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

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Problems of high technological interest, for example the development of gas turbine engines, span disciplinary, and often organizational, boundaries. Although collaboration is critical in advancing the technology, it has been less a factor in gas turbine research. In this paper it is proposed that step changes in gas turbine performance can emerge from collaborative research endeavors that involve the development of integrated teams with the needed range of skills. Such teams are an important aspect in product development, but they are less familiar and less subscribed to in the research community. The case histories of two projects are given to illustrate the point: the development of the concept of "smart jet engines" and the Silent Aircraft Initiative. In addition to providing a capability to attack multidisciplinary problems, the way in which collaboration can enhance the research process within a single discipline is also discussed.

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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.

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

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

[3] The 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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[4] IGTI Scholar Lecturers A.H. Epstein in 2003 and B.T. Zinn in 2005, respectively.

[5] Perhaps 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 compression 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.[6] 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,[7] 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 disciplines 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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[6] Specifically to extend the applications from pressure disturbances, the major domain of the acoustician, to the entropy and vorticity disturbances that are inherent in gas turbine operation.

[7] This was true for the silent aircraft project as well.

[8] One definition of a *team* 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].

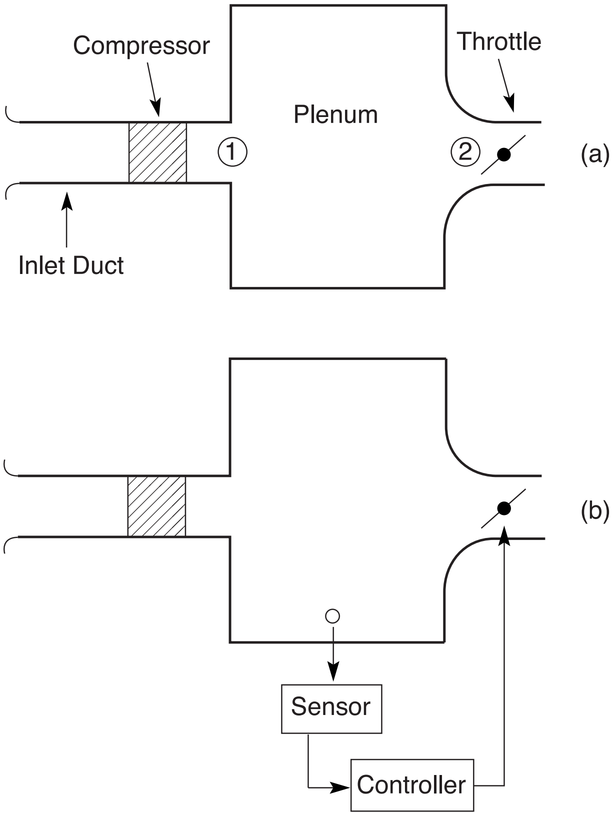

Fig. 1 Lumped parameter compression system: (*a*) no control, and (*b*) controlled system with sensor in plenum and throttle actuator

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 as measured by steady-state instrumentation. Without control, the surge oscillations were greater than 100% of the prestall value in mass flow and 30% in pressure rise, leading to a time-average pressure rise 20% below the prestall value. With the controller, the amplitudes were reduced by an order of magnitude, the time mean pressure rise was maintained roughly at the prestall value, and the useful flow range was increased by nearly 25%. Switching on the controller when the system had entered surge also enabled the compressor to recover from a limit cycle oscillation back to a stable operating point.

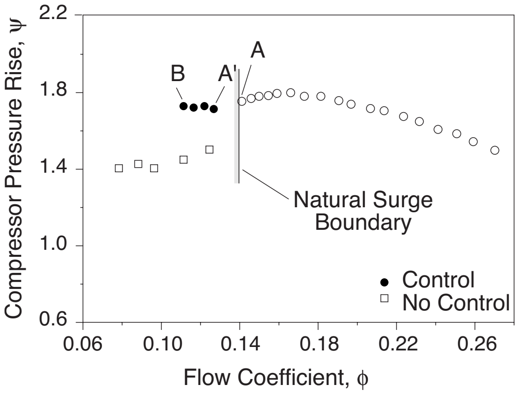

Fig. 2 Compressor pressure increase characteristic indicating time-mean operating points with and without control [13]

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

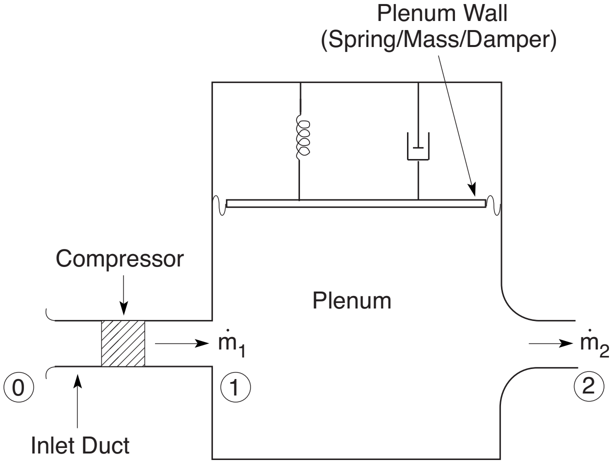

Fig. 3 Schematic of moveable plenum wall compression system [18]

