# Generic Actuator Requirements and Actuation Technologies

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***ABSTRACT***

*The three generic gas flow actuation principles in a gas turbine engine, namely flow manipulation, flow switching, and mechanical manipulation, are reviewed. The requirements for these principles associated with the principal gas path engine components are discussed, and current actuator technologies are summarized. Subsequently it is pointed out that a proper technology choice for future actuators requires consideration of the interaction of the actuation with the engine cycle, consideration of the integration into the engine components, and evaluation of actuation on performance benefits and future system requirements, costs, maintenance, failure modes, etc. Finally, new and emerging technologies for future actuator developments are reviewed.*

## 1. INTRODUCTION

Considerable developments have already been made towards all aspects of the more intelligent gas turbines, however actuation is considered to be the most problematical and yet seems to have received the least attention, relative to sensors and control methods. Actuation involves the transduction of relatively large amounts of energy; although the basic methods are understood and available for many functions within a gas turbine, there has previously been little incentive to develop them for gas turbine environments. As a result, actuation within a gas turbine has largely been limited to the five main variables of fuel input, variable guide vanes, bleed valves and variable geometry intakes and nozzles. First generation tip clearance control using casing temperature has also recently been added. The actuators themselves have followed largely conventional lines using hydraulics for high force applications and electromechanical methods for low force applications such as valves etc. Even so, they are also limited to the relatively benign areas, predominantly as a result of temperature considerations. As a general rule, the most productive areas for actuation improvement have been identified as the most challenging environments within the engine such as the high pressure turbine. From Figure 1, which shows the extremes of the environment, it is clear that all but the most robust actuators will be precluded from some areas. Initial applications are likely to be limited to less demanding areas.

The new and emerging actuator technologies offer the potential to provide extended applicability and other requirements such as improved weight, reliability, cost, environmental impact etcetera, but in order to address the requirements identified in the following Section 2, considerable developments will be required. Although this lecture is limited largely to gas path control, considerable enhancements of other areas of the gas turbine will also be possible in the future from these technologies.

## 2. BACKGROUND

Three common requirements can be identified for the entire gas path; these are flow manipulation, large scale flow switching, and mechanical manipulation. Requirements for these three common functions have been identified for each element of the gas path and are discussed later in Section 3. The generic requirements are presented here and summarised in Table 1.

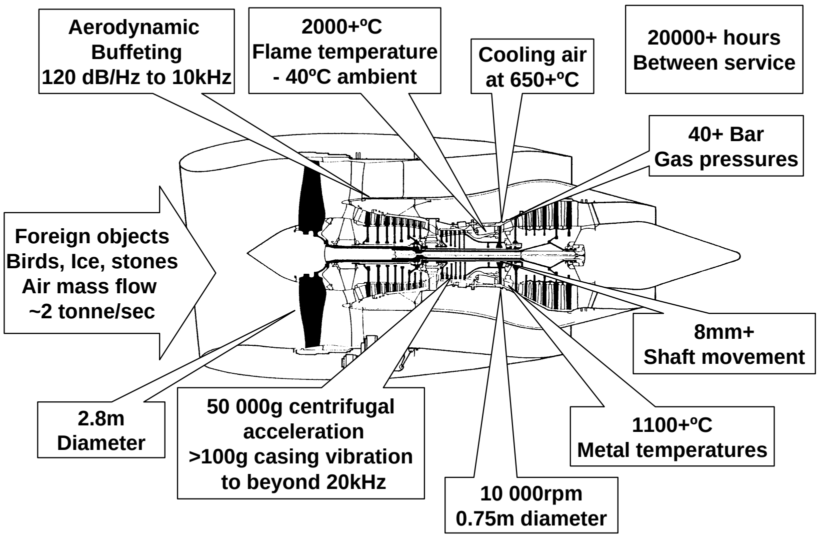


**Figure 1: Environment within a Gas Turbine**

## 2.1. Flow Manipulation

This generally involves manipulation of the boundary layer within the main flow of the engine and can be either mechanical effects such as turbulence inducers, roughened surfaces or shock control bumps etc. or aerodynamic control, which involves blowing or sucking air through the component surface in order to affect the bulk flow, generally via the boundary layer.

Some programmes have investigated flow improvements using passive means and there have been proposals for active systems [1], but the author is not aware of any research for gas turbines.

