincide with a high emulated energy level, then we can *reset* these states to remove the emulated energy so that the emulated energy is not returned to the plant. Since active energy flow resetting control for interconnected systems gives rise to discontinuous closed-loop motions, impulsive differential equations provide the mathematical foundation for analyzing hybrid resetting controllers.

To date, we have developed a general framework for feedback systems possessing discontinuous motions by addressing stability, dissipativity, feedback interconnections, and optimality of nonlinear impulsive dynamical systems. The results provide a general analysis and synthesis framework for hybrid feedback control systems in that they apply to nonlinear dynamical systems with abstract energy notions for which a physical system energy interpretation is not necessary.

We have applied this approach to a combustion model (time-averaged) that captures thermoacoustic instabilities. Utilizing this model, we developed active energy flow resetting controllers to mitigate combustion induced pressure instabilities in combustion systems. The hybrid resetting controller can be viewed as a specialized technique for severing the coupling between the acoustics and unsteady combustion to effectively enhance the removal of energy in the combustor. In particular, significant modal energy dissipation is achieved via the hybrid resetting controller to suppress thermoacoustic oscillations.

COMPRESSOR CONTROL

The current work aims to produce active/passive control strategies that will result in reduced stall margin requirements. This involves efforts toward improved understanding of compressor stall and surge phenomena through modeling, simulation and experimentation; investigation of control mechanisms for reducing compressor stall and surge; and development of hybrid control methods by combining control-theoretic and decision-theoretic techniques.

MODELING AND SIMULATION

We have developed a general analytic model for compressor dynamics that includes finite duct effects and compressibility in the inlet and exit flows. The model indicates stall inception variations about the pressure peak as a function of inlet geometry, Mach number, and gas properties. In addition if the flow at the inlet is slightly yawed in the direction of blade rotation, then the stall inception is delayed beyond the peak performance point.

The Navier-Stokes solver for simulating unsteady viscous fluid flow in turbomachinery components, developed during the previous years, was used to study fluid dynamic phenomena that lead to instabilities in centrifugal compressors. These studies indicated that large flow incidence angles, at reduced flow rates, can cause boundary layer separation near the blade leading edge. High-pressure jets upstream of the compressor face were studied as a means of controlling compressor instabilities. Steady jets were found to alter the leading edge flow pattern and effectively suppress compressor instabilities. It was also observed that yawed jets are more effective than parallel jets and an optimum yaw angle exists for each compression system. Pulsed jets were found to yield additional performance enhancements and lead to a reduction in external air requirements for operating the jets. Jets pulsed at higher frequencies were found to perform better than low-frequency

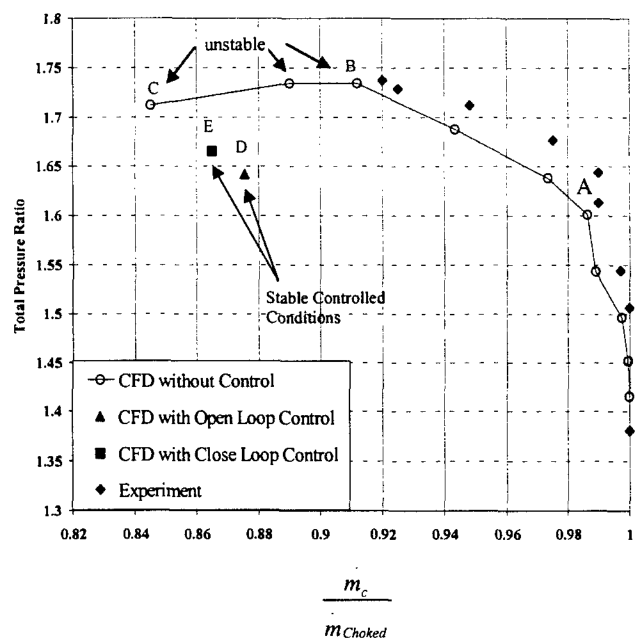

Figure 2. Stabilization of a NASA Lewis 4:1 axial compressor using open- and closed-loop control.

jets.