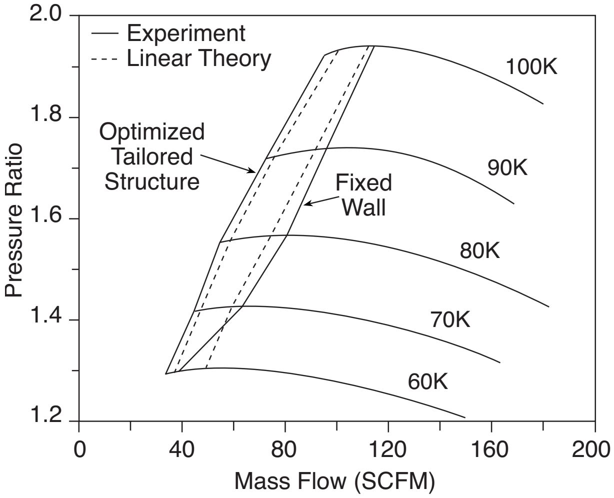

Fig. 4 Predicted and measured compressor stability limits with dynamic structural control; labels denote corrected speed (100 K=100,000 rpm) [18]

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 rotating 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, implying, at least for linear control schemes, the use of arrays of actuators and sensors. Rotating stall phenomena are less well understood 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 circumferential asymmetries (waves), which propagated around the annulus, with the fate of these small amplitude disturbances governed 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 disturbances 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,[9] disturbance waves would grow into rotating stall.

The theory implied that damping the waves would inhibit rotating stall. The objective was thus to sense small amplitude traveling 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 rotating 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 controls concepts.

Investigations of wave structure were carried out at the Gas Turbine Laboratory, MIT, and at the Whittle Laboratory, Cambridge University [23,24]. There was a strong interaction between these two organizations (electronically and face-to-face), which sometimes included heated discussion of apparently contradictory results, as discussed subsequently.

Stall sensing experiments were carried out on low speed single-stage and three-stage compressors, and a schematic of the latter is given in Fig. 5 [25]. The control scheme was a row of individually controlled inlet guide vanes upstream of the compressor. The required bandwidth (say up to two times the rotor rotation rate) could be achieved using off-the-shelf high bandwidth electric motors. As with surge, the control scheme was chosen to enable focus on demonstration of an actively controlled compressor rather than necessitating extensive development of actuator technology.

The results of stall control experiments on a three-stage compressor are given in Fig. 6, which shows the amplitude of the first Fourier mode of the propagating axial velocity disturbance versus time, expressed in terms of rotor revolutions, the natural time scale of the problem. Wave phase measurements, not shown here, indicate a disturbance phase speed approximately 30% of rotor rotation. Measurements such as this confirmed the existence of the small amplitude propagating perturbations. The figure also shows the theoretical results; in spite of the approximate nature, the theory gives a useful description of the transient behavior. Small amplitude waves are seen for tens of rotor revolutions; the transition from conditions when the perturbations are small to near-final amplitude occurs over a shorter time (several rotor revolutions). At the final amplitude, the nonuniformities in axial velocity are larger than the time-mean value.

Figure 7 shows the open-loop response for a single-stage compressor, i.e., the transfer function from inlet guide vane angle perturbation to compressor inlet axial velocity perturbation for the first spatial harmonic of the disturbance. The upper plot is the amplitude and the lower plot is the phase, plotted against frequency of disturbance normalized by rotor frequency. The resonant peak near 20% of rotor speed corresponds closely to the rotating stall propagation speed. As the compressor is throttled to stall, the peak height increases as the system damping increases in accord with the theoretical concepts. The behavior is well described by a second order fit, also in agreement with the theory. The experiments thus gave confidence that the association of rotating stall with the growth of the eigenmodes in the compressor annulus was well founded and that control approaches based on this idea would be worth pursuing.

Closed-loop control results are given in Fig. 8 for the low speed single-stage compressor. Control of the first mode alone yielded an 11% increase in range, control of the first and second modes yielded a 20% increase, and control of the three modes together gave a 25% percent range increase.

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 Gysling [26,27] with an array of reed valves controlling the injection of high pressure air in front of the compressor. An increase of 10% in stable flow range was obtained. Gysling [26] also provided a unifying view of structural and active control of rotating stall through the examination of the energetics 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 controlled. This work gave a framework in which to view all linear control schemes examined up to then.

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[9] In terms of the variables shown in Fig. 2, this means operation in a regime in which $d\psi/d\phi$ is positive.

