Actuator Applications and Roadmaps

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ABSTRACT

The issues and considerations, which must be made in the choice of any actuator for a specific application, are reviewed. This is followed by an assessment of available actuators and their application to specific components. The chapter is completed with a table of the applications, actuator specifications, time to maturity, and expected challenges.

1. INTRODUCTION

The first actuator lecture has dealt with generic technologies and applications. The nature of actuator applications also requires application-specific developments, which are addressed in this lecture.

2. APPLICATION SPECIFIC DEVELOPMENT REQUIREMENTS

The specific requirements for specific engine components are summarized in Table 1. Each component is discussed in the following.

	Technology	**Controlled Variable**	**Environ ment**	**Special Requirements**
Inlet	Control of inlet shock position	Inlet geometry		
Inlet	Inlet distortion control	Vortex generator geometry, jet, suction		Pulsed micro jets
Inlet	Active noise control	Honeycomb geometry, acoustic waves		
Compressor	Active stall / Surge Control	jet, guide vane movement, bleed air	200°C	Fast actuation < 4ms, pulsed jets

Compressor	Active Flow Control	Jet, suction, airfoil geometry	-50 - 600°C	Fluidic actuation devices at different frequencies: a)200-300Hz, b)5-20kHz, c)50-100kHz Shape memory alloys for airfoil shape variation, Installation in airfoil, robust design required
Compressor	Active Clearance Control	Casing geometry	up to 700°C	Thermal, mechanical, pneumatic devices Actuation > 0.1mm/ms
Compressor	Active Vibration Control	Airfoil geometry	300-650°C	pressure > 3000 N/cm² deformation > 0.5mm installation in airfoil
Combustor	Combustion instability control	Fuel modulation, acoustic energy, jets, moving surface	~ 1400 ºC	high-band width actuation, typically in the l00Hz to 500Hz frequency range.
Turbine	Active Clearance Control	Casing geometry	~ 700 ºC	Thermal, mechanical, pneumatic devices Actuation > 0.1mm/s Force 10kN Stroke 3mm Accuracy 0.02 mm
Nozzle	Active noise control	Nozzle geometry, jets		Shape memory alloys

Table 1: Application / Actuator Requirements

2.1. Inlet

2.1.1. Inlet Geometry

Variable inlet geometry has been accepted as essential for supersonic aircraft for many years and very capable systems developed. These are invariably hydraulically actuated. It is tempting to promote alternative methods of actuation, although none of the advanced technologies covered earlier seem to be capable of the high speed, high displacement actuation to provide a direct replacement. An alternative approach was used in the US research programme SAMPSON [1]. Boeing achieved a full size wind tunnel demonstration of an SMA actuated F15 intake with variable upper ramp and smooth shape changing lower lip. The prime limitations were however the low temperature SMAs leading to a slow cooling and hence retraction time and the availability of the SMA in wire form only, which necessitated an over complex, chain driven mechanism (Figure 1).

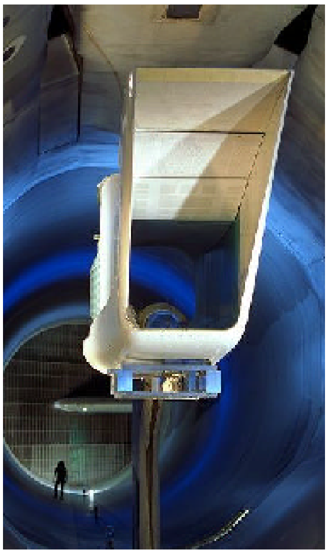

Figure 1: Boeing / SAMPSON Programme SMA Actuated Intake

The programme also demonstrated a more ambitious compliant throat mechanism, replacing the rigid ramps with a flexible membrane and appropriate control mechanisms. This advanced thinking can be expected to give greater benefits, but also presents larger risks and development time.

Subsonic intakes can potentially use much slower actuation mechanisms for gross movement. A particular limiting factor being the need to accommodate cross winds and other off-axis flows, again, SMAs are a prime candidate, although simpler mechanisms such as air pressurised bladders may also be appropriate.

