Some Aerodynamic Problems of Aircraft Engines: Fifty Years After -The 2007 IGTI Scholar Lecture-

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1 Introduction and Theme

A half-century ago, Sir William Hawthorne, a pioneer in our field, presented a masterful survey of gas turbine aerodynamics entitled “Some Aerodynamic Problems of Aircraft Engines” [1]. In that paper (which would have been an excellent IGTI Scholar Lecture), he described a number of issues, which had major impact on the performance of aeroengines and for which there was no first-principles understanding.1 In fact, if the latter is taken as a metric, some problems he mentioned are not yet resolved.2 The title of this lecture is taken from Hawthorne’s paper in recognition not only of the time that has passed since then but also the enormous advances in gas turbine technology that have occurred.

Several aspects of this progress are directly relevant to the present discussion. First, while deeper understanding can provide a route to better products and more effective processes, the history of the jet engine is a monument to the ways in which designers have produced an excellent and highly sophisticated product even when such understanding did not exist. This point, which is made in the introduction to Hawthorne’s paper, is echoed (with the benefit of 50 additional years of jet engine history) by Koff [2] and by Cumpsty and Greitzer [3]. Second, the deeper understanding referred to has been achieved in a number of areas. In terms of impact on the product, therefore, an argument can be made that achieving additional understanding in the above sense is less important than when Hawthorne wrote his paper.3

Third, the framework of Hawthorne’s paper, and the problems he described, were single discipline issues. To avoid any misunderstanding, let me state at the outset that the point of the lecture is not that there are no important problems of this sort that need to be addressed. However, as in the two previous IGTI Scholar Lectures, microengines and active control of combustion,4 both of which described activities that cut across disciplines to offer potential for step changes in performance, the thesis here is that the major technology gains now lie in research that requires the integration of disciplines.5 Put another way, the highly interactive nature of modern engine design means that the engine needs to be looked at as a system. This type of approach, which almost invariably involves collaboration across disciplines, enables greater reach in attacking such technical challenges and offers opportunities for achieving goals beyond those defined by conventional design constraints.

The above so far are just assertions, but I will endeavor to make them more plausible through the histories of two research collaborations, which (I claim) illustrate the points. The first involved the theoretical description and experimental realization of enhanced turbomachinery range capability through the use of dynamic control, i.e., through alterations of the unsteady compression system behavior. The second was the conceptual design of an aircraft, which would be imperceptible from a noise standpoint outside the perimeter of an urban airport.

It seems helpful to provide some explanation for the choice of examples and the overall perspective taken in this paper. For the former, it is hoped that the topics are of interest to a broad technical community. Further, because the projects achieved the stated goals and the research led to results not foreseen before the project started, there is some justification for viewing them as successful. The narrative of the technical aspects thus provides context, and perhaps some credibility, for the message concerning collaboration. For the latter—and I cannot emphasize this too strongly—it is the intention to highlight some of the difficulties through recounting, from the personal perspective of someone deeply embedded in the technology, the learning about collaboration that took place. The focus of the description is therefore one particular team rather than a broad survey of the field. However, recognizing that many other organizations have had similar (or even more successful) experiences, several other collaborative enterprises, within IGTI and elsewhere, are introduced in the latter part of this paper.

1The word “understanding” is used here to indicate predictive capability that stems from clear definition of the important mechanisms.

2Operability and stall inception and combustor design are examples of two areas that still rely heavily on empirical information.

3The tendency to strive for additional refinement is portrayed succinctly by Bridgeman [4]: “No analysis is self-terminating, but it can always be pushed indefinitely with continually accumulating refinements.”

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5IGTI Scholar Lecturers A.H. Epstein in 2003 and B.T. Zinn in 2005, respectively.

6Perhaps a clearer way to state this is given by J. A. Armstrong, former VP for research at IBM: “God did not make the natural world according to the departmental structure of research universities” [5].
2 Dynamic Control of Compressor Instability: Smart Jet Engines

The first example concerns control of compressor and compressor system aerodynamic instability. We describe the concepts, technical issues, specific achievements, and lessons learned about the overall process.

The idea of a smart jet engine appears to have been initially articulated by Epstein [6] in a National Research Council Workshop, where he posed the challenge of altering the nature of gas turbine engines from open to closed loop operation through the aggressive use of sensors, actuators, and on-board computing. A number of potential applications were identified including active noise control, use of magnetic bearings, and active control of aerodynamic instabilities in compression systems.

Interest in the third of these possibilities was sparked by the visit to MIT of J.E. Ffowcs Williams from Cambridge University, who saw potential for extending concepts from antinoise research [7] to a different and much broader range of flow disturbances. The preliminary objective was to determine the applications, benefits, and requirements of greatly increased real-time computation and closed-loop control in turbine engines. This evolved through internal and external discussions to a more specific goal of defining one promising technology, demonstrating this in the laboratory, and pursuing transition to practical devices.

We focused on control of the turbomachinery compression system instabilities, surge and rotating stall, because of their importance. These two phenomena put fundamental limits on gas turbine compressor operating range and thus limit the design space. A sizable stall margin, or distance between the nominal operating point and instability boundary, must be factored into the compressor design, compromising the ability to utilize the peak pressure rise in the machine as an operating point. Instability limits are difficult to predict and can lead to costly surprises during development. In addition to the technological considerations, rotating stall and surge were topics we knew something about.

The underlying idea was that rotating stall and surge are mature forms of small amplitude disturbances that are the natural modes of oscillation in the compression system. The modal amplitude grows when background (mean flow) conditions cause the damping to become negative. Feedback control operating on these small disturbances, and hence not power or force limited, could change the dynamic behavior of the system, render a given unstable operating point stable, and enhance the operating range [8].