Continuous blowing and sucking have been used in airframes for many years, largely to provide flow stability and increased lift under extreme conditions. Several studies have concluded that similar effects within a gas turbine would require too much air flow due to the high momentum transfer requirements. Developments for airframe applications over the last 10 to 20 years have shown the benefits of modulated sucking and blowing to provide increased effect or reduced energy input. The currently favoured method seems to be synthetic jets where a volume of air is drawn in slowly from the main flow, followed by rapid expulsion through the small orifice. Several mechanisms have been used, and systems have been flown in programmes such as the XV15 experimental tilt rotor [2]. Recent work [3] for gas turbine applications has concluded that synthetic jets are unlikely to provide sufficient momentum transfer to give effective control within a gas turbine, so modulated jets seem to be the preferred option.

A generic requirement for multiple modulated jets applied through holes typically of much less than 1mm has been identified. Dependent upon the application, these can be required at a spacing of only a few millimetres. The majority of work on jets is investigating the use of jet frequencies which are matched in some way to a characteristic frequency related to the flow, although there seems to be no agreed method of defining this frequency or the relationship of the actuation frequency to it. This approach implies that each micro jet must have some form of sensing, decision making and actuation, potentially a massively complicated system. There has recently been suggestions that in some airframe applications it may be possible to use a fixed frequency for restricted applications [4]. Since the operation of a gas turbine is largely predictable, it may be possible to use this approach in order to use a fixed frequency, self excited jet modulator, allowing a much simplified system which can be turned on simply by supplying air to it.

To minimize secondary mass flow for active control (for example secondary fuel mass) and therefore the size of the valve, it is necessary to establish a high authority coupling with the flow (or with the combustion process). In separated flows, maximum amplification of actively generated local disturbances occurs near the separation point. In large-scale structure (vortices) dominated flows, maximum amplification occurs at the initial region of vortex development as demonstrated in [5] for combustion instability control in dump combustors. The presence of large-scale vortices has been also demonstrated in laboratory gas turbine tests [6]. Another approach to minimize secondary mass flow is pulsating flow instead of steady injection.

### 2.2. Large Scale Flow Switching

Large scale flow switching has been identified as a requirement for applications such as stall / surge control, handling bleeds, cooling flows and STOVL. Several low speed valves have been developed around these applications and of course are already in service for handling bleeds. Large scale air injection for stall /surge control has achieved a status of a holy grail of advanced engine control. Several studies over the last 20 years have concluded that although sensing and control for this application are difficult, high speed actuation is the limiting factor. Despite several short term demonstrations, no solution for long term service applications has been achieved.

### 2.3. Mechanical Manipulation

Mechanical manipulation is well established for intakes, Variable Guide Vanes (VGVs) and nozzles. First generation tip clearance control systems using thermal casing expansion manipulation are also established, they give some improvement over passive methods, but are recognised as severely limited when compared to an ideal system. The requirements for each application vary considerably, particularly in the temperatures over which the systems must operate. Virtually all systems currently use hydraulics, although electromechanical systems are also now available. Many actuator systems have been investigated, some giving significant weight advantages, but the usual issues of temperature and reliability seem to be limiting progress.

## 3. OVERVIEW OF REQUIREMENTS AND CURRENT CAPABILITIES

Each section of the engine will be handled in turn.

### 3.1. Intakes

Variable geometry intakes largely rely on conventional hydraulic actuators. Some electrical devices are also used. These devices provide generally efficient actuation, but the mechanisms are limited and require significant aerodynamic compromise, with rigid surfaces, steps and gaps from the hinged surfaces. Weight of the overall system and high maintenance costs are also significant issues.

### 3.2. Fans and Compressors

Variable guide vanes are almost exclusively controlled by hydraulic or fueldraulic mechanisms. Bleed valves again use hydraulic systems, both systems now use electromagnetic control valves, although fluidic control has been used in the past.

### 3.3. Combustors

Fuel input was the first control input employed in a gas turbine, today's actuators are an efficient series of valves, using a combination of solenoids and hydraulic control.

### 3.4. Turbine

Due to the harsh environment, actuation within the turbine has only recently been achieved. Even now, it is limited to first generation tip clearance control systems. These use casing temperature control to shrink the whole casing. Since this is a relatively slow process, only simplified control can be achieved, although broader application has been limited by patents [7] and lack of development.

### 3.5. Reheat and Exhaust Nozzle

Nozzle control for re-heat is probably the most demanding actuation process in current engines. The high forces, rapid response time, high temperatures and vibration environment are accommodated to provide a very effective system, albeit at the expense of high construction and maintenance cost.