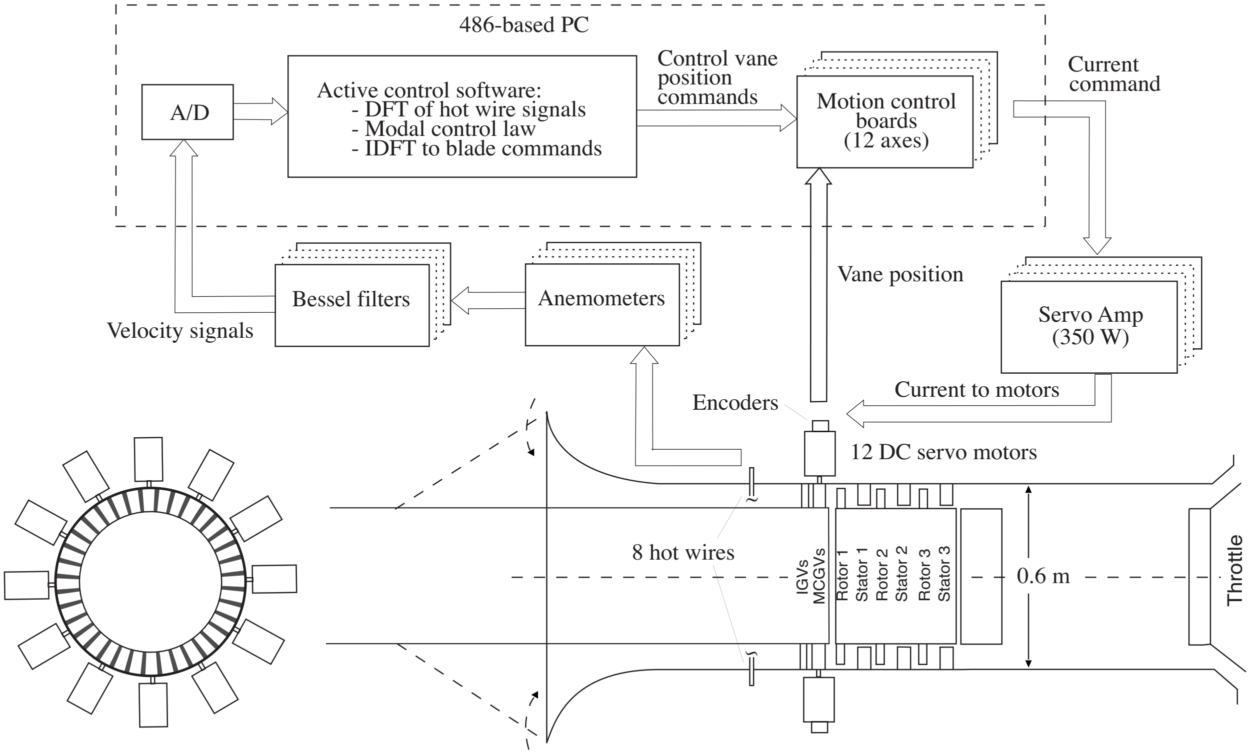

Fig. 5 Closed-loop control feedback path for three-stage compressor [25]

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 Day [28] 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

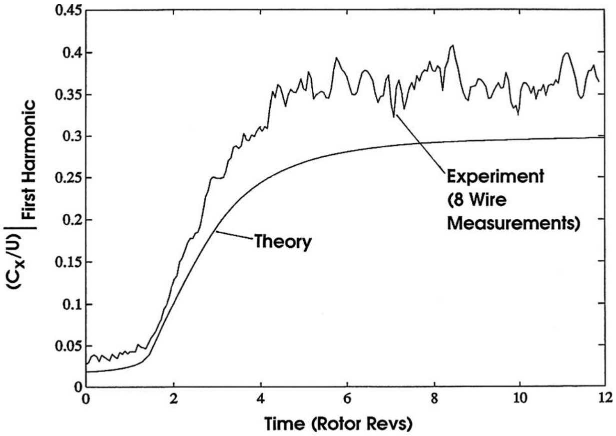

Fig. 6 Time evolution of first harmonic of the axial velocity in a three-stage compressor during rotating stall inception [24]

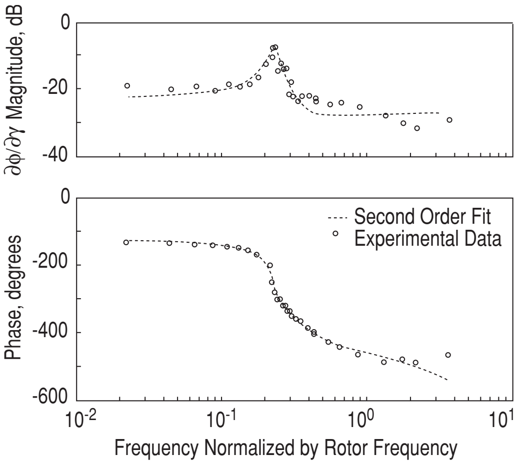

Fig. 7 Bode plot showing single-stage compressor response to a sine wave forcing excitation at ϕ=0.475 [16]

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[10] Phrase due to Dr. D. C. Wisler.

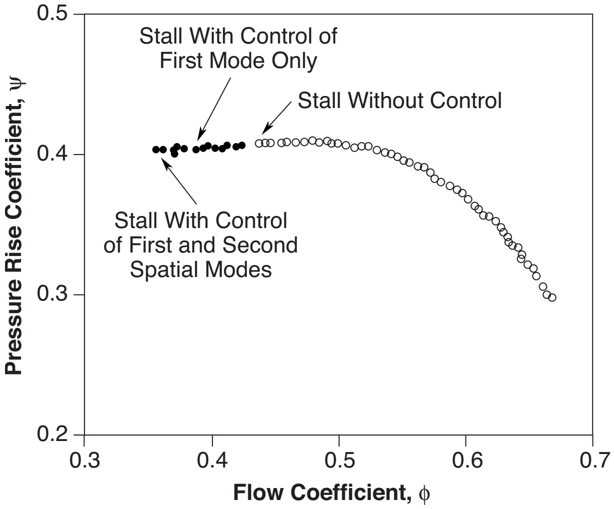

Fig. 8 Single-stage compressor characteristic with active control of first and second spatial modes [14]

growth to the mature form of the disturbance from first sensing of these "spikes"[11] 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 [29], 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[12] 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.

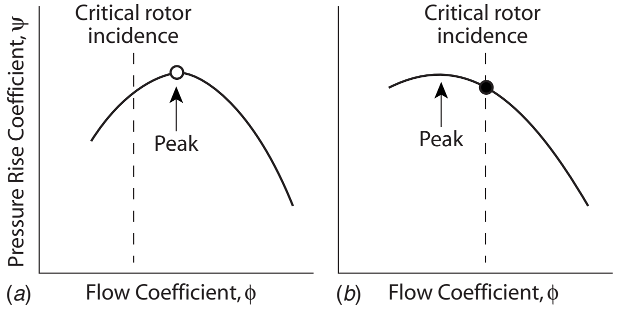

Fig. 10 Hypothesis for spike versus modal behavior as a route to rotating stall [29]; (*a*) modal stall inception, and (*b*) spike stall inception

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. [30] 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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[11] The 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.

[12] The value of the critical incidence depends on the compressor parameters; it is not the same for all compressors.

