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Electromechanical Measurement of Turbomachinery Blade Tip-to-Casing Running Clearance

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ABSTRACT

It is difficult to make a reliable measurement of running clearance in the hostile environment over the blading of modern gas turbines. When the engine manufacturers require the measurement to be made during tests lasting many hours, or even days, measurement system ruggedness and reliability are of primary importance.

This paper describes how a second generation tip clearance measurement system of much reduced size and weight was developed. The reduction of size and weight facilitates the use of this measurement system for blade tip-to-casing measurements on all engine development tests from rig to flight worthy engines. During the course of commissioning, the measurement system was tested first in the laboratory, then on progressively more demanding test vehicles. The final test was on the high pressure turbine of a modern military full scale development single spool core. During the course of this test, the mean engine Turbine Entry Temperature through the blading over which clearance was measured, exceeded 1800 K and is typical of the applications for this second generation system.

1 INTRODUCTION

In this paper a program of work is described which was undertaken by the authors to develop and test a second generation clearance measurement system. The objective of the work was to reduce the clearance measurement system size and weight to enable its use in applications where available space is at a premium. This increased the installation envelope from the rig and test environments to flight worthy engines. In principle this enables a single tip-to-casing measurement technique to be used throughout an entire engine development program. The work reported falls, broadly, into two sections. Firstly, the mechanical design of a new clearance measurement system and, secondly, its commissioning in four stages. The paper concludes by reviewing the second generation systems performance during the commissioning exercise.

The tip clearance measurement system described is an electromechanical device first reported by Davidson et al [1983]. This clearance measurement system utilises a Stepper Motor driven Probe (SMP) and a spark/discharge technique to ascertain the proximity of an electrically grounded target, typically a rotating compressor or turbine blade. A spark/discharge clearance measurement system was first introduced in the 1950's by the Fenlow Company but suffered from thermal effects which limited its accuracy. These problems were addressed, and solved, by Davidson et al who developed a novel spring loaded probe. The probe would be spring loaded against a "datum face", Figure 1, on the inner casing. This maintained the probes datum close to the measurement point so eliminating thermal errors.

In the current program of work, the authors focused on minimising the size of Davidson et al's SMP without changing the original concept of a system which is completely self-calibrating over a wide range of temperatures and capable of a ±0.025 mm accuracy over a 6 mm range. The decision to undertake this development exercise was made after a thorough review of the gas turbine community's current and future clearance measurement requirements. The clearance measurement systems currently available for use in high temperature and vibration environments utilise one of several basic principles of operation. In addition to the spark/discharge principle, clearance measurement

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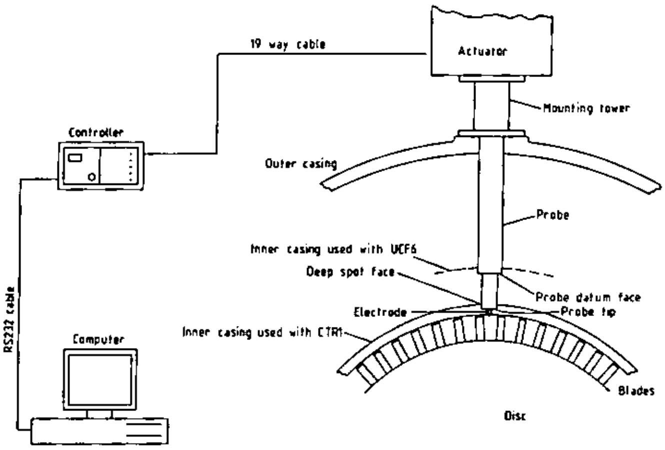

Figure 1 **A schematic layout of the spark/discharge clearance measurement system installation and component parts.**

systems may utilise optical, capacitive or microwave operating principles, Table 1.

In the majority of applications, the measurement of the longest blade is the most important parameter as the blade tip radii are normally ground to the same length. Other complimentary capacitance based systems are also in use which give information on all blades, described by Chivers [1989b], Parish [1990] and Killeen et al [1991]. These systems require calibrating prior to use, with the attendent risk that the calibration may drift.

The capacitance probe described by Sheard et al [1992a], is the subject of an ongoing development program to apply it to the engine environment. It is a self-calibrating capacitance probe which can be calibrated in situ, on-line immediately prior to measurement. This system is currently used for in-process gauging of rotor radius during the tip grinding process employed in the manufacture of bladed rotors, described by Sheard et al [1992b].

With the continuing viability of a clearance measurement system utilising the spark/discharge operating principle well established, the development of a second generation SMP was undertaken. The first phase of the development program was the design of a miniaturised electromechanical actuator and probe (a "mini" SMP). The system requirements are summarised and the conceptual design of the second generation system described. The mechanical design and mode of operation of the probe, electromechanical actuator and its electronic controller are described in detail, at which point the development programmes first phase may be considered complete.

TABLE ONE

GAS TURBINE USERS OF TIP CLEARANCE SYSTEMS

User		Electromechanical	DC Cap	FM Cap	Optical	Microwave
Pratt & Whitney	Hartford			O	E	
	Florida	D		O	O	
	Canada	D		O		
General Electric	Evendale	O		O		
	Lynn	D				
Rolls-Royce	Derby	O/D		D	D	D
	Bristol	D	C	K		
	Leavesden		C	K		
GTEC			O	O		
AGT		D		O		
Snecma		D		O		
MTU		O	O			
Textron				O		
WPAFB			O			
Turbomeca			O			
Alfa Avio			O			
Williams		D				
Teledyne CAE		D				
Fiat		D				

C = Chivers [1989a]
D = Davidson et al [1983]
K = Killeen et al [1991]
O = Own
E = Experimental

2 CLEARANCE MEASUREMENT SYSTEM CONCEPT

The electromechanical clearance measurement system comprises of three basic components, Figure 1, a probe, an electromechanical actuator and a rack mounted controller. The probe is spring loaded against a datum face which is physically close to the measurement point, typically on a casing around the blading. An insulated electrode runs through the probe which is moved towards the blading using a lead screw and stepper motor drive assembly. The electromechanical actuator contains an electronics module and a stepper motor drive assembly. The electronics module generates 400 Volts (V) which is applied to the electrode and detects, by low energy electrical discharge, the proximity of a passing blade. The controller generates the stepper motor drive pulses and interrogates the electronics module to ascertain whether a target has been detected. When the controller senses that a discharge has occurred the electrode is retracted to an internal datum. The distance from the position at which the discharge occurred to the internal datum is displayed on the controller front panel and the electrode then moved back in and the process repeated.