2.1.2. Inlet Distortion Control

The gross movements in the inlet will have a major impact on inlet distortion, but smaller scale actuation has also been demonstrated as significant. Boundary layer or shock wave manipulation in various forms has been investigated, but is still some way from a thorough understanding or practicality. The prime requirement is to provide a clean airflow to the fan whilst minimising the nacelle drag. In particular, the compromise between tolerance to cross wind and maintaining a thin nacelle is particularly important on transport aircraft with ever increasing fan size. Similar requirements have also been identified to maintain a clean flow in S shaped ducts. The AEROMEMS programme [2] built on many years of international work and demonstrated the capability for boundary layer manipulation by modulated microjets and synthetic jets on aircraft wings and engine intakes. Other programmes [3] have identified alternative strategies and operational frequency ranges which have been picked up by programmes such as ADVACT [4]. Alternative methods such as moveable vortex generators and shock control bumps have also been investigated in several programmes.

It is clear that the fundamental fluid mechanics is not yet sufficiently understood to provide a definitive specification for actuators. The first priority should be in understanding the requirements. Despite this, many programmes have investigated actuator mechanisms to provide jets or small scale geometry changes, a few have been aimed at gas turbine applications. Emphasis should be placed on understanding the airflow characteristics, actuator specifications and moving towards full scale demonstration.

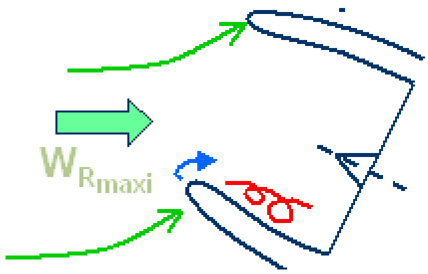

Figure 2: Intake Separation at High Incidence with Thin Intake Lip

2.1.3. Inlet Noise Control

Three main regions for inlet noise control have been investigated; these are the overall geometry, adaptive surface noise treatments and active noise cancellation systems. The gross methods discussed in 0 could be applied for noise reduction, but do not seem to have been investigated. It is considered unlikely that the additional complexity and weight could be justified to achieve this. Adaptive surfaces to provide optimised acoustic honeycomb by changes in acoustic impedance and resonance have been successfully demonstrated within the Silencer programme [5]. Provided these can be ruggedized and made suitable for routine use, this appears to be the most productive approach. Fully active noise cancellation systems have also been demonstrated, but again are likely to be heavy, complex and potentially expensive, making them less attractive.

2.2. Compressor

2.2.1. Compressor Active Surge Control

Active surge control has been an on-going goal for many years. The exact configuration, approach and response requirements have still to be defined, as have the conditions which must be accommodated. These range from very early detection of stall which can be identified as a pre-cursor to stall, to alleviation of the onset of a major surge. The initiation of stall is a much less aggressive phenomenon and can be controlled by a much lower authority actuator than early surge. The simplest form can be blade tip/ casing boundary layer control systems which are scheduled to be activated when stall is likely to occur, through relatively slow (< 1 sec) bleed forward systems relying on advanced detection techniques, to major, high speed (< 40ms) bleed forward systems controlling large airflows. With some systems likely to need many millions of actuation cycles, actuator lifetime is a major limiting factor with current actuators.

With the high importance of this subject, a large scale collation of available techniques and data should be carried out as soon as possible and a coherent plan produced.

2.2.2. Compressor Active Flow Control

Flow control is required in a compressor to accommodate the wide range of conditions which are encountered across the full operational envelope. Considerable design compromise is required even with the current practice of using variable vanes and bleed valves. These compromises significantly reduce the design performance, although the exact extent of lost efficiency is not widely reported. Active techniques are frequently identified as a very productive way forward.

The current mechanical systems of hydraulics, unison ring and levers are well established, but are also recognised as a source of reliability and cost issues. Alternative mechanical systems such as SMAs, piezo and distributed hydraulic systems have all been investigated, but none seem to have moved towards practical demonstration.

Airflow manipulation techniques such as boundary layer sucking and blowing have been known for many years. More recently, modulated blowing techniques have been raised as a more efficient possibility. It is clear that the aerodynamic requirements to achieve control are still not understood and must be clarified before larger scale demonstration can be achieved. The actuators themselves are also very immature, although several programmes have investigated MEMS devices providing appropriate characteristics. The preliminary specifications which are currently available should be sufficient to allow actuator development to continue in parallel with expansion of the airflow understanding.