Work was also performed on the stabilization of axial compressors through bleeding; both open- and closed-loop control were examined. In the open-loop case mass is removed at a fixed, preset rate from the diffuser. For closed-loop control, the rate of bleed is linked to pressure fluctuations upstream of the compressor face. The bleed valve is activated when the amplitude of pressure fluctuations sensed by the probes exceeds a certain range. Calculations show that both types of bleeding eliminate rotating stall and modified surge, and suppress the precursor disturbances upstream of the compressor face. It is observed that smaller amounts of compressed air need to be removed with the closed-loop control, as compared to open-loop control. These concepts were demonstrated by extending the useful operating range of a 4:1 transonic compressor (Fig. 2).

EXPERIMENTS AND CONTROLS

We have also developed and experimentally implemented (Fig. 3) an active control scheme based on a real-time observer that identifies the frequency and amplitude of the dominant modes of the pressure variations. Combined with a fuzzy logic control scheme that evaluates how close the identified frequencies and amplitudes are to a set of values that depend on compressor RPM, the active control system sends feedback signals to either bleed valves or to the combustor fuel flow rate in order to *prevent* (rather than suppress) surge. The compressor then operates at the maximum attainable pressure while avoiding surge. This system has been experimentally implemented, In addition, the control approach does not require high bandwidth actuators and requires little information on the specific compressor characteristics.

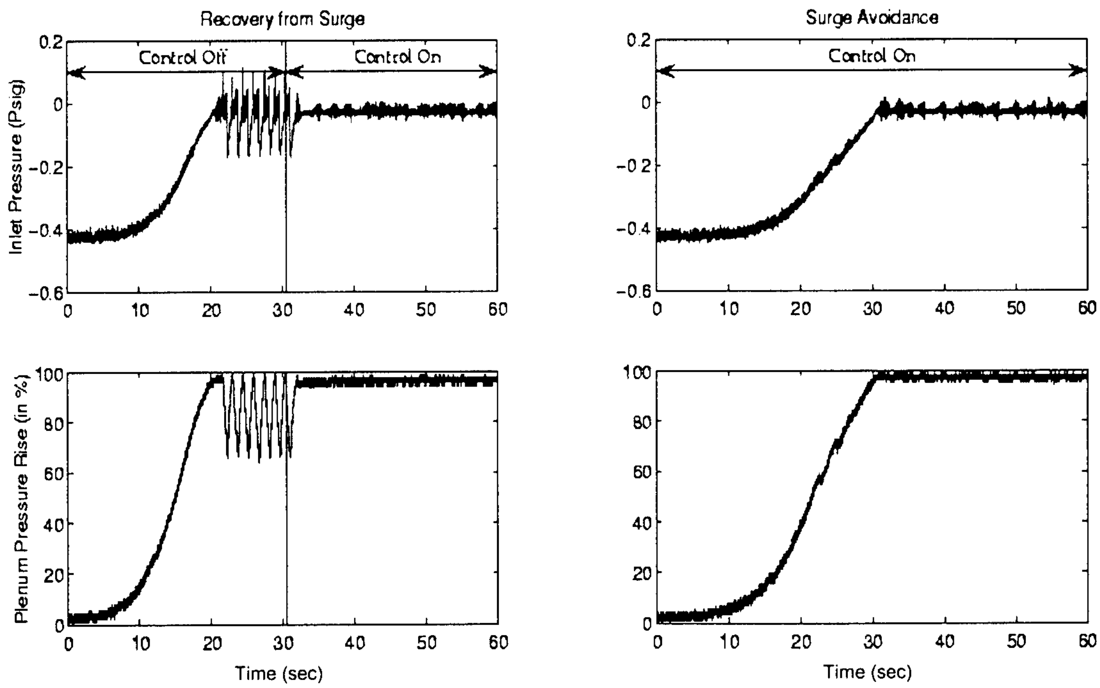

Figure 3. Supression and **avoidance** of surge in GT compressor facility using active control system and real-time observer.