The controller can function as a stand alone unit or be interfaced to a computer via an RS232 link. For multi-channel installations a control program may be used to enable multiple controllers to be set up and clearance measurements recorded from each.

2.1 THE PROBE CARTRIDGE

The mini SMP probe cartridge design is critical to system accuracy and to its ability to withstand the environment around modern gas turbine blading.

The probe cartridge, Figure 2, has an installed length of 100 mm, the distance from its mounting flange to tip. The installed length may be varied from 50 mm to over a meter and, in particularly difficult installations, it may even be angled to enable an otherwise impossible tip clearance measurement angle to be made, described by Valentni et al [1988].

To understand operation of the probe cartridge consider Datum Disc 1, Figure 2. The datum consists of a metal disc mounted on the electrode and prevented from shorting to ground by an insulated sleeve. The datum disc is shown against the outer datum face with the electrode in its fully retracted position. During normal operation, the electromechanical actuator drives the electrode in until it senses that the 400 V on the electrode has shorted to ground. This electrical discharge can occur for one of two reasons, either the electrode tip has discharged to a passing target (a blade), or the datum disc has contacted the inner datum and the electrode shorted to ground through the probe center housing. Once the controller senses that the electrode has shorted to ground it is retracted and re-charged to 400 V. Stepper motor pulses are counted as the electrode is retracted until a second discharge is sensed as the datum disc contacts the outer datum. The number of stepper motor pulses between first and second discharge are a measure of the distance from the first discharge point to the outer datum.

The mechanical construction of the probe cartridge is such that the inner and outer datum faces are rigidly fixed relative to the probe datum face. The probe is spring loaded against the datum face, the mechanism by which this is accomplished is explained later. As the inner and outer datum faces are mechanically connected to the probe datum face, all three are maintained in a fixed position to each other. This point is significant as thermal effects result in the distance between the probe datum face and probe cartridge mounting flange changing. Secondly, due to the probe materials coefficient of expansion, it grows when heated. By maintaining the probe datum physically very close to the electrode tip, changes in casing relative position and thermal effects do not influence the measurement of distance from the target to outer datum.

The probe cartridge is kept against the probe datum face by compressing Spring B during installation. The spring force is usually kept below 50 N to minimise load on the often light casings. Thermal expansion of the probe center housing is taken up by further compression of Spring B, without altering the relative position of the probe cartridge on the probe datum face.

The casings on which the mounting flange and probe datum face sit will also change their relative position due to thermal effects. The net effect of the combined change in casing relative motion and probe center housing expansion is defined as "float". The float of the probe is accommodated by Spring B. If the thermal

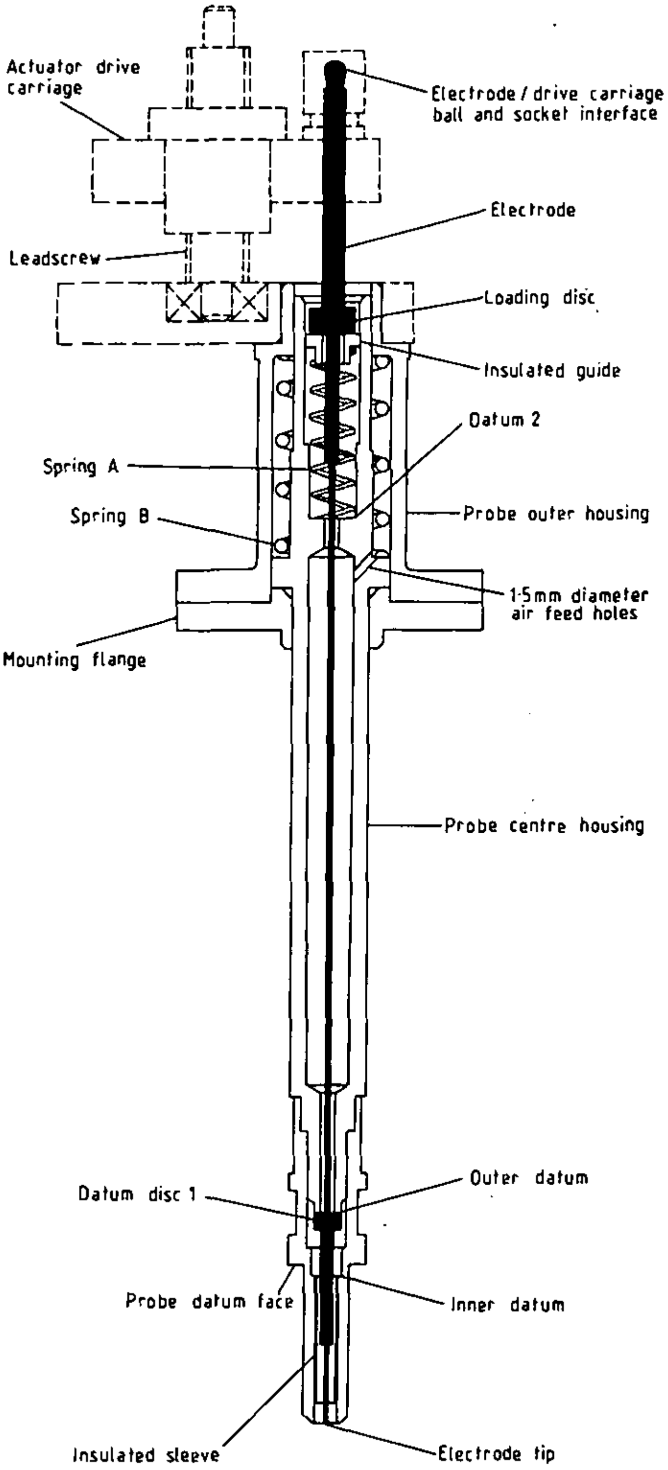

Figure 2 A 100 mm Installed length, 6 mm stroke, probe cartridge. Probes with installed lengths from 50 mm to 1.5 M may be used.