From the beginning, the technology strategy was based on the observation that data are by far the most effective convincers in the gas turbine industry. The plan was to demonstrate often, use these successes to leverage the next steps, and keep close contact with individuals at companies to build support. Furthermore, early in the project, system studies were carried out to identify the impact of the technology that we were proposing. Not all the gains (and costs) were obvious, and the benefits shown by the system study provided an excellent framework for discussions with customers, both current and potential.

Another important practice was to ensure that focus remained on the overall objective, control of compressor instabilities, rather than on the supporting pieces. Each of the latter has its own interesting scientific and engineering issues, and the challenge is to identify and address those truly necessary for project success.

The project described is inherently multidisciplinary and the development of a team that spanned several disciplines took a year or more. There is sometimes a tendency in academic institutions to regard one’s field as challenging whereas the research of others is much more straightforward. A consequence in the beginning was thus questioning whether, for example, compressor experts really needed the help of controls and structures experts. Positive answers to these questions were initially motivated purely by short-term self-interest: to obtain sponsor support from an interdisciplinary pool, to talk to sponsors in their own discipline, and to obtain the software we saw as necessary. As will be seen, however, this perspective changed markedly as the project progressed.

Initial meetings of the group (the word team [8] does not describe the situation at that point in time) were characterized by a lack of understanding between the various camps and a lack of intellectual and language commonality; the same physical problem was thought about and described differently by different parts of the group. Time was needed for group members to convince themselves that the others brought something to the table and to learn enough of the vocabulary and mindset to be able to communicate effectively. In doing this, we had the enormous advantage of a cadre of energetic, intelligent, and high achieving students who had not yet learned that doing a multidisciplinary project is difficult. The students acted as technical translators for the faculty and accessed expertise wherever appropriate, creating links that strengthened the function of the group. We also co-supervised students so that, in some instances, there would be three faculty (with expertise in control, turbomachinery, and structural dynamics, respectively) that met with a student whose project spanned all three areas. Although this style of supervision carries an increased time commitment, it was useful in team building and in providing insight into the intellectual challenges of the other discipline involved.

Weekly technical meetings with a presentation on one aspect of the work, ranging through the different disciplines (fluids, structures, and control), were also useful in team building. The presentations started out very much as student talks with questions by faculty, but as the former gained more knowledge (and more confidence), the meetings became dominated by student-student interactions.

3 Control of Surge

3.1 Active Surge Stabilization. The different technical problems addressed during the program had increasing degrees of complexity. The facilities needed also grew in complexity, from laboratory-scale demonstrations using small truck turbochargers to experiments on transonic fans and complete gas turbine engines. The first achievement was active stabilization of compressor surge, a basically one-dimensional phenomenon, in which nonlinear limit cycle oscillations occur in system mass flow and pressure rise. In most instances, the amplitude of the oscillation is large enough so that over a portion of the surge cycle the flow reverses in the compressor.

Surge is important for both centrifugal and axial compressors. In many types of centrifugal machines surge control alone, as opposed to control of rotating stall and surge together, is sufficient to yield a large increase in useable flow range. A centrifugal compressor was thus used as the initial test bed. The focus on surge as an entry point carried several advantages. There was a theoretical framework [10–12] in terms of simple lumped parameter models, which fit well into a control framework. The phenomenon of interest was one-dimensional and control could be achieved with a single sensor and a single actuator. The frequency of the instability was low enough (10–50 Hz) so both sensing and actuating could be achieved with (almost) “off the shelf” devices. This aspect, which will be seen again in the discussion of rotating stall, meant that we could move rapidly to address the proof-of-concept questions that were at the heart of early success demonstration.

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8One definition of a team [8] is an enterprise that judges success in terms of a collective work product. This can be contrasted with a working group in which the success metric is individual work products [9].
rather than spending a great deal of time on actuator development.

The modeling and control schemes have been described elsewhere [13–16] and will receive only brief mention. A lumped parameter compression system representation is shown in Fig. 1(a), which illustrates a compressor and associated ducting, a plenum (representing the combustor volume in an engine), and a downstream resistance. For feedback stabilization, one measures the system output, compares it with some desired reference level, determines the error, and computes an input signal (command to some actuator) based on this error to drive the error to zero. Figure 1(b) shows a schematic of the controlled compression system. The sensed variable was the plenum pressure, and the controller was a throttle valve at the plenum exit. Surge is a dynamic instability in which the compressor adds energy to small oscillations in the system, increasing their amplitude [17]. A proportional controller, with perturbation in throttle area proportional to plenum pressure, created the necessary dissipation of mechanical energy to offset the perturbation energy put into the system by the unsteady flow through the compressor.

The results from the feedback control are shown in Fig. 2. The abscissa is nondimensional mass flow and the ordinate is nondimensional pressure rise. The symbols represent the performance virtually unaltered.

3.2 Stabilization of Surge Using Structural Feedback. To achieve stabilization, one must alter the dynamic behavior of the compression system. There are ways to do this, however, which do not necessitate the use of sensors and external actuators and can be easier or more robust to implement than active control. A tailored structure, such as that in Fig. 3, can absorb energy and damp pressure and mass flow oscillations. The figure shows the original compression system (compressor, plenum, and throttle) plus a moveable plenum wall, which is a mass-spring-damper dynamically coupled to the aerodynamic system. The combined device, with non-rigid walls, gives greater damping of aerodynamic perturbations than did the original [18]. Details of the analysis, experiment design, and results are given in Refs. 18 and 19, but Fig. 4 illustrates some main findings. The figure shows an increase in stable flow range of between 20–30% over the range of speeds examined. It also indicates that the lumped parameter model that was used in designing the structural feedback adequately captures the system parametric behavior. Even for this simple configuration, there are five nondimensional parameters, which characterize different aerodynamic, structural dynamic, and aeromechanical effects, and modeling played a critical role in negotiating the path to a useful solution. In summary, both active control and structural feedback enhanced stability by altering the dynamic behavior of the system, with the steady-state performance virtually unaltered.

