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# Active Control Symposium for Power Systems and Propulsion

Technical Evaluation Report

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## Executive Summary

The major themes in the symposium were compression system instabilities and combustion system instabilities, both important limiting factors of gas turbine performance. Results were presented in the area of active control of combustion instabilities demonstrating effectiveness across scales from laboratory rigs to full scale engines and a good understanding of the modeling and control issues. The status of compression systems is somewhat behind this, primarily lacking in successful demonstrations on a full-scale engine. The tradeoffs between cost and performance are also less clear in this case. Issues that have been identified for further study include actuation systems, especially the need for high frequency, high reliability actuators, sensing systems capable of operating in high temperature and high vibration environments, and control theory, specifically proving robustness and fundamental limits for controllers which are already working in application.

## 1 Introduction

Gas turbine engines face a variety of design constraints and operational requirements that limit the achievable performance. Fluid instabilities are a major constraint and determine many of the key features of a gas turbine engine (eg, number of compressor stages, emissions levels, noise levels). Active control presents an opportunity to radically change the behavior of a system and achieve better performance, reliability and affordability.

Feedback control of gas turbine engines has been an active area of research for over 20 years, since the full authority digital engine controller (FADEC) became a standard part of gas turbine engines. Combined with advances in sensor technology, the improvements in computational power have enabled the use of feedback control of increasingly complex phenomena. Feedback control is already an integral part of modern flight control systems ("fly by wire"), leading to a rich understanding of feedback principles in theory and practice of aerospace systems.

Early uses of feedback control in gas turbine engines were for low frequency phenomena such as scheduling of fuel flows and for component feedback loops such as servo control of rotational actuators and valves. In the last 10 years there has been increased interest in using control to alter the behavior of more complex instabilities, such as those associated with compression and combustion instabilities (the focus of this symposium).

The primary compression system instabilities which have been studied for possible application of feedback control are rotating stall and surge. Rotating stall is a non-axisymmetric flow condition in which a portion of a compressor experiences stalled flow near the peak pressure rise of the system. In multi-stage compressors, rotating stall can occur in some or all of the stages, full span or part span, and grow suddenly or relatively slowly. Surge is an axisymmetric instability mode in which the compression system drives a Helmholtz instability, with the combustion chamber acting as the resonant cavity. Rotating stall and surge can occur separately or together and the overall dynamics of the system near these instabilities is quite rich.

Active control of rotating stall and surge relies critically on the coupling of the actuation mechanism with the physics. A variety of actuation schemes have been developed, including high response inlet guide vanes, high response bleed valves and air injection. All of these techniques have been demonstrated to work in systems ranging from low-speed, single stage rigs to full-scale compression systems. The key difficulty is in obtaining actuators which have sufficient authority and frequency response at the same time as being low weight and highly reliable.

Combustion instabilities are a thermo-acoustic instability that arises from coupling between the combustion process and the acoustics of the combustion chamber. Combustion instabilities in rockets have been studied for several decades and great progress has been made in understanding some of the fundamental mechanisms responsible for these instabilities. In the context of gas turbines, combustion instabilities are a limiting factor in low-emissions combustion (for lean, pre-mixed industrial power) and operability in high-power applications (especially in afterburners).

Over the last five years, several organizations have demonstrated the use of active control to significantly enhance the operation of combustors by allowing them to operate beyond their natural operability limits. The primary actuation mechanism has been modulation of primary or secondary fuel systems. Alternative approaches to low emissions combustors include catalytic combustion and "wet" combustion (where the combustion temperature is reduced through injection of water).

There are many other instabilities in gas turbine engines to which active control techniques may be relevant. These include separation control in the engine inlet and internal diffusers, shear layer control for affecting jet noise, flutter suppression, enhanced mixing in combustors, tip clearance control and wake management for reducing fan and compressor noise. Most of these are under current study both in industry and academia and they face similar challenges to those described in this symposium.

## 2 Overview of the Symposium

The symposium was held in parallel with two other active control symposia, one on performance stability and control of fluid physics (PSF) and the other on mechanical systems, structures and materials (MSSM). All three meetings shared an opening session with four keynote addresses and there was a fifth shared keynote address on the second day.

The power systems and propulsion (PPS) symposium consisted of 33 papers (of 36 originally planned) split into six sessions:

- Applications Overview: 7 papers
- Compressor Stall/Surge—Measurements: 6 papers
- Compressor Stall/Surge—Control: 3 papers
- Combustion Instabilities—Measurements and Predictions: 3 papers
- Combustion Instabilities—Control Fundamentals: 7 papers
- Combustion Instabilities—Control Applications: 7 papers

In addition there was a keynote speech by Anne Dowling on "Active Control of Instabilities in Gas Turbines".