effects cause a reduction of spring compression (negative float) the force Spring B exerts to keep the probe on its datum faces reduces. If they cause an increase (positive float) then Spring B force increases. In practice, thermal effects almost always result in positive float as at machine design point the void between the two casings is usually at an elevated temperature, resulting in the probe cartridge center housing expanding, with the inner casing at a higher temperature than the outer casing resulting in its radius increasing more. The range of float that the probe cartridge can accommodate is +5.0 to −1.0 mm at which Spring B loads are 100 N and 10 N respectively.

2.2 THE ELECTROMECHANICAL ACTUATOR

The major design criterion when designing the mini SMP electromechanical actuator was minimum overall size. The final design, Figure 3, incorporates two principal components; the stepper motor drive assembly and an electronics module. The design specification is summarised in Table 2.

The stepper motor drive assembly consists of a miniature stepper motor and a lead screw on which the probe electrode drive carriage is mounted. When the probe is fitted to the actuator mounting tower the probe electrode sits in the ball and socket joint on the cartridge, Figure 2. By incorporating a ball onto the end of the electrode and socket in the carriage, the probe cartridge may be readily changed to facilitate the use of a single actuator with many probes for different installation geometries. The 200 step motor is half stepped to give 400 steps per revolution driving a 1.0 mm pitch lead screw, giving a step size of 2.5 microns. The spark gap of the electrode to a passing blade is from 3 to 5 microns depending on gas temperature, pressure and target geometry. As the step size of the drive is less than the spark gap there is no possibility of the electrode physically contacting a passing blade under normal operating conditions.

TABLE TWO

Second Generation Tip Clearance Measurement System Specification

Range	6.0 mm
Resolution	0.01 mm
Repeatability	±0.01 mm
Accuracy	±0.025 mm
Sample rate	6 per sec max
Minimum target presentation time	2 micro seconds
Probe diameter at the tip	3 mm min, 6 mm nom
Max uncooled probe temp	900 K
Max gas temp	1800 K
Actuator dimensions	44.5 x 48.2 x 165 mm
Actuator weight	0.75 Kg
Actuator environmental limit	50 C
Outputs from the control system	9.99 V = 9.99 mm probe pos. 9.99 V = 9.99 mm clearance RS232 output

The electronics module contains the high voltage generator for the electrode and the spark/discharge detect circuit. The high voltage generator is a DC to DC converter which generates 400 V from a 24 V input. A voltage of 400 V was chosen as the minimum which could successfully breakdown the dirt and oxide coatings on both electrode tip and target.

The spark/discharge detect circuit senses the sparking of the electrode to a target and cuts the current off with less than 2 pJ of charge being transferred. By

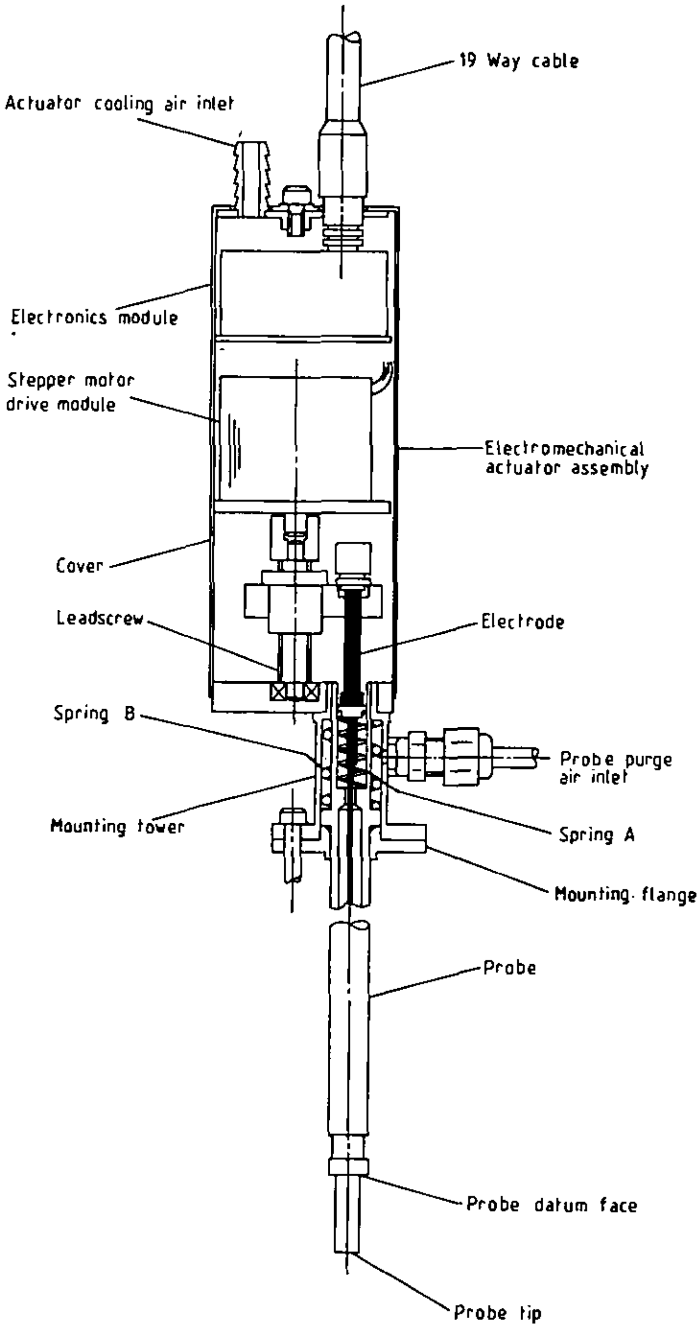

Figure 3 The electromechanical mini SMP actuator design, with a probe cartridge shown for clarity.