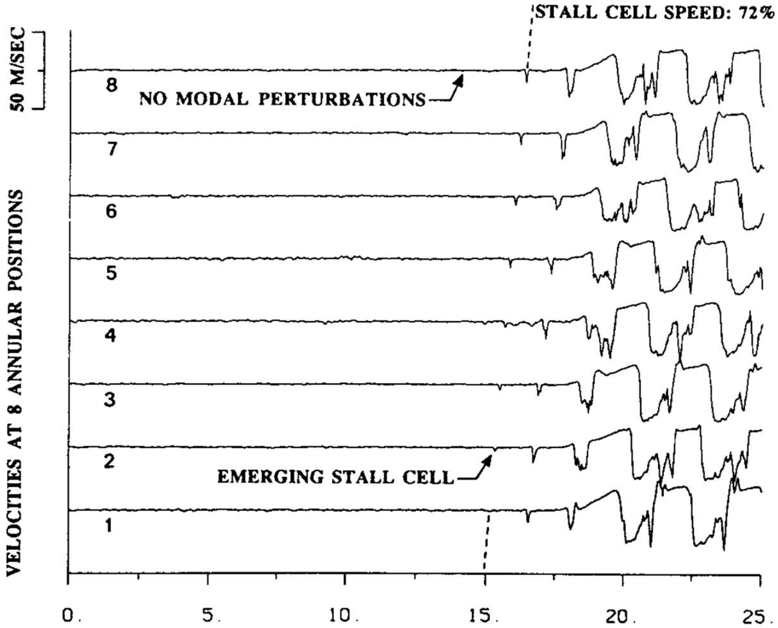

Fig. 9 Rotating stall onset preceded by "spikes;" hot wire measurements at eight circumferential positions upstream of a four-stage compressor [28]

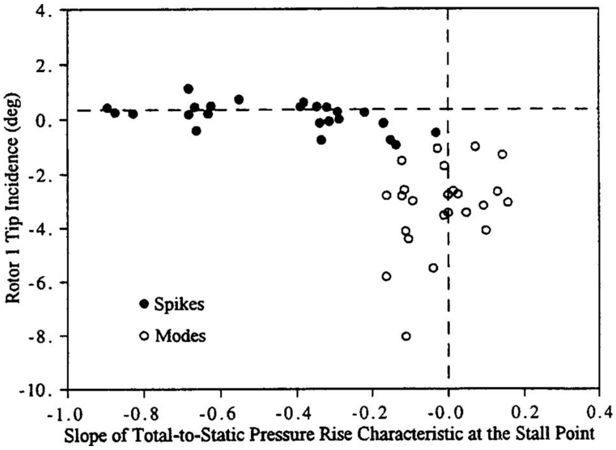

Fig. 11 Compressor stall inception results showing spike and modal behavior [29]

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.[13] 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 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-

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[13] This is a concept whose importance is noted at the CEO level in major corporations: "We did have to kill not-invented-here. We have to make 'reapplied with pride' just as important a part of the culture as 'invented here' " [32].

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.

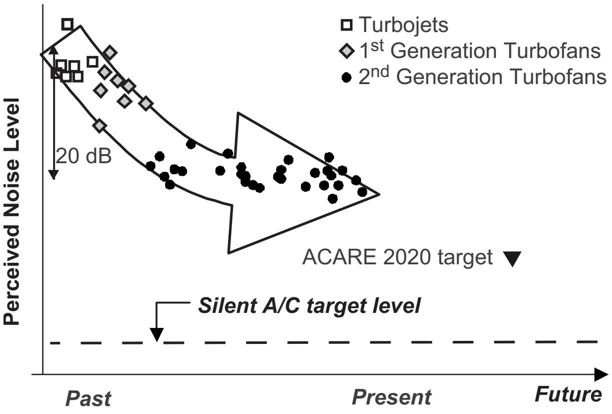

Fig. 12 Progress in noise reduction [45]

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 aircrafts 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

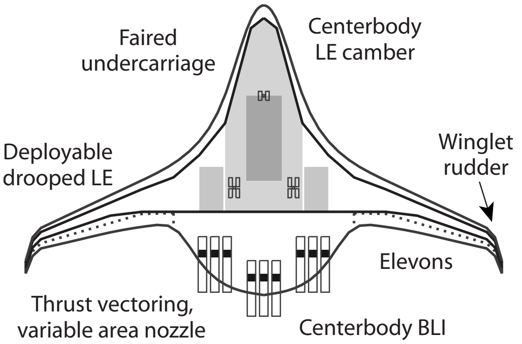

Fig. 13 SAI conceptual design: major features of SAX-40 [44]

work together.[14] 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 compressed time frame (three years) and which was seen from the start as an enterprise with different efforts in parallel, it is more appropriate to describe the overall project from the perspective of 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) [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 depth at a public dissemination meeting and in a special session at the 2007 AIAA Aerospace Sciences Meeting [44–50]. Only a summary of the performance and underpinning technology is therefore given.

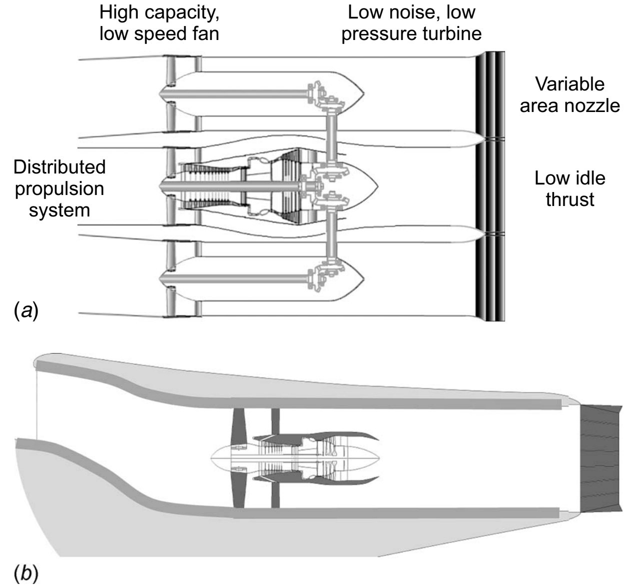

Fig. 14 Propulsion system for the SAX-40 design [47]; (*a*) top view of gas generator and two gear-driven fans for each inlet cluster, and (*b*) side view of engines in duct