4 Control of Rotating Stall

4.1 Active Stabilization of Rotating Stall. For axial compressors, one also needs to control rotating stall, a situation in
which cells of stalled flow propagate round the circumference of
the turbomachine at between (roughly) 20–50% of rotor speed,
depending on the configuration. Time mean performance in rotat-
ing stall causes much decreased efficiency (an order of magnitude
in some cases) and pressure rise compared to the prestall value
[20]. Further, the decrease in pressure rise during rotating stall
development can cause the overall system stability criteria to be
violated leading to surge. In this sense, one can say that rotating
stall in a multistage axial compressor “triggers” surge, with the
consequence that one needs to control both types of instabilities.

For rotating stall, the control problem is multidimensional, im-
plying, at least for linear control schemes, the use of arrays of
actuators and sensors. Rotating stall phenomena are less well un-
derstood than surge and, at a conceptual level, the approach taken
could have been expressed as follows. Theory [21,22] suggested
that rotating stall was the mature form of small amplitude circum-
ferential asymmetries (waves), which propagated around the an-
nulus, with the fate of these small amplitude disturbances gov-
erned by the mean operating conditions. For operations near
design, the disturbances decay. As the flow rate was decreased,
however, the disturbance decay rate would decrease until at some
flow condition (peak pressure rise or slightly beyond) the distur-
bances would be neutrally stable, neither damped nor amplified.
For further reductions in flow, and consequent operation on the
positive sloped part of the pressure rise versus flow compressor
pumping curve,5 disturbance waves would grow into rotating stall.

The theory implied that damping the waves would inhibit ro-
tating stall. The objective was thus to sense small amplitude trav-
eling waves in the compressor and to use actuators to establish a
real-time traveling disturbance that was coupled to these waves.
Doing this in an appropriate manner provides an alteration to the
dynamic behavior that renders the system stable, enhancing the
rotating-stall-free operating range. The elements for realization
were wave sensing, wave launching, closing the loop, and the
hardware implementation of all three. Demonstration that the
waves existed, namely, that the eigenmodes in the compressor
annulus were modes in the forms of Fourier harmonics in the
circumferential coordinate, was directly tied to the theory for ro-
tating stall control. If so, for a linear system the control could be
carried out on a Fourier mode-by-mode basis as separate single
input, single output control systems. The overall direction of the
experiments was based on this close integration of fluids and con-

4.2 Stabilization of Rotating Stall With Structural
Feedback. Many of the comments about structural control of
surge apply to rotating stall. The main difference is that one now
has, as for active control of rotating stall, a distribution rather than
a single structural element. The use of structural feedback was
demonstrated by Gyssling [26,27] with an array of reed valves
controlling the injection of high pressure air in front of the com-
pressor. An increase of 10% in stable flow range was obtained.
Gyssling [26] also provided a unifying view of structural and ac-
tive control of rotating stall through the examination of the ener-
getics of the wave growth process. He showed that the flexible
structure created phase relationships between pressure and flow
rate perturbations through the valve similar to those in an active
control system in which pressure was sensed and flow was con-
trolled. This work gave a framework in which to view all linear
control schemes examined up to then.

In terms of the variables shown in Fig. 2, this means operation in a regime in
which \(\frac{d\phi}{db}\) is positive.
5 A Counterpoint Concerning Collaboration: The Benefits of “Putting Your Theories in Jeopardy”10

A counterpoint to the main theme provides an illustration of a way in which collaboration can also be a strong enabler for technical progress within a discipline. The control philosophy presented so far has been in terms of a scenario for instability associated with the growth of small disturbances. The results for compressor response, and the mode-by-mode ability of the controller to delay rotating stall, provide clear evidence for the reality of this mechanism. However, the linear theory fails to address the observation that some compressors encounter rotating stall in a regime where the slope of the compressor pressure rise characteristic is negative, and the theory states that the flow is stable with respect to small disturbances.

Major steps to resolve this dilemma were taken at Cambridge by Day28 who showed there was a qualitatively different process, with a different physical mechanism than the route described above. The disturbances associated with rotating stall inception in this second process were much shorter in circumferential extent than the modes (the relevant length scale was several blade pitches rather than the annulus circumference, which is the appropriate length scale for the modes). The disturbances were also seen in the tip region of rotors rather than being roughly two-dimensional, and they were large amplitude even when first observed at the measuring stations that were used. The time for

10Phrase due to Dr. D. C. Wisler.
growth to the mature form of the disturbance from first sensing of these “spikes” was typically only several rotor revolutions. Figure 9 shows this behavior with data from eight hot wires equally spaced around the circumference in front of the compressor; here modal disturbances are not apparent prior to the onset of rotating stall. The spike disturbances were found on the negatively sloped portion of the compressor speed lines, another indication that the mechanism was different than the modal disturbances.