The 33 papers represented authors from 8 different countries, broken down as follows:

| | | | |
|---|---|---|---|
| Belgium | 1 | Poland | 1 |
| France | 3 | Switzerland | 1 |
| Germany | 5 | UK | 5 |
| Italy | 2 | US | 15 |

The breakdown in terms of type of organization was:

| | |
|---|---|
| Government Institutions | 5 |
| Academic Institutions | 21 |
| Industry | 7 |

As indicated by the session breakdown, the majority of papers were concerned with combustion instabilities, with approximately one third of the papers focusing on compression system instabilities.

## 3 Keynote Address

The keynote address was given by Professor Ann Dowling from the University of Cambridge and was entitled "Active Control of Instabilities in Gas Turbines". Professor Dowling described work related to both compression and combustion instabilities, with primary motivation from combustion dynamics and control. She listed a number of challenges in this general area, including the fact that the dynamics are spatially distributed, with relatively limited models available, that the systems are open loop unstable with high instabilities frequencies, and that the system contains time delays.

Despite the difficulties in active control of these systems, there have been a variety of demonstrations of control working at full scale, including demonstration of 17 dB reduction in combustion noise by Siemens in 1998 and 25% increase in pressure rise on a Rolls-Royce Viper compressor in 1998. From these demonstrations, the main limitations appear to be actuators and intelligence (control design).

In the context of actuation, the needs include robust and durable operation, high frequency response, and wide amplitude range (combining small and large signals).

For control design, the current practice is to tune the control laws by hand or use relatively simple adaptation schemes. The next generation of control law will use more model-based control techniques, perhaps by measuring the system dynamics near the instability point and using this model to design the control law. A major challenge is developing controls that give guaranteed robust performance. Ongoing work in Professor Dowling's group includes the use of $H_\infty$, $\mu$-analysis, and integral quadratic constraint (IQC) methods for proving robust stability and the use of adaptive control to extend the operating range of the control law.

In summary, Professor Dowling felt that active control of gas turbines was feasible at full scale, with key technical challenges in the area of reliable actuation systems and provably robust control laws. These control laws have yet to be tested at full scale and this is needed in order to demonstrate the efficacy of these approaches in practical applications.

A second keynote address was given by Professor Chih-Ming Ho of the University of California on "MEMS Application to Active Control", which centered on air vehicle applications rather than their propulsion systems.

# 4 Technical Sessions

The technical presentations were broken into six main sessions, covering four broad themes:

- Applications overview from industry, government, academia
- Compression system instabilities: rotating stall and surge
- Combustion instabilities: LPP, afterburners (rumble)
- Sensing technology and control algorithms (linear + adaptive)

## 4.1 Applications overview

The first session of the workshop consisted of seven papers that gave high level descriptions of the current state of the art in applications of active control to gas turbine engines. The presenters were from academia (Paduano [1], Zinn [6], and Mettenleiter [7]), industry (Moran [2], Hermann [3], and Proscia [5]) and government (Richman [4]).[1]

The presentations from industry demonstrated that active control of combustion instabilities were successful in demonstration on full scale engines and rigs. Rolls-Royce [2] has demonstrated control of afterburner rumble as far back as the early 90s, although these results had not yet been made public until this meeting. Similarly, both Siemens [3] and UTRC [5] have shown active control of combustion stabilities in low-emissions, industrial gas turbines with premixed fuel and UTRC has recently built a rig for studying main combustor instabilities (without substantial premixing). The level of understanding of the underlying physical processes varies from strong physical insight of the underlying instabilities mechanisms to high fidelity modeling of the acoustics and flow field, combined with reduced order modeling of the flame dynamics.

The academic researchers focused more on fundamental aspects of dynamics and control of fluid instabilities and it is clear that there is a rich set of understanding of some of the main control techniques as well as modeling processes. However, it is clear that the current industrial demonstrations are moving more quickly than the theory for systematically designing and analyzing feedback controllers. This leaves a gap between what we are able to demonstrate in the field and what we are able to guarantee will work in the presence of uncertainty and noise.

Only Paduano described results in the area of compression systems. Although Dowling noted in her plenary talk that control of compression systems had been demonstrated by Rolls-Royce on a full-scale system, it seems clear that work in active control of combustion stabilities has been more successful in applications. This is despite convincing evidence by Paduano that the basic physics is understood and that control can be achieved. The evaluator's own experience in this area indicates that one of the key bottlenecks is effective actuation (high bandwidth, long life with low cost, low weight) and robust operation. In particular, for aeroengines (where rotating stall and surge are strong limiters of performance) the actuators required to achieve performance benefits do not

[1] Numbers in brackets refer to the paper number in the Symposium program.

trade well against the costs (price, weight, reliability) and the effects of failure in the control are potentially severe due to the nature of the instability.