### 3.6. Other Applications

Other applications such as helicopters and STOVL have special requirements, but are not considered here.

| Generic Actuators Requirements | | | |
|---|---|---|---|
| Actuator variable | Actuator Operation | | Notes |
| | Environment | Requirements | |
| Microscale airflow manipulation | 15-105 kPa, -60 - 55 C | Bandwidth and mass flow (1-2% of the core flow) | inlet flow control |
| | | | |
| | | | |
| | 15-105 kPa, -60 - 55 C | 15psi differential, < 10kHz | Inlet noise control |
| | 15-1800 kPa, -60-800 C | Fast actuation < 4ms, pulsed jets; Bandwidth for all control variables – by W, source form Sanjay | Compressor surge control |
| | 0-800 kPa, -60-150 C | a) 200-300Hz, b) 5-20kHz, c) 50-100kHz; total <.5 % of core flow | Compressor flow control |
| | | | |
| Large scale flow switching | 15-105 kPa, -60 - 55 C | Flow control bandwidth, input from W | Fan stall control |
| | 0-800 kPa, -60-150 C | steady-state, up to 2% of core flow | Compressor stator vane flow control |
| | Up to 1800 kPa, 800 C | 1-5 rad/sec bandwidth, 20% modulation of base-line cooling flow | Turbine cooling flow control |
| | 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 |
| | | | |
| Fuel flow control | Fuel system pressure, -60-500C | high-band width actua-tion, typically greater than 500Hz to 1000Hz fre-quency range.<br>Fuel flow modulation goal at 1 - 5% of mean flow | Combustion instability control |
| | | | |
| | Fuel system pressure, -60-700C | Schedule on emission sensing<br>Fuel flow modulation on each nozzle at 1-5 rad/s | Emission control |
| | Fuel system pressure, -60-700C | Fuel flow modulation on each nozzle at 1-5 rad/s | Pattern Factor Control |
| | | | |
| 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 |
| | | | |
| | 0-800 kPa, -60-150 C | < 10Hz, 20 degrees | inlet guide vane for surge control |
| | | | |
| | 0-800 kPa, -60-150 C | 1-2 Hz | vane geometry/shape |
| Misc | 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 |
| | | | |
| | | | |
| | | | |
| | 15-1800 kPa, -60-700 C | pressure > 3000 N/cm²; deformation > 0.5mm; installation in airfoil; bandwidth? W | Compressor blade vibaration control |
| | | | |
| | 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 |
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| | | | |
| | | | |

**Table 1: Generic Actuator Requirements**

# 4. TECHNOLOGY CHOICE

## 4.1. Requirements and Assessment

Actuation can be considered as a method of changing some physical parameter. In it's purest form, this is simple mechanical movement either in translation or rotation. Actuation within a gas turbine however requires capability well beyond this simplistic view it must consider the interaction with the engine cycle such as the effect on air flows, combustion temperatures etc and must consider integration into the engine components. The starting point of any survey must be to understand the actuation requirements, followed by evaluation of simple transduction method to provide movement or force to affect this change.

Comparison of the various transduction methods can be a complex process. The prime considerations must include the basic technical requirements of

- Maximum force
- Energy density
- Stroke
- Speed / repetition rate
- Input energy type
- Resolution / controllability
- Support system requirements
- Environment limitations eg. temperature

In addition, business and support issues must be considered such as

- Cost
- Service requirements
- Environmental impact
- Ownership

Numerous studies have reported comparisons of the many actuation techniques, however great care is needed in any interpretation of relative performance. It is quite common to see studies which are quite clearly biased to favour one particular technology, or where out of date data may unintentionally provide a misleading guidance. A further source of error may be where commercially sensitive data is not available to the researcher. One study which has striven to provide a comprehensive and impartial study has been carried out by Granta Designs Ltd during development of their materials selection database software [8-9]. Generally data was collated using information provided from published journals and conference proceedings. For example Bell DJ et al. compare 120 actuators gathered from existing literature on prototype devices [10]. Key mechanical properties (maximum force, maximum displacement, displacement resolution and maximum frequency) were considered. Due to the infancy of many smart actuation systems it can be assumed that a proportion of the data employed is generated from laboratory/prototype testing and not commercially viable solutions. This must be considered when making comparisons between the various smart actuation systems especially when using maximum values of an actuator's operational envelope. It is also evident that there may be some confusion between the transduction element and the overall system which may be needed to achieve actuation. For example, a hydraulic cylinder may appear to have a very good energy density, but when the full system including the pump and it's driving mechanism, fluid reservoir pipes etc. are considered, the weight will increase considerably. Hydraulics are however well established, very efficient and can be attractive in a high duty cycle and become more attractive when many cylinders can be actuated from a single pump. In comparison, Shape Memory Alloys (SMAs) have a very high energy density are intrinsically robust and require little support equipment, but they are slow and very inefficient, so are particularly suited to applications where infrequent use is required. Whilst hydraulics are well developed and established, SMA is still immature and only readily available in very small sections, often with variable properties.