The existence of the two routes is important both for capturing the phenomenon in a rigorous prediction methodology and also with relevance to one’s ability to enhance compressor stability. The criterion for which of the two routes would occur was shown in an incisive experimental investigation to be the incidence at the tip of the stalling rotor, and Fig. 10 gives the concept that underpins this result. The figure shows two situations: one in which the compressor characteristic slope becomes zero (or slightly positive) before critical incidence is reached (Fig. 10(a)), the other in which the critical incidence occurs at a higher flow coefficient than the zero slope condition (Fig. 10(b)). In the former, the compressor is unstable to propagating modes; in the latter, modal perturbations decay so that rotating stall onset only occurs as a result of spikes.

Experimental data supporting this hypothesis are given in Fig. 11. The abscissa is the nondimensional slope of the compressor pressure rise curve, and the ordinate is the incidence angle at the tip of the stalling rotor in a three-stage compressor. Spike behavior is found at conditions of negative compressor pressure rise slope where the critical incidence for that compressor is exceeded. A subsequent computational study by Gong et al. examined the evolution of the spikes and found that, as one would expect for a nonlinear system, the structure of a fully-developed single cell

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11The name is at least partly due to the way the disturbances appear in time-resolved data such as Fig. 9, in which the “emerging stall cell” can be characterized as a spikelike form.

12The value of the critical incidence depends on the compressor parameters; it is not the same for all compressors.
in a multistage compressor is not dependent on the initial route. For additional details of the fluid mechanic origins of this type of disturbance, see Vo et al. [31].

The connection to the theme of collaboration is that close interaction between research groups during the sorting out of two diverging views led to a dialectic “thesis, antithesis, synthesis” scenario. The initial wave description was the thesis, the description in terms of the spikes was the antithesis, and the work by Camp and Day [29] (and the later computations of Gong et al. [30]) was the synthesis unifying the two concepts into a more powerful and general statement about compressor rotating stall inception.

There is no claim here that the results could not have been achieved in isolation by one or the other group, or (perhaps more likely) by someone else. However, the observation is that a number of new statements were made about a complicated process in a period that is short on the academic time scale, and it is useful to look at possible contributing factors. Two of these seem key. First was the willingness to engage in substantive discussions including open sharing of ideas and thoughts (see the phrase in the section heading). Second, and much related, was an explicit respect for the other party’s technical arguments; there was a desire to understand how the two different views could be resolved rather than a “not invented here” attitude. The perspective was not a zero sum game but rather a recognition that even though someone else’s idea is correct it does not necessarily mean that your idea is not or detracts from any credit. Both these factors led to the rapid uptake of ideas into each group and the ability to use pieces of the concepts in new and different ways.

6 Application of Dynamic Control to More Complex Situations

The applications described to this point are appropriately regarded as a first phase of work on smart engines, with the aim of providing proof-of-concept demonstrations of both the theoretical framework and the ability to enhance stable flow range (i.e., both theory and execution). Once achieved, the focus shifted to technical challenges associated with implementation in devices that are closer to the actual product. The collaboration also expanded to organizations (NASA and GE), which had the capabilities to take on the different issues that arose from this shift.

6.1 Compressor Operation With Inlet Distortion. The experiments introduced in Sec. 4 were conducted with a uniform inlet flow, but many compressor instability problems are associated with inlet distortion, commonly circumferential asymmetries in inlet stagnation pressure. With inlet distortion, the modes are no longer pure sinusoids (the analogy is wave propagation through a nonhomogeneous medium). The first mode, for example, will have not only a first Fourier harmonic (a single lobed sinusoidal component) but also a zeroth harmonic, a second harmonic, and so on. The control can no longer be single input, single output, but needs to be multiple input and multiple output. The control problem was examined by van Schalkwyk et al. [33], whose experiments showed the coupling of harmonics, providing additional evidence for the wave theory of rotating stall inception.

In connection with defining compressor response to distortion, a detailed investigation of the fluid mechanics associated with time-dependent inlet distortion was carried out at the GE Aerodynamics Research Laboratory [34]. The specific aspect examined was the severe adverse effect on compressor stability found with a rotating distortion, i.e., a distortion that propagated around the circumference [35]. This is seen when a low pressure compressor in a jet engine goes into rotating stall, imposing this type of distortion on the high pressure compressor.

It was known that for propagation speeds near the rotating stall speed, the stable flow range could decrease markedly. While it is plausible to associate the cause of the decrease as a resonance with the modes (which are the “natural frequencies” of the flow in the compressor annulus) some compressors exhibited another band of propagation speeds at a higher frequency, where there was also a large effect. This additional decrease in stability occurred at rotation near the speed of spike propagation. Detailed time resolved measurements indicated that the compressors, which exhibited modal stall behavior, showed only a single region of decreased stability as a function of distortion rotation speed, while compressors exhibiting spike stall exhibited two regimes of decreased stability. The rotating distortions thus appeared able to excite either or both of the stall onset mechanisms.

6.2 Active Control of Transonic Turbomachinery. A second direction was toward representative engine Mach number regimes, in other words transonic turbomachines. Four distinct aspects of the problem have been addressed. Three of these were identification of wave structure in these machines, development of models for the compressible flow regime, and adaptation of the models to forms suitable for control [36,37]. For compressible flow, in contrast to the situation for incompressible flow, an infinite number of compressible propagating modes exist for each Fourier harmonic because there are now additional phenomena that support wave behavior. For a given harmonic (e.g., the first), there is thus more than one lightly damped mode which can exhibit instability. The issues associated with these modes were new and unanticipated, and they needed to be dealt with to achieve control of rotating stall.