## 4.2 Compression Systems

The next two sessions focused on active control of compression systems. Talks were presented from academic institutions [8, 9, 10, 11, 14, 15, 16], industry [12], and government labs [13]. The talks covered both control of rotating stall and surge, as well as sensors for compression systems.

In the context of modeling and control of compression instabilities, there were few new results presented in this collection of talks. This area is one which has been very active for the last 10 years and the physical phenomena of rotating stall and surge, as well as the measurement and control problems associated with this, appear to be well understood at this point.

One common thread through several of the talks was the distinction between stall avoidance and stall control. Roughly speaking, the idea of stall avoidance is to use pre-cursors to detect the onset of stall and then change the operating point before stall occurs. In this way, it is hoped that the stability margins might be reduced in some circumstances, allowing more efficient utilization of the compressor (through redesign). This is complicated by the fact that many compressors stall very rapidly, with no apparent precursor having slow growth characteristics. This area has been explored extensively in industry and academia over the past five years and the main bottleneck appears to be reliable detection of precursors in the presence of large amounts of noise and uncertainty. It did not appear that major new breakthroughs in this area are forthcoming.

Stall control consists of stabilizing the normally unsteady behavior associated with stall (or surge) and allowing the engine to operating beyond its normal operating limits. There is a large body of work in this area that has been developed in the last five years and most of the papers fell within the rough scope of the type of work that has been done in the past.

There were several talks on sensor technology for compressor systems, including one by Kulite [12], who is developing a new high temperature, leadless sensor, and one by the Polish Air Force Institute of Technology [13], who have used blade vibration sensors. These types of advances in sensing technology have the capability not only to enable stall avoidance and control, but also new diagnostic approaches that will allow self-tuning systems capable of higher performance. Given the difficulty in controlling stall behavior on practical systems, diagnostics systems for detecting wear and abnormal operating conditions may be the more important early application of control technology for compression systems.

## 4.3 Dynamics and Control of Combustion Instabilities

The largest portion of the workshop was devoted to combustion instabilities, which comprised the final three sessions of the workshop. Many of the leading research groups in the world were represented and the quality of the talks was very high. New results were presented, in addition to continued work that had been introduced at prior conferences and workshops. The talks spanned applications and theory.

### Measurements and Predictions

The first section focused on measurements and predictions of combustion instabilities. The talk by Austin and Tilston (presented by R. Cottington) described the use of fuel staging between the main and pilot zones to reduce oscillations. The approach was mainly empirical, but is representative of the use of passive mechanisms to reduce combustion oscillations. The talk by Balu Sekar of the US Air Force Research Laboratory [19] gave a high level overview of the tools and limitations from an Air Force perspective and described the development of LES tools for modeling combustion instabilities. The final talk of this section, by Vandsburger [20], explored the relationship between chemiluminescence and heat release, which is a primary means of obtaining data about flame dynamics.

### Control Fundamentals

The next session consisted of six talks in the area of modeling and control. The basic control algorithms being used for combustion instabilities are quite simple, usually consisting of a simple gain and phase delay between the sensor (typically combustor pressure) and the actuator (typically fuel modulation). A key feature in most combustion control approaches is the role of time delay between the actuation and the effect of that actuation. This is typically due to convection time constants associated with the mixing and combustion processes.

One common theme throughout these talks was the use of adaptive and learning algorithms for control. These techniques are required because of the sensitivity of the control to time delays, which can vary based on operating condition. A variety of approaches were explored, ranging from the application of neural nets [21], to Smith predictors and related approaches [22, 23, 27], to LMS techniques [24, 26].

A common problem in adaptive techniques is the robustness of the closed loop system. This was addressed explicitly by Evesque [22], who proved stability of a Smith predictor method using fairly broad assumptions on the underlying dynamics, rather than a specific model. These assumptions included second order actuator dynamics, stable flame dynamics, no energy addition from the walls and no unstable zeros in the plant dynamics. While the validity of these assumptions is not clear in a full-scale combustor, the approach illustrated the use of theory to identify fundamental limits of performance. A clear next step is to extend this work to study disturbance rejection (as opposed to just stabilization), for which time delays present a particularly difficult problem.

Another common limitation in applications of control to fluid systems is the effect of actuator limits, including magnitude, rate, and bandwidth restrictions. This seems to be less of a problem in combustion systems than it is in compression systems, but is likely to be a major limitation as high frequency combustion oscillations are considered. The work of Hathout *et al.* [23] used an on/off actuator with both deadzone and hysteresis effects, which allows a more realistic evaluation of true performance.

### Control Applications

Seven talks were given in this section, which focused on implementation of control algorithms in a variety of combustion rigs. All of the presentations demonstrated effective control of combustion instabilities, typically through the use of fuel modulation based on measured pressure oscillations.