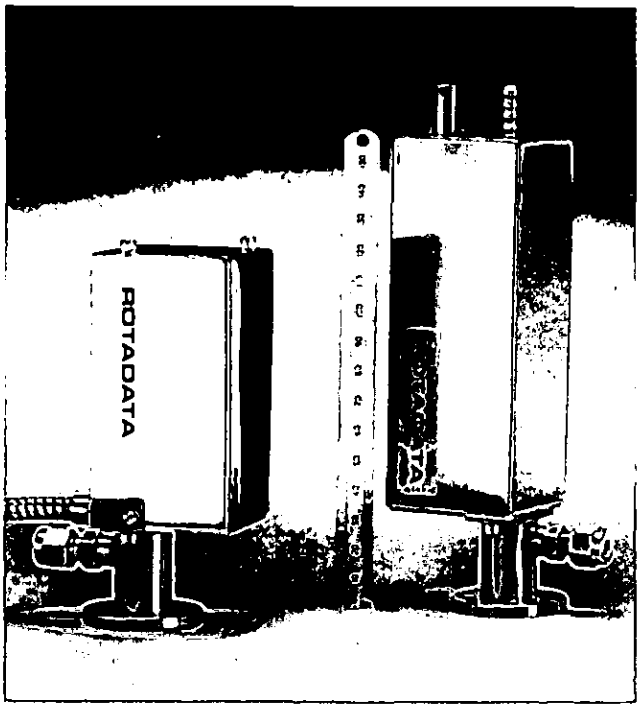

Figure 4 The mini and micro SMP electromechanical actuators, which are 23% and 18% the volume of Davidson et al's original SMP.

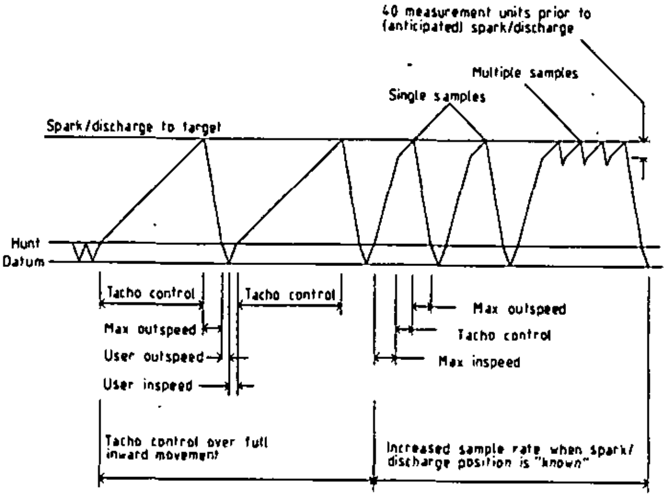

Figure 5 Controller operating modes which may be set up and changed by an operator via the controller's RS232 interface.

minimising the charge transferred the possibility of damage, due to, for example, sparking in a gas turbine's bearing, is avoided. It also ensures that if the electrode is accidentally touched by the system operator the effect, while shocking, is not dangerous. In order for a spark to establish itself in the first place, a target must be presented to the electrode for at least 2 micro seconds. Modern compressors have typical blade tip velocities of 400 m/s and thicknesses of 1.6 mm, presenting the blade tip to the 0.9 mm diameter electrode for approximately 6 micro seconds.

Further miniaturisation has been achieved by removing the electronics module completely and housing it in a separate box connected to the actuator via an armoured cable. This concept resulted in a "micro" SMP, Figure 4, to compliment the mini SMP design. The mini design occupies 23%, and the micro design 18%, of the volume of Davidson et al's original SMP, and 30% and 24% respectively of the weight.

2.3 COOLING REQUIREMENTS

The electromechanical actuator and probe cartridge are designed for use in modern gas turbines where Turbine Entry Temperature can exceed 1800 K and therefore cooling techniques must be employed.

The probe cartridge is cooled by a dry purge air supply which can be either compressor discharge air or externally supplied. It is fed into the mounting tower, Figure 3, and exits from the probe tip. The purge air also prevents contaminants from entering and causing false short circuits from the electrode to ground. For this reason the purge air must be clean and supplied even at ambient conditions when no cooling is required.

The electromechanical actuator is also cooled. For high heat environments a double skinned air cooled actuator case is used in addition to air cooling of the actuator. Similarly, if the casing on which the mounting flange is fixed is hot, a double skinned water cooled mounting tower interface washer can be used to minimise conduction up the tower.

2.4 THE ELECTRONIC CONTROLLER

The micro processor controller utilised to drive the electromechanical actuator comprises a half width 19" rack, power supply module and controller module. The primary function of the controller is to move the electrode inwards towards a target until a spark/discharge is detected. Once this occurs the electrode is retracted to its datum and the process repeated. The distance from target to datum is displayed on the controller front panel in engineering units and routed to the rear panel as an analog voltage.

The spark/discharge occurs on the longest blade which is closest to the electrode. To prevent mechanical contact there must be at least one complete revolution of the rotor between each inward step of the actuator. The inward step rate must be slow enough to ensure this. A tachometer signal can be used to synchronise the step rate to the rotor speed. This tachometer lock enables the rotor to be safely stopped with no possibility of mechanical contact between electrode tip and the blading.