This simple comparison highlights the difficulty in evaluating actuators for a particular application. The author is not aware of any study where the full implementation impact of actuation has been considered, even for established techniques. If the interest extends to new and emerging technologies, the comparison becomes more difficult. A thorough study including all aspects to produce a comprehensive comparison is urgently needed.

Some results from the Granta designs study are presented here to illustrate the key technology capabilities and current comparison methods. The capabilities of MEMS and Nano Electro Mechanical Systems (NEMS) are treated separately and shown in black on the charts, macro scale actuators being shown in green. Figure 2 shows maximum force versus displacement. As expected, forces and displacements currently available from MEMS and NEMS actuators are lower than macro actuators. Smart actuators that require temperature change within the operational environment, such as shape memory alloys, are presented as exerting the largest forces (~ 5 N) of the MEMS actuators. Macro shape memory alloy actuators are calimed to offer only slightly higher forces at around 20N, however [11] presents results from an engineering component demonstrator using 6kN in a single piece of SMA. Clearly a significant limitation of the survey.

Figure 3 shows what is probably a more realistic method for mechanical property comparisons using stress-strain, which also provides energy density (MJ/m3). This is a much more convenient method, giving the fundamental properties, but cannot take account of size limitations. Similar plots to present frequency response and efficiency can also be produced to provide the fundamental properties. The study does however largely only cover the basic transduction technology, the full system requirements are not considered, which causes major difficulty for an engineering evaluation.