For the concept aircraft, the community noise levels are estimated not to exceed 63 dBA for typical missions, comparable to the background noise in urban daytime environments. As described by Hileman et al. [44] 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].[15]

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.[16] 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

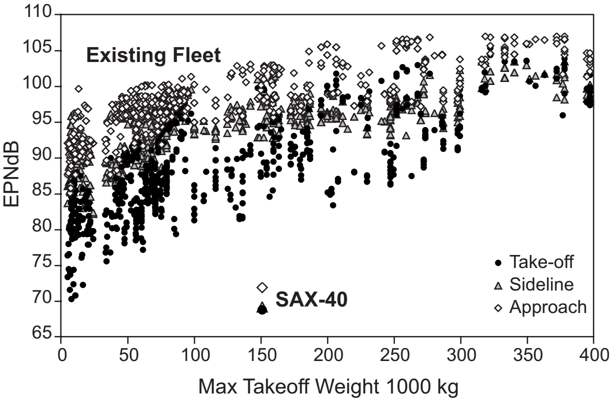

Fig. 15 Effective perceived noise level (EPNL) for existing fleet and (estimated) for SAX-40 [44]

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[14] 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.

[15] Tone corrections were neglected because tonal noise could not be computed for the airframe noise sources.

[16] For reference, the Toyota Prius hybrid car carrying two passengers is reported as having a fuel burn of 120 passenger-miles/gal [44].

	Passenger Miles per gallon	ML/D
SAX-40	~124	20.1
Toyota Prius hybrid car	~120 w/ 2 people	---
Boeing 777	86 - 101	15.5
Boeing 707	46 - 58	13.5

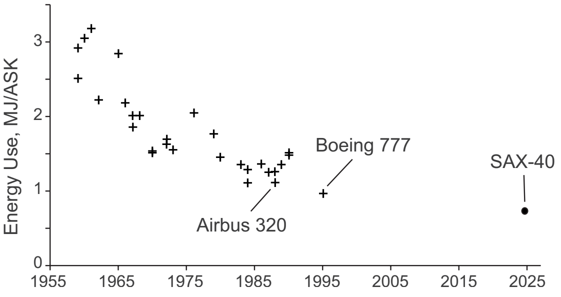

Fig. 16 Estimated fuel burn for SAX-40 [44]

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 decreased 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 airframe 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."

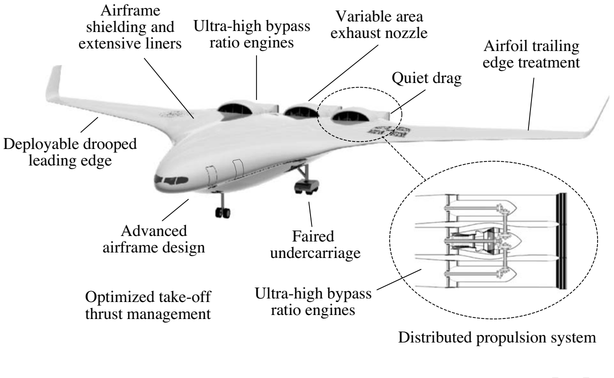

Fig. 17 Enabling technologies for noise reduction [46]

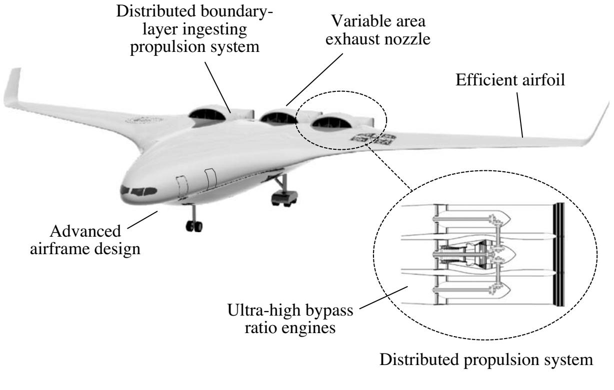

Fig. 18 Enabling technologies for decreased fuel burn [46]

- *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.
- *Faired 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. Deployment 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 combination of elevons and thrust vectoring can increase the induced drag to the required level, while trimming the aircraft.
- *Embedded, aircraft boundary layer ingesting, distributed propulsion system*. Boundary layer ingestion allows a potential 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 nonuniform flow into the engine (distortion), which must be addressed 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 decreased. 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 reduces the rearward fan noise and the airframe drag requirements.
- *Airframe shielding of engine noise*. Placing the engines above the airframe prevents engine noise from reaching the observer. Engine forward noise sources are virtually eradicated on the ground.
- *Optimized extensive liners*. The embedded propulsion system allows smaller engine diameter and thus increases nondimensional (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 reduction 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 $\mathrm{SPL} \propto ((\mathrm{velocity})^n/(\mathrm{distance})^2)$, 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).