The fourth aspect was implementation of the idea on a transonic fan, examined in experiments at NASA Glenn Research Center [38,39]. The rotor speed was high enough so moveable inlet guide vanes were not feasible and the fluid dynamic effectors were injectors fed by high bandwidth (400 Hz) valves. Flow range extensions of approximately 10% at a tip Mach number of unity were achieved. The experiments also showed that the modes of interest can have propagation speeds at or greater than the rotor speed, consistent with the behavior of the newly discovered class of disturbance modes in the compressible theory. It was also found that (with radial distortion) the inclusion of tip blowing could change the instability behavior from spikes to modes, in accord with the findings of Camp and Day [29] introduced in Sec. 5.

6.3 Engine Stability Management. Reference [40] discusses the development and full-scale engine rig demonstration of an active stability management system, yet another step in complex-
ity and scope. In the context of collaboration, the paper provides an illustration of a successful university-industry teaming, carried out as part of a targeted alliance strategy to provide the capability to tackle a product-oriented situation calling on a range of skills. The nine coauthors span different disciplines, in line with the sentiments expressed in the Abstract.

7 Lessons Learned

Several lessons can be taken from the history of the smart engine project. First is that an interdisciplinary (fluids, control, structures, and instrumentation) approach was needed for success because the “systems” aspects are critical. To this end, there was focus on teaming to create the end product, including the development of a viewpoint not as fluids people, controls people, or structures people, but rather smart engines people. Some of the difficulties in team building have already been noted: possible long start-up time, lack of a common language and of an appreciation for cross-disciplinary challenges, and a tension between the need for breadth across and depth within the different disciplines. To aid the process, it was important to have tangible recognition from project leaders for work in other than their home disciplines (in our case, the senior faculty were from the turbine engine aerodynamics community). One measure of the teaming can be seen from the reference list, which contains publications with three or more faculty and with colleagues from the industry and the government.

Second, as known all along by control practitioners, adding feedback control can change the system dynamics. A controlled compressor is thus a different machine with different stability properties. This difference can mitigate or remove design constraints that previously existed. The lesson for device experts is to recognize that some of the tried and true rules of thumb for fluid machinery may have to be reexamined in light of new approaches.

A third lesson relates to knowledge flow and learning. A feature not apparent when we started is that such flow can occur in (at least) two directions. The author’s initial (naive) view was that we would gather information from the various disciplines and meld it together to enable the development of an actively controlled compression system. What was found was quite different. The controlled compressor, in association with system identification techniques, is a new diagnostic tool for exploring compressor fluid dynamics, offering enhanced ways to obtain information. This is an exciting aspect with a benefit that does not need to wait for the development of flight-critical active control systems and that can carry over to other unsteady phenomena.

An illustration of the learning is found in forced response experiments such as those leading to Fig. 7. The original theory treated the unsteady flow in the blade rows as an inviscid channel flow, with the consequence that all modes were calculated to become unstable at the same flow coefficient. The forced response experiments showed this was not correct and that a simple first order rate-process description of the unsteady viscous response would be an appropriate addition, leading to the agreement between experiment and theory seen in Haynes et al. [25]. The use of the controlled compressor as a diagnostic tool thus provided insight into compressor fluid mechanics which was not previously achievable.

A fourth aspect, inherent in projects spanning a range of disciplines, is that there are fields with which some of the participating senior technical experts are not well acquainted. For academia this is a departure from the tradition in which faculty advisors use their expertise to guide the students. For the smart engine project, there were numerous situations in which the students in a given field were much more knowledgeable than most of the faculty. This posed no difficulties (except perhaps for the time needed to explain basic ideas to various faculty), but it can be a potential bar to creating the necessary linkages between technical experts.

Finally, the idea of demonstrating often, of aiming at specific targets rather than trying to formulate the most general (with the implication also of longest to develop) success goal for active control, and of having a clearly defined road map of objectives and barriers which is shared by all participants cannot be overemphasized. This carries over directly into the second case history, the silent aircraft initiative (SAI), where, although the project was very different, we will see many of the same points concerning collaboration.

8 The Silent Aircraft Initiative (SAI)

Aircraft noise is recognized as a major barrier in the expansion of airport operation [41,42]. The evolution of noise reductions shows a progression that had an initially steep downward trend but is now leveling out. As stated in Ref. [43], “the downward trend in noise exposure around airports of past years has now flattened out at major airports. Virtually all the older aircraft have been phased out and, while the continued fleet renewal will introduce progressively quieter types, the benefit will be appreciably less than has been achieved from phasing out of Chapter 2 aircraft.” Figure 12 is one version of an often-seen chart showing the evolution of aircraft noise reductions.

SAI was created to address this challenge. The approach was to set the objective of a radical reduction in noise as a primary design criterion, taking a “clean sheet of paper” outlook. The specific project goal was to provide the conceptual design of an aircraft quiet enough to be imperceptible to people in the urban environment around airports. A key question is how such an aircraft would compare to existing and next generation aircraft in terms of fuel burn and emissions, i.e., what would be the penalties for designing for low noise? As seen below, the answer was that, according to the design calculations, one can reduce both the noise and the fuel burn.

A number of noise limitation targets have been set by the aviation industry, but SAI aimed at a major step beyond these. This stretch goal called for highly integrated airframe and engines as well as for operations and design optimized together for low noise, implying that the capabilities of a range of partners in academia, industry, and government would be needed. From the beginning, therefore, the project was viewed as involving collaboration between organizations and between individuals with different skills and interests. The scope of work included airframe and engine research, ways to reduce noise by changing takeoff and approach procedures, and an economic assessment of the scenarios under which the aircraft would present an attractive business case to an airline and of the possible benefits to the UK economy, both nationally and regionally.