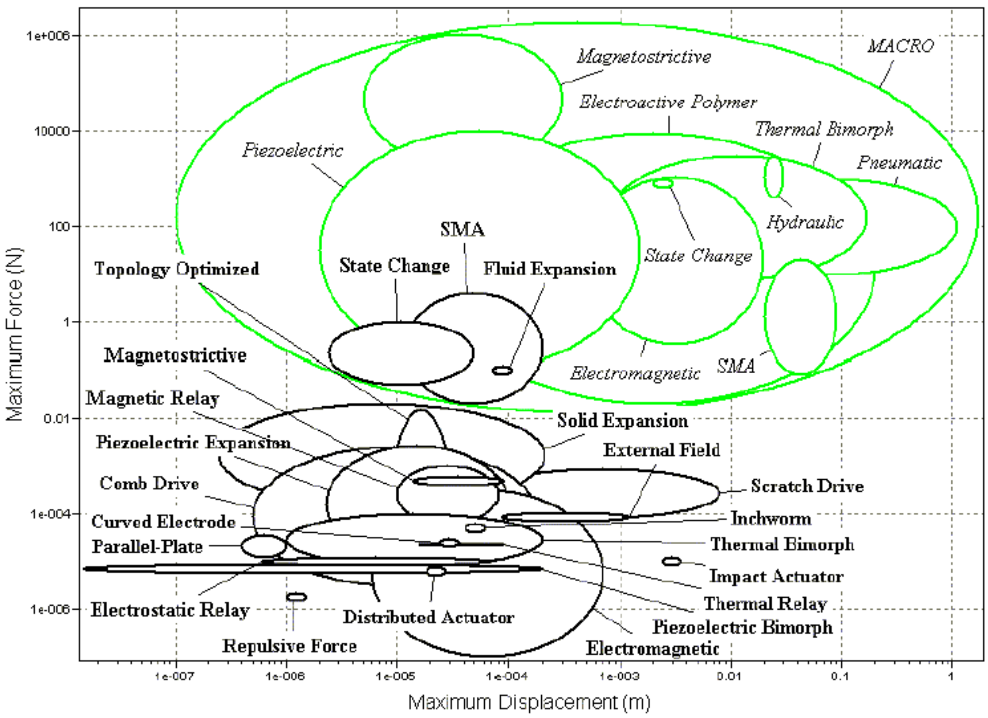


**Figure 2 : Maximum Displacement versus Maximum Force [10]**

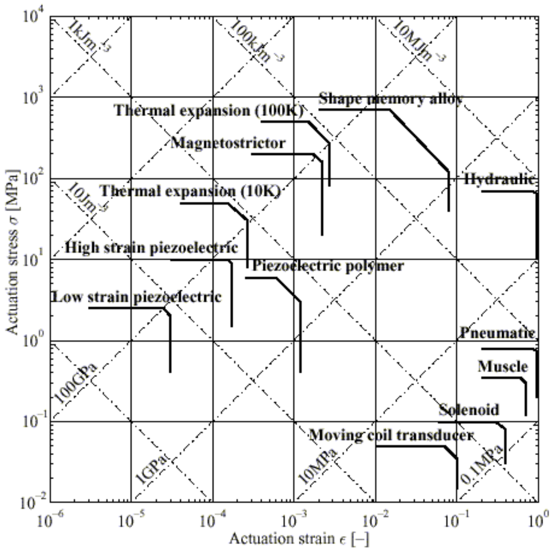


**Figure 3: Actuation Strain versus Actuation Stress [9]**

# 5. DEVELOPMENT REQUIREMENTS

As discussed earlier, each section of the engine already has some level of actuation. These largely rely on well established technologies. Although many studies have been carried out into new technologies, some have resulted in experimental engine tests, but very few have found their way into production engines. The requirements and limitations have been considered at an application level, there seems to be no thorough systematic study of the overall potential for advanced actuation. Two thorough generic studies are required before logical development of new applications and technologies can be achieved. These are

- Application evaluation with performance etc. benefits and actuator specification. This is essential to identify the most productive areas for application development and to produce an actuator specification.
- Technology evaluation, to identify the current capabilities and likely future developments including future system requirements, costs, maintenance, failure modes etc.

Proposals for initial evaluation of existing and some emerging technologies are included below.

## 5.1. Identified Technologies for Future Developments

### 5.1.1. Established Technologies

Although potentially overlooked in the rush to newer and emerging technologies, the established actuators such as hydraulics, electrical and even fluidics still offer considerable opportunity for future developments. Opportunities to develop higher temperature and miniaturisation capabilities should be pursued. This will enable extended and distributed opportunities to be realised.

### 5.1.2. New and Emerging Technologies

A selection of the more promising emerging technologies are discussed here. Many of the technologies have been demonstrated at a laboratory scale, but development towards practical engineering applications suitable for large scale gas turbine applications is still lacking. The discussion must however be at a generic level, since the detail is far too extensive for this summary document. The prime requirement is to move the capabilities towards actuators which can be utilised in practical gas turbine applications.

*Electroactive Materials*

This class of materials produces strain in response to an applied voltage, and includes piezo electric ceramics, Electro Active Polymers (EAPs) etc. They offer very simple, highly efficient electrical actuation with minimal current, but require high voltages to operate. Although available for many years, the broader potential still requires considerable development.

*Piezo Electric Ceramics*

Current piezo devices are well established in general use and dominated by Lead Zirconate Titanate (PZT). This is very effective for many applications, but despite a higher Curie point, is limited to around 1500C for most practical work. Although limited in strain (~ 0.02%), very high forces are possible. Many mechanisms to provide higher displacements have been investigated, from simple lever mechanisms, through discrete flexural structures to fully integrated systems providing low stiffness flexing surfaces. These have potential for many gas turbine applications, but must largely be coupled to higher temperature developments. Alternative elements such as Lithium Niobate have been available for some time with a temperature capability in excess of 8000C, but can only provide very small displacements. More recent developments have investigated a range of materials providing higher strain and improvements in the 1500C temperature capability. Development towards the identified applications should largely follow this route, preferably coupled towards specific applications. Mechanical amplifier development specific to identified applications are also needed.

*EAPs*

These are new, but can reportedly provide strains of up to 400%, albeit at very low stress. They are generating considerable interest for morphing wings due to their very high energy density, but are severely limited in temperature capability (~700C). Some discrete actuator devices are also now commercially available. The author is not aware of any gas turbine specific developments, although applications within the intake and exhausts could be considered soon.