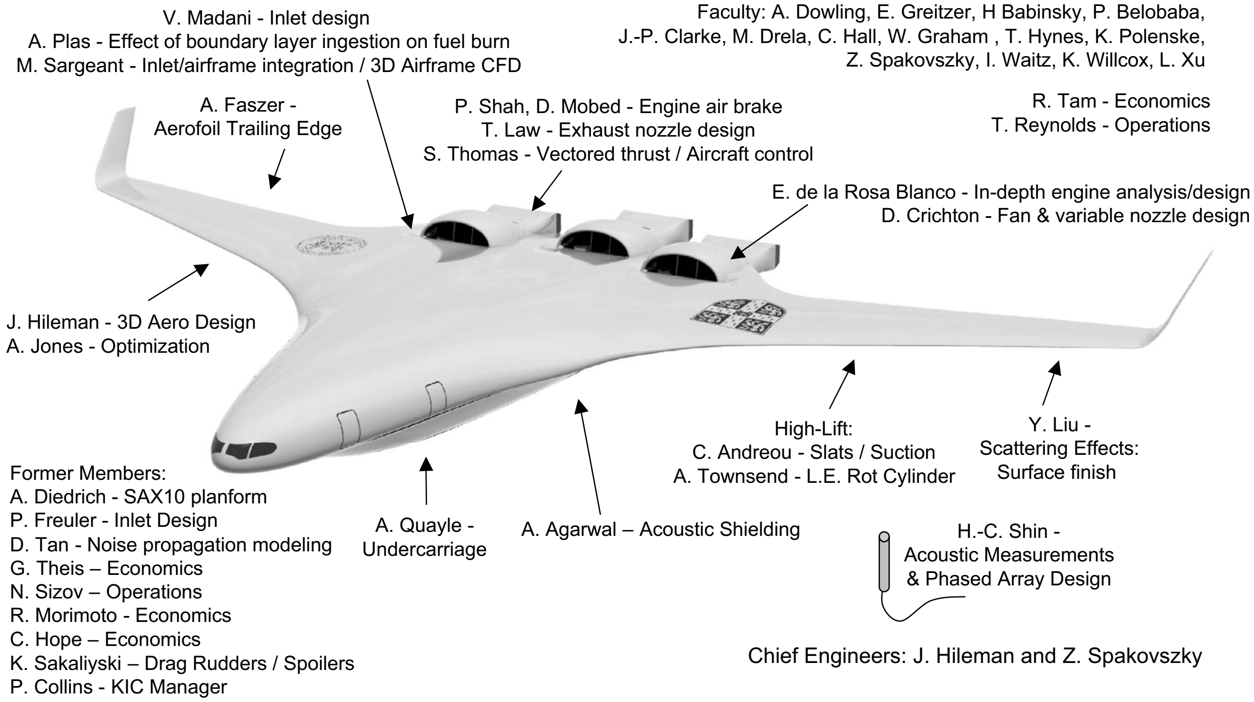

Fig. 19 Cambridge/MIT silent aircraft team

10 The SAI Collaborative Process

10.1 University-Industry-Government Interaction. A range of skills and interests beyond those of the two universities were needed to address the above technologies and the collaboration included regulators, airport operators, airlines, aerospace manufacturers, and representatives of community groups. Our observation in this regard is that SAI has been an instructive and useful experiment in academic-industry interactions on several levels, from strategic planning and decisions (input from the KIC members 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 much 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 mission, and academic researchers were able to use Rolls-Royce design, 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 integrated 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 faculty 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 responsibility 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 advisor and student as to what the expected intellectual contribution for the thesis would be and how it was consistent with participation 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 embedded?” 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) building 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 assessed 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, government, and academia and provided an exciting way to address problems with a large reach and a potential for step-change improvements. 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, collaboration 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 representatives of a more general application, and it is useful to now place the ideas in a broader context. This will be done along two different 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 IGTI 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, technology 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 Timoshenko 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 all 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 science 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 outside 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 Organizing 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 IGTI and the interests of its members. For gas turbine engine manufacturers 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 multicompany. This is a part of the business we are in.

Participants in IGTI conferences have also seen the emphasis on teaming and collaboration in major presentations at the meetings. 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 important 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 targeting of strategic needs relating to different technologies and the formation of long-term relationships with universities having expertise in those areas.

A different sort of successful joint project was highlighted in a previous IGTI 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 organization, 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 differences in research questions, specific objectives, organizations, and team members, but an attribute in all was that the resulting enterprise 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 collaboration to attack them will be more and more a key part of the professional activity of IGTI 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 development 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 members 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 intellectual, technical, and organizational issues inherent in research, 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 organization
- a realization that although collaboration can have its own overhead there can be a major return on the investment

Acknowledgment

The smart engines work and the SAI research and design information are the results of contributions from a number of individuals, many of whom are listed in the authorship of the cited papers. It has been a pleasure to work with the students on these projects. In addition I would like to mention my gratitude to (in alphabetical order of organization) J. D. Paduano (Aurora Flight Sciences); R. H. Liebeck (Boeing Phantom Works), F. E. Marble (Caltech), I. J. Day, A. P. Dowling (the Cambridge lead for SAI), J. E. Ffowcs Williams, C. A. Hall, T. P. Hynes, and J. P. Longley (Cambridge University), D. L. Gysling (Cidra); D. C. Wisler (GE Aircraft Engines); N. A. Cumpsty (Imperial College); A. H. Epstein, J. I. Hileman, Z. S. Spakovszky, C. S. Tan, I. A. Waitz (MIT); A. J. Strazisar (NASA Glenn Research Center); G. J. Hendricks (Pratt & Whitney). I also thank J. J. Adamczyk and R. J. Shaw (NASA), M. G. Dunn (OSU), and reviewers, for useful comments and D. I. Park for superb help in preparing the manuscript.

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References

[1] Hawthorne, W. R., 1957, "Some Aerodynamic Problems of Aircraft Engines," J. Aeronaut. Sci., **24**, pp. 713–730.

[2] Koff, B. L., 2004, "Gas Turbine Technology Evolution: A Designer's Perspective," J. Propul. Power, **20**, pp. 577–595.

[3] Cumpsty, N. A., and Greitzer, E. M., 2004, "Ideas and Methods of Turbomachinery Aerodynamics: A Historical View," J. Propul. Power, **20**, pp. 15–26.

[4] Bridgeman, P. W., 1961, *The Nature of Thermodynamics*, Harper, New York.

[5] Armstrong, J. A., 1994, "Is Basic Research a Luxury Our Society Can No Longer Afford," The Bridge, **24**(2), pp. 9–16.