To ensure that failure of the electronics module will not cause the electrode to be traversed into the blading, the micro processor controller tests the electronics module prior to each and every motor step. A transistor gate between the electrode and ground can be closed. The module senses a spark/discharge. Assuming the microprocessor registers this spark/discharge, the gate is opened, the module assumed functional and the motor will then be stepped.

The controller's full range of operating parameters are illustrated by Figure 5. When in the datum state the controller is not passive, but instructs the SMP to continually hunt its outer datum, monitoring thermal growth which might otherwise damage the electrode. Once switched to run, the controller moves the electrode in until a spark/discharge is detected. The controller then retracts the electrode at a user defined speed until the hunt point is reached when it reverts to a low withdrawal speed to contact the outer datum.

The user defined parameters are set using an RS232 interface on the controller's rear panel. A pre-set configuration may be downloaded prior to a test and the controller interrogated via the interface during the test. Additionally, probe position and clearance are available on the controller rear panel as 0 - 10 V analog outputs.

The controller performs all functions relating to the drive of the SMP. The user may either link controller analog outputs into a data logger, or acquire data via the RS232 interface. The last valid measured clearance is always displayed on the controller front panel and may be recorded manually.

3 COMMISSIONING

Following the mini SMP design a four stage commissioning program was undertaken comprising of a laboratory test and a three stage rig test. The rig tests, summarised in Table 3, were chosen as a gradual progression from the laboratory to a high pressure military spool test which is representative of the most severe environment likely to be encountered.

3.1 LABORATORY TESTS

The laboratory test comprised three separate investigations of different aspects of system performance. The mini SMP was calibrated, left running against a target for forty eight hours then re-calibrated. Secondly, it was run in an oven for two hours. Thirdly, a vibration test was performed to ascertain its natural frequency. This test series gave the authors confidence that the mini SMP was safe for use on a rig test.

TABLE THREE

Commissioning test vehicle conditions

Rig	Gas Temp	Air Temp	Vibration
UCF6	400 K	25°C	10 mm/s
CTR1	650 K	35°C	20 mm/s
FSS	1800 K	50°C	50 mm/s

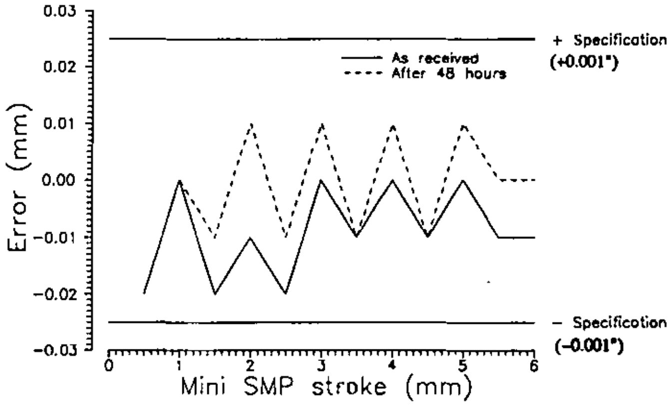

Figure 6 Mini SMP calibration as delivered and after forty eight hours continuous operation, illustrating system accuracy.

A micrometer measuring tool with a traceable calibration was used to ascertain system accuracy. The micrometer was used as a target for the electrode. The micrometer was retracted in 0.5 mm steps and the reading on the controller recorded. The difference between micrometer and controller reading was defined as system error. The calibration of the mini SMP, Figure 6, as received and after forty eight hours continuous running indicate an accuracy of ±0.02 mm before and after the continuous test. Secondly, the results repeat closely enough to give confidence that there had been no degredation of performance during the forty eight hours of operation.

The probe/actuator assembly was designed to be run on hot turbine casings where the ambient air temperature may be elevated up to 50°C. In order to verify the probe/actuators ability to withstand this, it was run against a fixed target for two hours in an oven at 50°C. The actuator assembly is cooled to this temperature in operation if necessary.

The final laboratory test was a vibration test to ascertain the mini SMP's vibration characteristics. A natural frequency was encountered at 720 Hz, corresponding to a first order engine excitation at a speed of 43,200 rpm. The mini SMP was allowed to run against a stationary target while being subjected to a 15 mm/s excitation at 720 Hz. The vibration test was continued for twelve hours, at the conclusion of which the mini SMP was fully functional. At this point the mini SMP was cleared for rig testing.

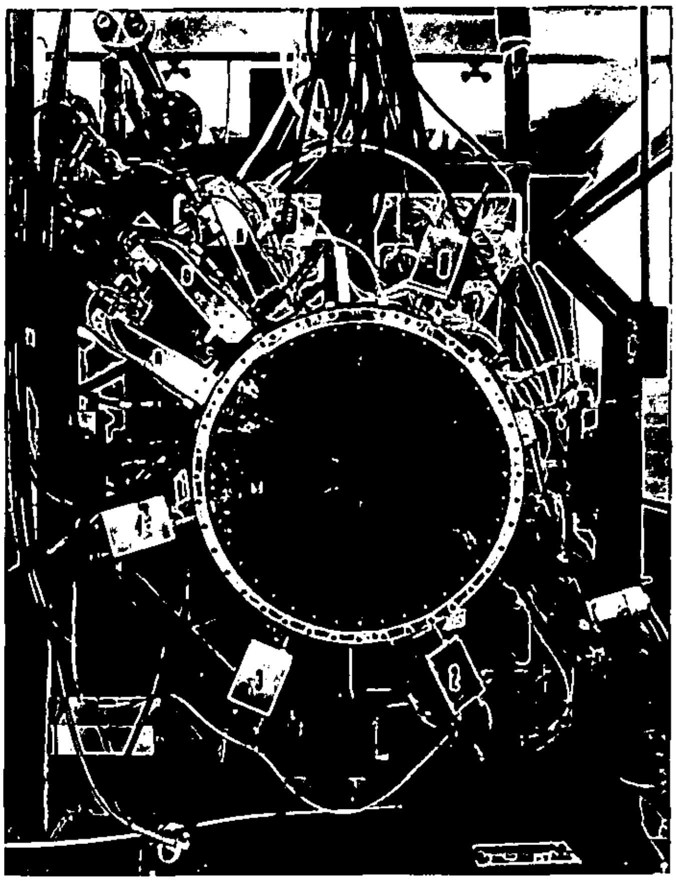

Figure 7 An end view of the UCF6 facility with three traverse actuators, A, B and C, and four of Davidson et al's SMP's, 1, 2, 3 and 4.