SAI was one of the Cambridge-MIT Institute’s (CMI) Knowledge Integration Communities (KICs), research communities exploring new ways for the academia, industry, and government to
work together.\footnote{The Cambridge-MIT Institute was a UK government-supported joint venture between Cambridge University and MIT. SAI was one of a number of projects that CMI supported in areas (such as aerospace) in which the UK industry has a demonstrable competitive position.} The role of the KIC is to foster linkages and two-way flows of information between academic researchers and their colleagues in commerce that enhance the impact of the research. SAI community was comprised of airframers, engine manufacturers, airport and airline operators, air traffic controllers, regulators and measurement specialists at over 30 partners, in addition to the academics.

The discussion of the smart engines research was presented along roughly chronological lines. For SAI, however, which had a broader competitive position.

The design results and then examine the critical aspects in achieving these. This is done in what follows.

9 Features of the Silent Aircraft Design

The aircraft mission is to carry 215 passengers with a range of 5000 nautical miles at a cruise Mach number of 0.8. The conceptual design, denoted as SAX-40 (SAX=silent aircraft experimental) is depicted in Fig. 13. The aircraft has a cruise \( ML/D \) of 20 (for reference the Boeing Phantom Works Blended Wing Body has an \( ML/D \) of 17–18 and the Boeing 777 has an \( ML/D \) of 17) \footnote{For reference, the Toyota Prius hybrid car carrying two passengers is reported as having a fuel burn of 120 passenger-miles/gal [44].}. The span is 67.5 m including winglet and the maximum take-off weight (MTOW) is 151,000 kg.

The SAX-40 airframe has major differences from civil aircraft either in current use or under current development. There are conventional supercritical wings but the fuselage is a lifting body with no flaps and no tail. The aircraft is propelled by high bypass ratio turbofans (cruise bypass ratio of 12) embedded in the fuselage. There are nine geared fans driven by three gas generators so each inlet feeds one turbofan engine driving the other two fans in that cluster. Figure 14(a) shows a top view of the engines, indicating the gearing for the cluster (of three fans/one engine) that sits in each of the three intakes. Figure 14(b) shows a side view of the engine in the duct, to illustrate the length of duct available for acoustic liners. The overall conceptual design is aimed at the 2030 time frame, but part of the project strategy is that some of the quiet technologies could be incorporated nearer term.

The features of the silent aircraft have been reported in some background noise in urban daytime environments. As described by Hileman et al. \footnote{Tone corrections were neglected because tonal noise could not be computed for the airframe noise sources.} a reduction in cumulative noise (sideline, takeoff, and approach) of 75 cumulative EPNdB is estimated relative to the ICAO Chapter 4 requirement. The estimated noise levels of SAX-40, computed according to the FAA procedures documented in Part 36, are compared to the existing fleet in Fig. 15 [44].

The estimated fuel burn is shown in Fig. 16 [46], in terms of energy per airline-seat-kilometer. The non-SAX data is from Ref. [51]. The predicted fuel use relative to current civil aircraft is 124 passenger-miles/gal compared to 101 passenger-miles/gal for a 777, a 23% increase.\footnote{An important point is that further fuel efficiency, even with respect to this saving, would be expected if the aircraft were targeted to minimize fuel consumption rather than noise.} An important point is that further fuel efficiency, even with respect to this saving, would be expected if the aircraft were targeted to minimize fuel consumption rather than noise.

9.1 Enabling Technologies. The low noise is not achieved by a single design feature but results from many disciplines integrated into the design and operation of a noise-minimizing aircraft system. These are portrayed in Fig. 17 [46], which indicates that a
number of aspects of the aircraft must undergo major alteration to
give the desired noise reduction. Many of the noise reduction
design choices are also beneficial in terms of fuel burn, as implied
in Fig. 18, which gives the corresponding technologies for de-
creased fuel burn.

The rationale for the features of the aircraft and propulsion
system can be briefly listed as follows:

- Efficient airframe centerbody design. On approach the air-
  frame generates half the noise. To create the desired noise
  reductions, the aircraft has conventional supercritical wings
  that blend into a lifting body fuselage. As described by
  Hileman et al. [44] “the leading edge region of the
centerbody...achieves an elliptical span load on cruise
yielding a 15% improvement in ML/D compared to current
blended-wing body aircraft design.”

- Airfoil trailing edge treatment. Trailing edge brushes [52]
have been found to reduce scattering of turbulence from the
trailing edges. The estimated trailing edge noise reduction
for SAX-40 is 4 dBA.

- Fair ed undercarriage. The undercarriage noise sources can
  be mitigated by partially enclosing wheels and axles. The
  estimated noise reduction from the use of fairings is 6 dBA.

- Deployable drooped leading edge. A deployable drooped
  leading edge can provide the required lift during low speed
  operations without the use of slats, thus eliminating slat
  noise. The drooped leading edge is stowed at cruise. De-
  ployment power levels are comparable to a conventional
  slat. (This configuration is used on the Airbus A380.)

- Quiet drag (needed on approach) via increased induced
  drag. Large wing area and high angle of attack provide the
  lift at low speed without using flaps, eliminating a major
  source of airframe noise on takeoff and landing. A combi-
  nation of elevons and thrust vectoring can increase the in-
 duced drag to the required level, while trimming the aircraft.

- Embedded, aircraft boundary layer ingesting, distributed
  propulsion system. Boundary layer ingestion allows a poten-
tial reduced fuel burn [48,53]. There is a trade between this
  gain and the losses due to increased duct length for noise
  attenuation. Embedding the engines within the airframe
  implies a need for a high level of airframe-engine integration
  because the airframe and engine flow is much more strongly
  coupled than in tube and wing designs. In particular, there
  are several major challenges associated with the ingestion of
  the fuselage boundary layer and the creation of a nonuni-
  form flow into the engine (distortion), which must be ad-
dressed for a practical aircraft configuration.