[6] Epstein, A. H., 1986, "Smart Engine Components: A Micro in Every Blade?" Aerosp. Am., **24**(1), pp. 60–64.

[7] Ffowcs Williams, J. E., 1984, "Review Lecture: Anti-Sound," Proc. R. Soc. London, **395**, pp. 63–88.

[8] Epstein, A. H., Ffowcs Williams, J. E., and Greitzer, E. M., 1989, "Active Suppression of Aerodynamic Instabilities in Turbomachines," J. Propul. Power, **5**(2), pp. 204–211.

[9] Katzenback, J. R., and Smith, D. K., 1993, "The Discipline of Teams," *Harvard Business Review Reprint Collection, Harvard Business Review's Ten Most Requested*, Product No. 49512, pp. 13–25.

[10] Emmons, H. W., Pearson, C. E., and Grant, H. P., 1955, "Compressor Surge and Stall Propagation," Trans. ASME, **77**, pp. 455–469.

[11] Greitzer, E. M., 1981, "The Stability of Pumping Systems—The 1980 Freeman Scholar Lecture," ASME J. Fluids Eng., **103**, pp. 193–242.

[12] Hansen, K. E., Jorgensen, P., and Larsen, P. S., 1981, "Experimental and Theoretical Study of Surge in a Small Centrifugal Compressor," ASME J. Fluids Eng., **103**, pp. 391–395.

[13] Pinsley, J. E., Guenette, G. R., Epstein, A. H., and Greitzer, E. M., 1991, "Active Stabilization of Centrifugal Compressor Surge," ASME J. Turbomach., **113**, pp. 723–732.

[14] Paduano, J. D., Epstein, A. H., Valavani, L., Longley, J. P., Greitzer, E. M., and Guenette, G. R., 1993, "Active Control of Rotating Stall in a Low-Speed Axial Compressor," ASME J. Turbomach., **115**, pp. 48–56.

[15] Greitzer, E. M., 1998, "Smart Jet Engines: Case History of a Multidisciplinary Research Program," JSME Int. J., Ser. B, **41**(1), pp. 90–102.

[16] Paduano, J. D., Greitzer, E. M., and Epstein, A. H., 2001, "Compression System Stability and Active Control," Annu. Rev. Fluid Mech., **33**, pp. 491–517.

[17] Greitzer, E. M., Tan, C. S., and Graf, M. B., 2004, *Internal Flows: Concepts and Applications*, Cambridge University Press, Cambridge.

[18] Gysling, D. L., Dugundji, J., Greitzer, E. M., and Epstein, A. H., 1991, "Dynamic Control of Centrifugal Compressor Surge Using Tailored Structures," ASME J. Turbomach., **113**, pp. 710–722.

[19] Paduano, J. D., Greitzer, E. M., Epstein, A. H., Guenette, G. R., Gysling, D. L., Haynes, J., Hendricks, G. J., Simon, J. S., and Valavani, L., 1993, "Smart Engines: Concept and Application," Integr. Comput. Aided Eng., **1**, pp. 3–28.

[20] Cumpsty, N. A., 2004, *Compressor Aerodynamics*, Kreiger Publishers, New York.

[21] Moore, F. K., and Greitzer, E. M., 1986, "A Theory of Post Stall Transients in Axial Compressors: Part I—Development of the Equations," ASME J. Eng. Gas Turbines Power, **108**, pp. 68–76.

[22] Greitzer, E. M., and Moore, F. K., 1986, "A Theory of Post Stall Transients in Axial Compression Systems: Part II—Application," ASME J. Eng. Gas Turbines Power, **108**, pp. 231–239.

[23] McDougall, N. M., Cumpsty, N. A., and Hynes, T. P., 1990, "Stall Inception in Axial Compressors," ASME J. Turbomach., **112**, pp. 116–125.

[24] Garnier, V. H., Epstein, A. H., and Greitzer, E. M., 1991, "Rotating Waves as a Stall Inception Indication in Axial Compressors," ASME J. Turbomach., **113**, pp. 290–301.

[25] Haynes, J. M., Hendricks, G. J., and Epstein, A. H., 1994, "Active Stabilization of Rotating Stall in a Three-State Axial Compressor," ASME J. Turbomach., **116**, pp. 226–239.

[26] Gysling, D. L., 1993, "Dynamic Control of Rotating Stall in Axial Compressors Using Aeromechanical Feedback," MIT Gas Turbine Laboratory Report No. 219.

[27] Gysling, D. L., and Greitzer, E. M., 1995, "Dynamic Control of Rotating Stall in Axial Flow Compressors Using Aeromechanical Feedback," ASME J. Turbomach., **117**, pp. 307–319.

[28] Day, I. J., 1993, "Stall Inception in Axial Flow Compressors," ASME J. Turbomach., **115**, pp. 1–9.

[29] Camp, T., and Day, I. J., 1998, "A Study of Spikes and Modal Stall Phenomena in a Low-Speed Axial Compressor," ASME J. Turbomach., **120**, pp. 393–401.

[30] Gong, Y., Tan, C. S., Gordon, K. A., and Greitzer, E. M., 1999, "A Computational Model for Short Wavelength Stall Inception and Development in Multistage Compressors," ASME J. Turbomach., **121**, pp. 726–734.

[31] Vo, H. D., Tan, C. S., Greitzer, E. M., 2005, "Criteria for Spike Initiated Rotating Stall," ASME Paper No. GT2005-68374.

[32] Colvin, G., 2006, "An Interview with P&G and GE CEOs Lafley and Immelt," *FORTUNE*, C-Suite Strategies website, November 27.

[33] van Schalkwyk, C. M., Paduano, J. D., Greitzer, E. M., and Epstein, A. H., 1997, "Active Stabilization of Axial Compressors with Circumferential Inlet Distortion," ASME J. Turbomach., **120**, pp. 431–439.