*Shape Memory Materials*

These materials generally react to changes in temperature in order to cause a movement. Although other inputs such as acidity, light etc. are also possible, these are not yet sufficiently mature to be considered for practical applications. The temperature actuated materials are pre-set to a particular shape, to which it will attempt to return when activated. This can be used for a one-off assembly application, or as a repeated actuation. For the latter, a spring force is used to oppose the movement followed by movement in the opposite direction when de-activated.

Shape Memory Alloys (SMAs), are the most common, and have been commercially available since at least the early 1970s. The NiTi alloys now dominate although copper based alloys are also commercially available. Practical applications can achieve up to 8% strain for one-off assembly purposes, although 2% is a more practical limit for repeated applications in order to avoid premature fatigue failure. The one-way memory with spring return to provide two stable positions is by far the most common in research programmes. A “two way” effect where bi-stable position actuation can be achieved within a single piece of material is also available, but with current alloys and methods this tends to provide less movement and be less stable. Continuous movement has been achieved in several programmes, but the high hysteresis causes severe difficulty and requires temperature controlled feedback. Development of the materials and applications has been dominated by the medical market, so has largely been limited to small sections of relatively low temperature materials, 1500C being a practical limit. In order to provide any high authority actuation, a relatively large section is needed. These are not readily available, and basic limitation of the roughly 50Ni50Ti materials suggest that consistent properties across large sections are unlikely to be achieved. 60% Ni materials have been investigated as a method of providing increased stability and versatility, but are not extensively reported in the literature. Alternative alloys with higher temperatures have been investigated, with operating temperatures approaching 9000C reported, but are far from commercial availability. Development of these will be essential if the identified applications within the gas turbine are to be achieved.

Shape Memory Polymers can achieve much larger strains, but seem to be limited to assembly applications. Reports on re-lining of water pipes claim great success. Shape Memory Ceramics have similar properties and offer much higher temperature capabilities albeit at lower strains, they have been proposed for high temperature assembly purposes, but seem to have attracted relatively little research.

*Magnetic Strained Materials*

The magnetostrictive effect has been known in Nickel alloys for many years. An applied magnetic field causes strain generally parallel to the lines of magnetic flux. More recently, the commercial alloy Terfenol D and others have been developed to provide greater strain, but even then, only around 0.04% strain can be achieved, it requires large magnetic coils to provide the field and is limited in temperature. Robust, large and small scale commercial devices have been produced. A realistic assessment of the capability for a full system is required. Further investigation into the potential for higher temperature materials seems to be rare, the available knowledge requires collation and assessment.

*Magnetic Strained Materials*

also known as Ferromagnetic Shape Memory (FSM) materials provide much greater strain ~ 8% by phase transformations in a similar manner to thermal SMAs, but again activated by a magnetic field. These relatively new materials are commercially available, but possibly only from one supplier (AdaptaMat in Finland). They seem to offer significant potential, but are limited to around 700C and have very low modulus which limits their effectiveness. The potential for higher temperature materials would be a very worthwhile activity.

*Microsystems, Micromachines and Micro Electro Mechanical Systems (MEMS)*

Although strictly having slightly different meanings, these are three terms are used for miniaturised actuator systems, often incorporating sensing and decision making. The basic transduction methods are smaller scale versions of larger devices, but the miniaturisation coupled to multiple manufacturing techniques borrowed from electronics methods provide significant potential advantages. The most widely known applications are for ink jet printer heads and automotive air bags. These exploit the small scale and very low unit cost of this technology. With the required production volumes anticipated for aerospace, it is widely considered that the very low costs are unlikely to be achieved, but the other advantages could well out weigh the cost considerations. As an actuator, the scaling effects produce some interesting results, where electrostatic forces become significant to the extent that practical actuators have been produced and the low strain of piezo electrics is a less significant limitation. A plethora of small scale devices including valves, gear mechanisms and even an operating gas turbine with 5mm diameter rotor have been produced. The opportunities for multiple distributed systems, particularly for boundary layer manipulation, have been identified, although the provision of this within the constraints of damage tolerance, cost and maintainability have not been fully explored.

### 5.2. Other Technologies

The previous sections have considered the available and emerging actuator technologies which are likely to be developed in the near future. Others which have been investigated at an academic level such as local combustion effects, optically actuated polymers and vibration actuation are not yet sufficiently mature to consider in-depth development, but the future potential should be monitored and enhanced funding considered as appropriate.

## 6. 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.

## 7. ACKNOWLEDGEMENT

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