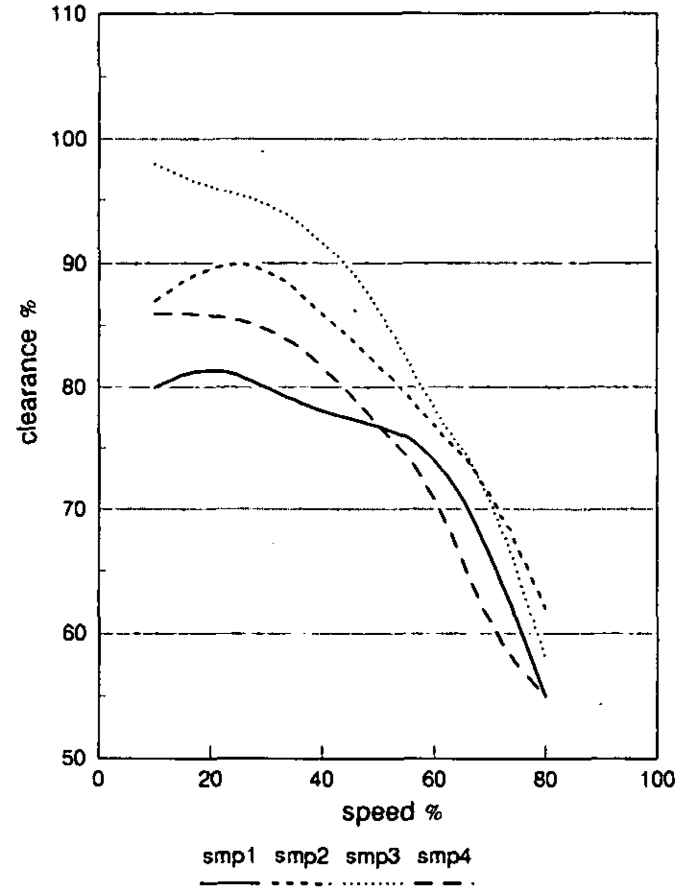

Figure 8 Tip clearance results (percentage design clearance versus percentage design speed) from UCF6 when fitted with four of Davidson et al's SMP's.

3.2 UNIVERSAL COLD FLOW RIG NUMBER 6 (UCF6)

The UCF6 facility is a general purpose facility designed to accommodate 100% size aerodynamic models of high pressure turbines. The facility achieves correct pressure ratio and non-dimensional speed, therefore achieving correct gas angles and Mach numbers through the stage. Total conditions of temperature and pressure are not achieved, therefore Reynolds numbers and gas to wall temperature ratio are not represented.

The facility is extensively instrumented, Figure 7, with three traverse actuators and four SMP's. The traverse actuators are able to position aerodynamic probes in the gas path, described by Killeen et al [1988], all three are mounted on a rotating casing to facilitate area traversing of the flow field.

In order to ascertain the performance of the mini SMP a repeat test was run using four of Davidson et al's SMP's as a basis for comparison. The test consisted of a slow zero to 100% speed acceleration from a cold start, Figure 8. The Number 4 SMP was then replaced with a mini SMP and the test repeated. The results, Figure 9, show the mini SMP performance to be comparable to the original units. In all UCF6 ran for thirty hours with a mini SMP fitted and running for ten. No operational problems were encountered.

3.3 COMPRESSOR TEST RIG No 1 (CTR1)

The CTR1 facility is a general purpose compressor test facility. Its specification is similar to that of UCF6, however, being a compressor test facility mean gas path exit temperatures can reach 250°C, leading to an elevated ambient temperature in the test cell. Secondly, the vibration levels experienced on this facility are significant and therefore some vibration tolerance is required of equipment mounted on it.

The installation on CTR1, Figure 10, is externally similar to UCF6 with one significant difference. The installation technique utilised on CTR1, which has thin lightweight inner casings, was to use the probe tip as a datum face with the rig casing being machined with a deep spot face to give the tip a flat against which to rest, Figure 1. The UCF6 facility utilised the probes intended datum face, not the probe tip. The CTR1 installation was more typical of those used in high

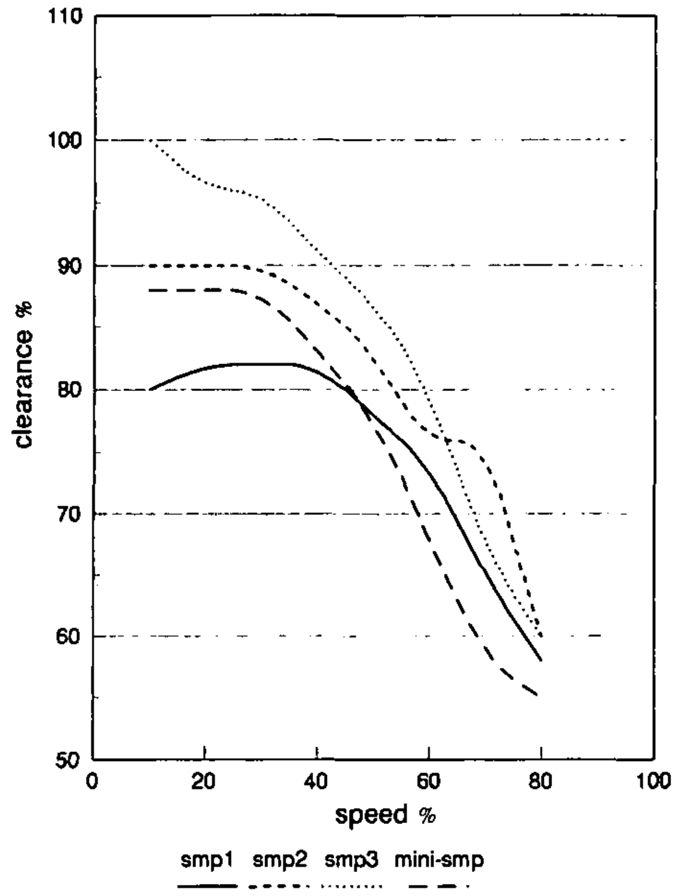

Figure 9 Tip clearance results (percentage design clearance versus percentage design speed) from UCF6 when fitted with the mini SMP probe and actuator, plus three of Davidson et al's SMP's.