A common theme through these talks was the use of fuel-air ratio modulation as a control mechanism and the focus on low emissions as a required output. The effect of control on emissions has not been modeled directly, but it appears that reducing pressure oscillations and allowing the system to run at lower fuel air ratios does give lower emissions [30]. Unlike most approaches, which feed back pressure oscillations and use fuel modulation to reduce these oscillations, McDonell [33] closed the loop on emissions explicitly and used fuel staging as the control mechanism. Although this does not stabilize the system explicitly, it did result in reduced emissions and appears to be a reasonable approach to improving system operability, if a sensor with sufficient reliability is made commercially available.

An issue raised by Santavicca [35] was the need to model spatial dependencies in combustion system models. This issue will become particularly important if distributed actuation is allowed, of the sort that would be required for better pattern factor control. Yu [36] also discussed the importance of large scale fluid structures, which can interact with liquid sprays during the active control process.

The success demonstrated by all of the talks in this session demonstrates the feasibility of active control of combustion instabilities in a variety of applications. The most likely early entry of active control appears to be in low-emissions, land-based applications, where stricter government requirements are pushing the limits of what can be achieved with other approaches. (However, it should be noted that catalytic combustion, which was not discussed in detail in this symposium, is one promising alternative.) If active control techniques are deployed in land-based applications, this will allow reliability and performance issues to be addressed under relatively favorable conditions and would presumably be a precursor to more broad application of active control to other gas turbine applications.

## 5 Summary and Conclusions

The symposium consisted of a broad cross-section of talks representing several fundamental areas in active control of propulsion and power systems. The work in compression systems continues to move forward but fundamental issues of high response, reliable actuation in an engine environment appear to be limiting the application of these results in full-scale engine hardware. Combustion concepts have been demonstrated in laboratory-scale rigs, full-scale rigs and engine hardware. Feasibility of the concept has been established and clear benefits are available for power generation (emissions and operability) and propulsion (operating envelope).

There are several areas where further research is warranted and should be encouraged by RTO:

**Actuation** Actuation continues to be a major bottleneck in the application of active control concepts to gas turbine engines, particularly aeroengines. The primary issues are low authority coupling to the physics and high reliability. These issues will be exacerbated as military engines move to higher fuel air ratios (requiring pattern factor control) and low emissions become a more important factor for land-, sea-, and air-based gas turbines. Novel approaches to actuation which involve low-weight, high-reliability actuation should be more vigorously explored.

**Sensing** Sensing requirements are likely to driven by diagnostic and prognostic applications, which will benefit active control as well. The main issues are reliable operation in high temperature and vibration environments. Control of pattern factor will require new sensing techniques in extremely harsh environments.

**Control** More work is required on developing systematic methods for control of fluid instabilities that result in provably robust control laws. Even if the assumptions required to prove robustness are not always valid, the insights from looking at representative problems will be valuable in understanding the fundamental limits of performance of compression and combustion systems. In developing these techniques, more attention should be paid to the role of actuator limits (spatial resolution, magnitude and rate constraints, bandwidth limits) and also to the possibility of passive solutions that exploit the dynamics of the system ("design of dynamics"). Additionally, there is a need to more effectively harness existing control techniques, such as adaptive and nonlinear control methods.

**Modeling** Although there has been significant progress in modeling of compression and combustion instabilities, there is a basic lack of system-oriented models that capture key interactions that are responsible for thermoacoustic instabilities and more work is required on development of procedures that link CFD models and control designs (along the lines of the work by Mettenleiter et al [7]). In addition, the methodology for incorporating actuators into fluid models is not well developed and the coupling between various engine components (inlet, compressor, combustor, afterburner/nozzle) has not been explored in detail. Finally, scaling laws that allow results from laboratory rigs to be evaluated against engine requirements are needed (this philosophy and an initial start was described by several presenters [5, 27, 30, 31].

**Applications** The use of control-enabled systems for diagnostics and life extension should be considered as an early benefit of active systems. Although this is done to some extent in almost all commercial gas turbines, rapid advances in sensing technology and computational capability will allow more sophisticated signal processing techniques that can provide high value information for improving life-cycle performance. Early insertion of diagnostic sensors into gas turbines will speed the development of active control techniques as experience is gained in incorporating higher levels of electronics and software into modern turbomachines.

An additional issue which is often ignored in early consideration of active control for gas turbines is cost benefit analysis. While active control can extend the operability of engines in a variety of situations, the overall life cycle costs, including maintenance and repair, must be considered as well. While initially it may appear that such analysis would preclude the use of more sophisticated systems, lessons from the automotive industry (where emissions restrictions forced the use of electronic controls in engines) show that it is possible to achieve low cost, high reliability, and consistent performance in long term, harsh environments. Careful analysis of these types of considerations should be a more vigorous part of the overall activity in research and development of active control technologies for gas turbine engines.