2.2.3. Compressor Active Clearance Control

Considerable effort has been expended on turbine blade tip clearance control, with many concepts being developed, as exhibited by the number of patent applications made. In comparison, compressor tip clearance control has attracted very little attention. Although lower overall improvements are expected from compressors, the demands on any actuation system is far less demanding. In particular, the peak temperatures are in the order of 6500C in the higher pressure ratio engines and pressure differences across the stages are also reduced. Many of the techniques raised for turbines should be applicable to compressors, but must be achieved at lower cost and weight to reflect the lower returns achievable within the compressor. Recent developments of electromagnetic and piezoelectric actuators are bringing them into the temperature range of compressors and should be vigorously pursued. The mechanisms required to achieve smooth and efficient movement without introducing other loss factors such as leakage, steps and gaps may however prove to be a bigger challenge than the actuators themselves and must also be pursued.

2.2.4. Compressor Active Vibration Control

At the design stage, vibration alleviation of all aerodynamic components, particularly fans continues to require considerable design compromise. When this is further compromised by the requirement to accommodate changes due to FOD, improvements in blade and vane damping control offers the potential to provide significant performance improvements.

Investigations of passive blade and vane damping have been successful at the laboratory and rig stage, but few have yet to find their way into service. Active techniques using piezo patches have been developed for airframe applications such as the F18 tail fin, but are not known for engine applications.

Whilst significant benefits might be achievable, the emphasis previously placed on vibration control seems to be very low. The benefits and costs of any potential system should be fully evaluated before significant developments are initiated.

2.3. Combustor Instability Control

Recent developments towards lean burn methods for civil engines have shown considerable benefits, but have also exacerbated combustion noise issues which cause issues for community noise and potential fatigue of other components. Similar issues might be expected within military engines. Active instability controls have been achieved in experimental engines, but the attributes of high authority, high freq and long life have been difficult to achieve. Numerous actuation techniques are available, although temperature may be an issue dependent upon their mounting position.

2.4. Turbine Active Clearance Control

As discussed previously, much effort has previously been expended in the pursuit of effective tip clearance controls. The leading technique is currently casing temperature control to shrink it towards the blades. This is a significant improvement over previous uncontrolled methods, but the ultimate goal of independent control at all circumferential points still seems to be a long way off. The prime limiting factor is the temperature. Successful actuator, sensor and seal mechanism development will be essential to achieve the ultimate goal. In the shorter term, less sophisticated techniques such as two stop and uniform circumferential positioning are likely to give significant advantages, but again will need significant developments.

2.5. Nozzle Active Noise Control

Geometrical jet noise reduction measures have been under investigation almost from the start of the jet era. Developments continue with the aim of reducing the jet noise without increasing drag or other inefficiencies. For civil applications, the chevron nozzle on the Rolls-RoyceTrent1000 / Boeing 787 is the latest of a series of developments. Experimental adaptive chevron nozzles using SMAs were flown as part of the Boeing / General Electric programme of the Quiet Technology Demonstrator 2 (QTD2) programme. Investigations of systems suitable for use in service are also under investigation. These systems could potentially be deployed in the relatively near term and should be pursued.

Chevrons are believed to work by interrupting the shear layer between the jet and the free air stream. Longer term options of aerodynamically causing a similar effect are under investigation. Although currently more speculative, these may cause less disturbance when not deployed and could be more attractive.

3. SUMMARY AND CONCLUSIONS

Enhanced actuation has been identified as potentially the most productive area for improving the performance and availability of the gas turbine, although the actual benefits have generally not been fully quantified. The first requirement is to provide an accurate evaluation of this potential and an outline specification for the actuator technology. Many base actuator technologies are available which have some capability towards the currently identified requirements, but in every case, limitations have been identified. The most significant of these is the operating environment which is far more aggressive than the vast majority of industries. Although generic requirements can be identified, developments towards these environmental requirements must be intimately coupled to the specific application requirements in order to satisfy the overall constraints. With the new technologies which will inevitably be introduced, issues which are well established for current technologies such as certification and supply chain will also require considerable developments.

The prime aim should be to move the technologies which have already been demonstrated at a laboratory scale towards practical applications.

Actuator applications to various components together with specifications, candidate technologies, current technology status, time to availability, and the challenges are summarised in Table 7.3. Estimated availabilities range from 2010 (for miniaturized electro-magnetic valves for fuel flow control & large-scale flow switching for compressor stator vanes and pneumatic tip clearance control), to 2013/2018 (for micro-scale flow manipulation depending on operational temperatures) and 2020 (for high temperature shape alloys for turbine tip clearance control).