temperature applications where the thin inner casing prevents the machining of a shoulder deep enough to enable the use of the probe datum face. This, coupled with the real thermal shift of engine casings, vibration during operation and the elevated environmental temperature around the actuator, provided a good pre-run for the high temperature installation.

The CTR1 test envelope limits were established using Davidson et al's SMP. Once this had been done a mini SMP was fitted and the performance map completed. In all over one hundred operating hours with the mini SMP were logged, during which no operational problems were encountered. The results obtained were in accordance with those of Davidson et al's SMP.

3.4 FULL SCALE SPOOL (FSS)

The FSS test utilised to evaluate the mini SMP was a full scale engine condition test on a high pressure military engine core utilising flight standard discs, blades and casings. The Turbine Entry Temperature was in excess of 1800 K at some points during the engine cycle. As there was no low pressure stage around the core, the outer casings were close to the gas stream and ran hot. There were very high peak and transient vibration loads during the test. The prime objective was simply a successful installation that was still functional at the conclusion of the test.

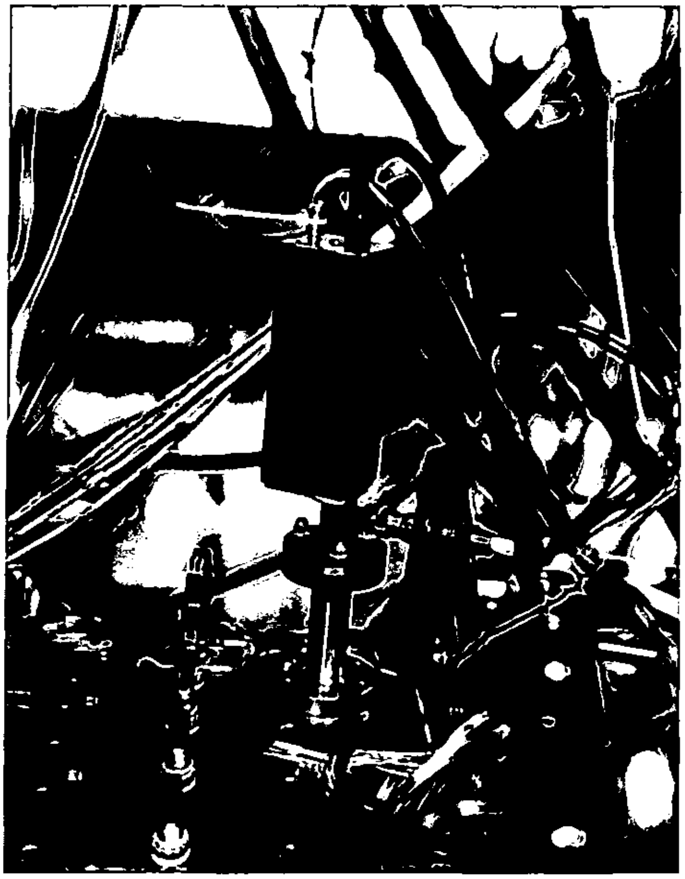

Figure 10 A side view of the CTR1 facility with the mini SMP probe and actuator fitted.

In hot applications probe installation considerations are paramount to the success of the test. The installation geometry, Figure 11, is deceptively simple, however, was the product of hard won experience. Firstly, the probe was spring loaded onto its tip against a spot face on the spool liner. The inner casing comprises individual liner segments which, while mechanically restrained, were free to move under thermal and differential gas loads. The cooling arrangement for the liners were also such that access to the spot face was severely restricted. The restricted access required the machining of two flats on the probe tip, Figure 12.

A seal washer was fitted around the probe as it passed through the outer casing. The actuator itself was fitted to a heavy duty bracket to transfer the weight of the SMP from the outer casing to a mounting flange,

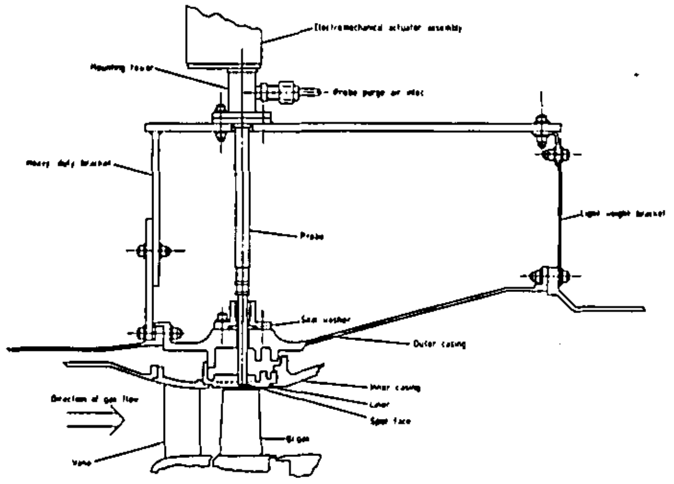

Figure 11 The installation design for the mini SMP in FSS with the heavy and light weight brackets used to match probe thermal growth to that of spool casings.

the far end of which was restrained with a light weight bracket. The cold installation loads the probe against the far side of the outer casing. When the facility thermally soaks through at design point, the engine outer casing expands more than the bracket and un-loads the probe. The initial loading of the probe was arranged such that it was fully unloaded at design conditions. The lightweight bracket prevents the installation natural frequency falling low enough to be directly excited by the engine but was flexible enough not to influence the thermal behaviour of the heavy weight bracket. The actual installation, Figure 13, clearly shows the bracket arrangement with the mini SMP standing off the outer casing. The low weight of the mini SMP would enable it to mount directly on the casing in future installation designs.