[34] Longley, J. P., Shin, H.-W., Plumley, R. E., Silkowski, P. D., Day, I. J., Greitzer, E. M., Tan, C. S., and Wisler, D. C., 1996, "Effects of Rotating Inlet Distortion on Multistage Compressor Stability," ASME J. Turbomach., **118**, pp. 181–188.

[35] Kozarev, L. A., and Federov, R. M., 1983, "Aspects of the Appearance and Elimination of Breakdown in an Axial-Flow Compressor in the Presence of a Rotating Non-Uniformity at the Inlet," Izevstiya VUZ Avioatsionnaya Teknhika (IzAvT), **26**(1), pp. 33–37.

[36] Tryfonidis, M., Etchevers, O., Paduano, J. D., Epstein, A. H., and Hendricks, G. J., 1995, "Pre-Stall Behavior of Several High-Speed Compressors," ASME J. Turbomach., **117**, pp. 62–80.

[37] Feulner, M. R., Hendricks, G. J., and Paduano, J. D., 1994, "Modeling for Control of Rotating Stall in High Speed Multi-Stage Axial Compressors," ASME Paper No. 94-GT-200.

[38] Weigl, H. J., Paduano, J. D., Frechette, L. G., Epstein, A. H., Greitzer, E. M., Bright, M. M., and Strazisar, T. J., 1998, "Active Stabilization of Rotating Stall and Surge in a Transonic Single Stage Axial Compressor," ASME J. Turbomach., **120**, pp. 625–636.

[39] Spakovszky, Z. S., Weigl, H. J., Paduano, J. D., van Schalkwyk, C. M., Suder, K. L., and Bright, M. M., 1999, "Rotating Stall Control in a High-Speed Stage With Inlet Distortion I: Radial Distortion, and II: Circumferential Distortion," ASME J. Turbomach., **121**, pp. 510–524.

[40] Christensen, D., Catlin, P., Gutz, D., Szucs, P. N., Wadia, A. R., Armor, J., Dhingra, M., Neumeier, Y., and Prasad, J. V. R., 2006, "Development and Demonstration of a Stability Management System for Gas Turbine Engines," ASME Paper No. GT-2006-90324.

[41] Green, J. E., 2006, "Civil Aviation and the Environment: The Next Frontier for the Aerodynamicist," Aeronaut. J., **110**, pp. 469–486.

[42] Walker, R. S., Aldrin, B., Bolen, E. M., Buffenbarger, R. T., Douglass, J. W., Fowler, T. K., Peters, F. W., Hamre, J. J., Schneider, W., Stevens, R. J., Tyson, N. deG., and Wood, H. R., 2002, Final Report of the Commission on the Future of the United States Aerospace Industry.

[43] Greener by Design Science and Technology Sub-Group, 2005, *Air Travel: Greener by Design, Mitigating the Environmental Impact of Aviation: Opportunities and Priorities*, Royal Aeronautical Society, London.

[44] Hileman, J., Spakovszky, Z., Drela, M., and Sargeant, M., 2007, "Airframe Design for 'Silent Aircraft'," AIAA Paper No. AIAA-2007-0453.

[45] Crichton, D., and Hileman, J., 2007, "Design and Operation for Ultra Low Noise Take-Off," AIAA Paper No. AIAA-2007-0456.

[46] Dowling, A., and Greitzer, E., 2007, "The Silent Aircraft Initiative—Overview," AIAA Paper No. AIAA-2007-0452.

[47] de la Rosa Blanco, E., and Hall, C., 2007, "Challenges in the Silent Aircraft Engine Design," AIAA Paper No. AIAA-2007-0454.

[48] Plas, A., Madani, V., Sargeant, M., Crichton, D., Greitzer, E., Hall, C., and Hynes, T., 2007, "Performance of a Boundary Layer Ingesting (BLI) Propulsion System," AIAA Paper No. AIAA-2007-0450.

[49] Hileman, J., Spakovszky, Z., and Reynolds, T., 2007, "Airframe Design for 'Silent Aircraft'," AIAA Paper No. AIAA-2007-0451.

[50] Tam, R., Belobaba, P., Polenske, K., and Waitz, I., 2007, "Assessment of Silent Aircraft-Enabled Regional Development and Airline Economics in the UK," AIAA Paper No. AIAA-2007-0455.

[51] Lee, J. J., Lukachko, S. P., Waitz, I. A., and Schafer, A., 2001, "Historical and Future Trends in Aircraft Performance, Cost and Emissions," Annu. Rev. Energy Environ., **26**, pp. 167–200.

[52] Herr, M., and Dobrzynski, W., 2005, "Experimental Investigations in Low-Noise Trailing-Edge Design," AIAA J., **43**, pp. 1167–1175.

[53] Smith, L. H., 1993, "Wake Ingestion Propulsion Benefit," J. Propul. Power, **9**, pp. 74–82.

[54] Reynolds, T. G., Ren, L., and Clarke, J.-P. B., 2007, "Advanced Noise Abatement Approach Activities at Nottingham East Midlands Airport, UK," Seventh USA/Europe Air Traffic Management R&D Seminar (ATM 2007), Barcelona, Spain.

[55] Broers, A. N., 2005, *The Triumph of Technology*, Cambridge University Press, Cambridge.

[56] Chesbrough, H. W., 2003, *Open Innovation*, Harvard Business School Press, Boston.

[57] Friedman, T. L., 2005, *The World is Flat: A Brief History of the Twenty-First Century*, Farrar, Strauss, and Giroux, New York.

[58] Dunn, M. G., 2001, "Convective Heat Transfer and Aerodynamics in Axial Flow Turbines," ASME J. Turbomach., **123**, pp. 637–686.