- Variable area exhaust nozzle to permit ultra-high bypass
  ratio, low fan pressure ratio, engines. To reduce the engine
  noise at takeoff, the engine exhaust velocity must be de-
  creased. To ensure fan operability at the low fan pressure
  ratio needed for low exhaust velocity, the exhaust nozzle is
  designed to have variable area, with takeoff bypass ratio of
  18 and cruise bypass ratio of 12. The low engine rotational
  speed during approach enabled by the variable nozzle re-
  duces the rearward fan noise and the airframe drag require-
  ments.

- Airframe shielding of engine noise. Placing the engines
  above the airframe prevents engine noise from reaching the
  observer. Engine forward noise sources are virtually eradi-
cated on the ground.

- Optimized extensive liners. The embedded propulsion sys-
tem allows smaller engine diameter and thus increases non-
dimensional (length/diameter) duct length. The long inlet
  and exit ducts allow additional acoustic liners, compared to
  conventional nacelles, to absorb engine noise. The use of a
  multisegment liner design provides an estimated 20 dBA re-
duction of engine noise.

- Optimized takeoff thrust management. Thrust, climb angle,
  and nozzle area would be continuously varied during takeoff
to maintain a set noise level outside the airport boundary,
  allowing the specified noise level to be met all through
  departure.

- Low noise approach operational procedures. The sound
  power level (SPL) scales as SPL \( \propto (\text{velocity})^n / (\text{distance})^2 \),
  with the exponent \( n \) between 5 and 6. Achieving low noise
  involves low speed approach (decreased velocity), displaced
  threshold for landing (increased distance), and a continuous
descent approach (increased distance and lower engine thrust).

\[
\begin{array}{|c|c|c|}
\hline
\text{Passenger Miles} & \text{ML/D} \\
\text{per gallon} & \\
\hline
\text{SAX-40} & \sim 124 & 20.1 \\
\text{Toyota Prius hybrid car} & \sim 120 \text{ w/ 2 people} & -- \\
\text{Boeing 777} & 86 - 101 & 15.5 \\
\text{Boeing 707} & 46 - 58 & 13.5 \\
\hline
\end{array}
\]

\[\text{Fig. 16 Estimated fuel burn for SAX-40 [44]}\]

\[\text{Fig. 17 Enabling technologies for noise reduction [46]}\]

\[\text{Fig. 18 Enabling technologies for decreased fuel burn [46]}\]
10 The SAI Collaborative Process

10.1 University-Industry-Government Interaction. A range of skills and interests beyond those of the two universities were
to support the above technologies and the collaboration
including regulators, airport operators, airlines, aerospace manu-
ufacturers, and representatives of community groups. Our obser-
vation in this regard is that SAI has been an instructive and useful
experience in academic-industry interactions on several levels,
from strategic planning and decisions (input from the KIC mem-
bers had a direct impact on the project goals) to detailed working
level technical interchange.

There were formal meetings of all the KIC partners at roughly
eight-month intervals, but interaction with some organizations
was more frequent and in-depth in terms of access to in-
house design codes and consulting help. For example, Boeing
made available their multidisciplinary design optimization code,
WingMOD, which optimizes the aircraft platform for a given mis-
tion, and academic researchers were able to use Rolls-Royce de-
sign, performance, and noise evaluation tools to examine concepts
for potential engine designs. In addition Boeing, Rolls-Royce,
NASA, and ITP conducted reviews and provided feedback on the
designs.

As mentioned previously, a team project that is carried out as
part of student degree programs contains a set of goals, which has
an inherent tension. Each student needs to develop the new ideas
that comprise his or her thesis to receive a degree; these need to
be visible as a contribution that the particular student has made.
However, there is also a need for the research results to be inte-
grated into a workable design concept. To help with this latter
issue, Fig. 19, put together early in the project and modified as
necessary, shows how the contributions of students, staff, and fac-
culty fit into the overall design. The figure, which appeared in a
number of presentations and which was almost an icon for the
project, provided a very real framework for discussions of responsi-
bility and deliverables, strengthening the ability to work as an
integrated product team.

Weekly videoconferences, and even more regular email and
telephone contact, were essential for this design integration. Also
essential was a clear, mutual, and explicit understanding of advi-
sor and student as to what the expected intellectual contribution
for the thesis would be and how it was consistent with participa-
tion in the overall design.

During several stages in the project, there were design decisions
to be taken, and ad hoc task forces were formed to address these.
Major questions dealt with in this manner were: “What should be
the design range?” and “Should the engines be podded or embed-
ded?” The task forces were focused activities of a few weeks
duration, drawing on members from all relevant aspects of the
research and involving exchanges of personnel, thus (again) build-
ing working relationships and diffusing “we-they” perspectives.

Collaboration was integral throughout the project, but it was
perhaps most critical in the area of aircraft operations, in which
the team in Operations worked to develop an advanced form of
continuous descent approach (CDA) for current aircraft to be as-
essed in trials at Nottingham East Midlands Airport [54]. Putting
the new procedures in place was a many-step task that required
agreements between air traffic controllers, regulators, suppliers,
airport operators, and airlines; it was an example of something
that could not have been achieved without this type of partnership.

The silent aircraft project brought industry, academia, and other
stakeholders together around a “grand challenge” that captured
the enthusiasm and imagination of the participants, who felt they were
involved in something special. The KIC included industry, gov-
ernment, and academia and provided an exciting way to address
problems with a large reach and a potential for step-change im-
provements. In addition to the conceptual design for a new type of
aircraft, some of the technologies developed could be introduced
into more incremental aircraft and engine designs. In short, col-
laboration and teaming occurred in basically all aspects of the
project and because of this SAI was very much an enterprise in
which the whole was greater than the sum of the separate parts.