Generic Actuators Requirements and Roadmap

Actuator variable	Actuator Operation		Notes	Technology	Current TRL	Year to Achieve TRL 6 Goal	Challenge
	Environment	Requirements					
Microscale airflow manipulation	15-105 kPa, -60 - 55 C	Bandwidth and mass flow (1-2% of the core flow)	inlet flow control	Pulsed micro jets	3	2013	Getting adequate mass flow for effective control
				Synthetic jets	3	2013	Getting adequate mass flow for effective control
				Mechanical microflaps	3	2013	Mechanical integrity
	15-105 kPa, -60 - 55 C	15psi differential, < 10kHz	Inlet noise control	pulsed microjets	3	2013	
	15-1800 kPa, -60-800 C	Fast actuation < 4ms, pulsed jets; Bandwidth for all control variables – by W, source form Sanjay	Compressor surge control	Pulsed microjets	3	2015	Adequate mass flow, durability, temperature
	0-800 kPa, -60-150 C	a) 200-300Hz, b) 5-20kHz, c) 50-100kHz; total <.5 % of core flow	Compressor flow control	Pulsed microjets	3	2018	Adequate mass flow, durability, temperature
Large scale flow switching	15-105 kPa, -60 - 55 C	Flow control bandwidth, input from W	Fan stall control	electromagnetic valve	4	2011	
	0-800 kPa, -60-150 C	steady-state, up to 2% of core flow	Compressor stator vane flow control	flow control valve based on electromagnetic/hydraulic/other	4	2010	Weight, reliability
	Up to 1800 kPa, 800 C	1-5 rad/sec bandwidth, 20% modulation of base-line cooling flow	Turbine cooling flow control	flow control valve based on electromagnetic/hydraulic/other	3	2014	temperature
	20-200 kPa, 300 – 500; Hugo to pro-vide with aug-menter	1.5% of core flow per degree of vector angle	Thrust vectoring control	flow control valve based on electromagnetic/hydraulic/other	3	2014	
Fuel flow control	Fuel system pressure, -60-500C	high-band width actua-tion, typically greater than 500Hz to 1000Hz fre-quency range. Fuel flow modulation goal at 1 - 5% of mean flow	Combustion instability control	magneto-strictive	3	2012	wieght, life, flow control control authority, temperature
				electro-magnetic	3	2010	weight, modulation frequency, temperature
	Fuel system pressure, -60-700C	Schedule on emission sensing Fuel flow modulation on each nozzle at 1-5 rad/s	Emission control	magneto-strictive	3	2014	
	Fuel system pressure, -60-700C	Fuel flow modulation on each nozzle at 1-5 rad/s	Pattern Factor Control	electro-magnetic			
Geometry control	15 - 105 kPa, -60 - 55 C	Geometry bandwidth control 15-20 rad/s,					
	15-105 kPa, -60 - 55 C	< 8mm deflection, < 0.5Hz	Inlet noise control	Pressure	4	2012	Durability, level of control
				Piezo electric	3	2012	Complexity, high movement
	0-800 kPa, -60-150 C	< 10Hz, 20 degrees	inlet guide vane for surge control	Electromagnetic	3	2012	Weight, response time, synchronisation
				Piezo electric	3	2012	Low strain, synchronisation
	0-800 kPa, -60-150 C	1-2 Hz	vane geometry/shape	SMA	2	2018	synchronisation, response time,
	15-1800 kPa, -60-700 C	Thermal, mechanical, pneumatic devices; Actuation > 0.1mm/s (1.5 Hz); Force 10kN; Stroke 3mm; Resolution 0.02 mm	Compressor clearance control	Pneumatic	5	2012	Stiffness, control
				Hydraulic	3	2015	seals, complexity, weight
				Piezo electric	3	2015	low strain, temperature
				Electromagnetic	3	2012	weigth, control
	15-1800 kPa, -60-700 C	pressure > 3000 N/cm²; deformation > 0.5mm; installation in airfoil; bandwidth? W	Compressor blade vibaration control	Piezo electric	3	2015	Complexity, control system weight
				SMA re-tuning	3	2015	synchronisation, control, temperature
	Up to 1800 kPa, 700 C	Actuation > 0.1mm/s (1.5 Hz); Force 10kN; Stroke 3mm; Resolution 0.02 mm	Turbine tip clearance control	electro-magnetic	2	2018	Temperature, weight
				pneumatic	5	2010	two stop system only,
				hydraulic	2	2015	Temperature, working fluid, weight, reliability
				High temp shape memory alloys	2	2020	adequate control authority, proportional control, stability

Table 2: Requirements for Specific Applications together with their Generic Specifications, Candidate Technologies, Current Level of Maturity, Time to achieve TRL6 and the Challenges

4. ACKNOWLEDGEMENT

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5. REFERENCES

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