The method utilised during the CTR1 test was repeated on the FSS test, with a Davidson et al's SMP being utilised to ascertain the extremities of the envelope and a mini SMP being used to in-fill the performance map.

While the test data are necessarily confidential, the mini SMP system survived the ten hour FSS test. Results obtained were in accordance with those obtained using Davidson et al's SMP. Following the FSS test the mini SMP probe and actuator were stripped and inspected. The high temperature in the probe tip region had resulted in it oxidising to dark blue, from which a probe tip temperature of over 300°C may be inferred. The probe was, however, fully functional at the conclusion of the test as was the actuator giving confidence that the mini SMP was performing as originally envisaged.

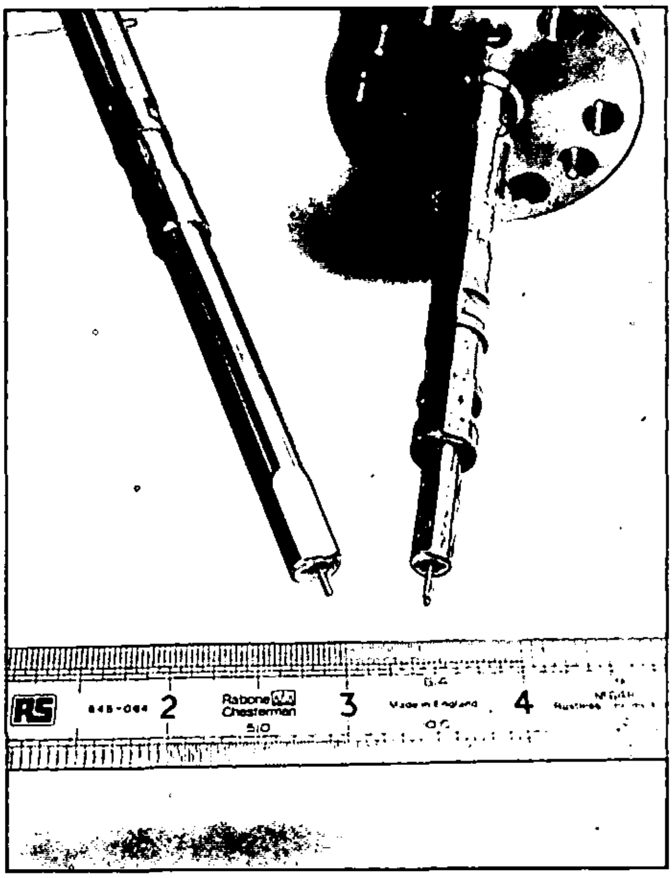

Figure 12 A close up view of the probe tip region of the probes used on UCF6 and CTR1 (right) and FSS (left) illustrating their different geometries. The probe used on UCF6 and CTR1 has run for over 100 hours and while well worn was still fully functional.

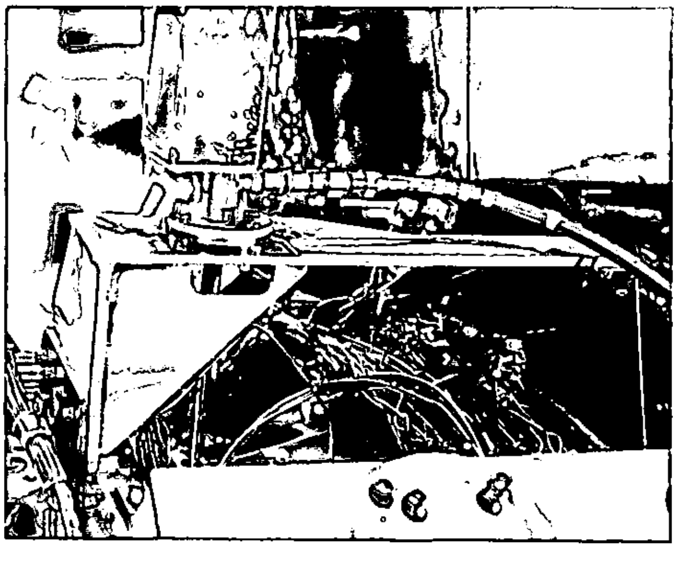

Figure 13 A side view of FSS with mini SMP probe and actuator fitted prior to test.

4 SUMMARY AND CONCLUSIONS

A second generation electromechanical clearance measurement system with an actuator of 23% the size and 30% the original weight has been designed. The concepts utilised in the original design have been retained, however a more compact stepper motor drive unit and electronics module have facilitated the reduction in size.

The mini SMP concept has been extended by housing the electronics module separately to produce a micro SMP. This reduced the size of the actuator to 18% of the original design, facilitating a further increase in the range of possible installations.

The probe design has been adapted to fit the reduced size actuator, but the same mechanism for spring loading it onto a datum face physically close to the measurement point has been retained.

Following the design of the second generation system a four stage commissioning exercise was undertaken. The first stage involved a series of laboratory tests to verify the systems performance. These laboratory tests were followed by three rig tests, starting with a cold flow rig and working up to the most demanding spool test. In all installations the second generation system performed reliably and gave results which were in accordance with those obtained using Davidson et al's original system.

At the completion of the commissioning tests, the authors concluded that second generation system performance was comparable to that of the original system. That this level of performance on highly demanding test vehicles was obtained with a actuator of 23% the original size was considered excellent, therefore the second generation has been fully commissioned.

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