11 Some Additional Perspectives and the Connection
With IGTI

The two project histories have been put forward as representa-
tives of a more general application, and it is useful to now place
the ideas in a broader context. This will be done along two differ-
ent lines. One is to give an indication of the extent to which these
ideas have impacted by including perspectives from outside the
gas turbine industry that are relevant to the overall theme. Second,
recognizing that a primary constituency is IGITI members, we can
briefly make the connection with other activities of individuals
and organizations within our professional society.

There are many examples that show the strong influence of the
collaborative process on engineering. Space permits discussion of
a few only, chosen to illustrate different venues: research, technol-
gy development, and business practices. While these cannot be
claimed to prove the case, what can be said is that there is much
other documentation that can be assembled to support the point.

In research, the most recent newsletter from my graduate
school contains an article about a materials engineering professor
recognized for collaborative research, as noted in the description
of the committee that chose him as recipient of the ASME Ti-
omoshenko Award. This individual comments: “Collaboration is
unquestionably effective in research. The synergy of multiple
minds working on a problem can be huge, especially when the
individuals bring different knowledge and skills to the table.”

In technology, a recent book by Broers [55] makes a clear case
concerning the need for interaction across the development
process of high technology devices. This is the only way to obtain
the necessary information to enable focus on the critical issues
that stand in the way of product development. (The second of six
chapters in the book is, in fact, entitled “Collaboration.”)

A historical trend described by Broers [55] is that the large
industrial laboratories, which had a major scientific presence
when he started his career, have either ceased to exist or have
changed their focus to product development. As a consequence, it
is now more likely that important new ideas will originate outside
of a company’s laboratory. Because of this, the aim is to partner
with other research entities and draw on “the entire world of sci-
cence and technology” [55].

The partnering theme and its relation to innovation (defined as
“how companies utilize and advance technologies to create new
products and services”) can also be seen in studies of several
corporations [56]. The open innovation paradigm described is one
in which there is a strong linkage between the technical personnel
within a company and universities and other research centers out-
side the company.

The third aspect, the way in which collaboration affects the
environment for conducting business, is described in compelling
detail by Friedman in the book The World is Flat [57], with one
chapter entitled “From Command and Control to Collaborate and
Connect,” and another with a section “Open Sourcing: Self Orga-
izing Collaborative Communities.” Friedman did not just say
that collaboration and partnerships are useful, he stated flatly that
this is now the way the business world works; not to recognize
and act on this decreases one’s competitive position.

As the final part of the discussion, I would like to focus on IGITI
and the interests of its members. For gas turbine engine manufac-
turers and suppliers, collaboration in product development is well
established. The interactions, which occur to bring an engine to
certification, in both civil and military aeroengines, are now often
multinational and multicompny. This is a part of the business we
are in.

Participants in IGITI conferences have also seen the emphasis
on teaming and collaboration in major presentations at the meet-
ings. The topic of the keynote address in the 2006 conference was
“The Global Market and Collaborative Ventures.” A large part of
this is the teaming between companies just referred to, but an
additional trend is that both aeroengine and land-based
gas turbine companies are now interested in developing strategic
relationships with universities. One of the keynote presentations,
in fact, described the background, rationale, and operation of an
engine company’s university connections, specifically the target-
ing of strategic needs relating to different technologies and the
formation of long-term relationships with universities having exp-
ertise in those areas.

A different sort of successful joint project was highlighted in a
previous IGITI Scholar Lecture [58] on turbine heat transfer and
aerodynamics. That lecture discussed an investigation of turbine
vane-blade interaction, with Allison (now Rolls-Royce) as the
main industry participant, Ohio State the main academic organi-
zation, and other industry and academic collaborators. One result
was multiauthor papers with participants from two (competing)
engine manufacturers, teaming together to define answers to an
important and longstanding problem.

The partnerships mentioned in the different parts of this paper
are all offered as illustrations of the way in which gas turbine
engine research can benefit from collaboration. There are differ-
ences in research questions, specific objectives, organizations, and
team members, but an attribute in all was that the resulting enter-
prise had the capability to address successfully a difficult problem
that was of high interest to the technical community. Cutting edge
problems in our industry increasingly bridge across disciplines
and across the technical skills of individuals; in-depth collabora-
tion to attack them will be more and more a key part of the
professional activity of IGITI members.

12 Summary and Conclusions

The content and process of two different multidisciplinary
projects have been described, as a way to illustrate features, and
benefits, of teaming and collaboration in research. One project
was a decade-long investigation on the phenomena of compressor
stability enhancement, leading to a number of basic results and
first-of-a-kind demonstrations. The other was a three-year devel-
oment of the conceptual design of an aircraft whose noise would
be imperceptible outside an airport in an urban environment. Both
projects involved industry and government organizations as mem-
bers of the collaboration enterprise. A common thread was that a
team approach, subscribed to by the participants, was essential to
the program success. In this, key aspects were:

• an emphasis on the overall project goal
• a system, rather than component or discipline, or focus
• an appreciation of cross-disciplinary challenges, including a
   willingness by experts in a given field to address the intel-
   lectual, technical, and organizational issues inherent in re-
   search, which spans several engineering disciplines outside
   this field
• a willingness to accept (and perhaps even embrace) ideas
   from outside one’s particular research group, field, or organi-
   zation
• a realization that although collaboration can have its own
   overhead there can be a major return on the investment.

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