

Latest Ruggedized High Temperature Piezoresistive Transducers

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ABSTRACT

In recent years, the need for semiconductor pressure transducers that can be used in applications that require operation in harsh environments that are corrosive, oxidizing, experiencing high vibration, and involving high temperatures has increased. Accordingly, not only must the stress-sensing network of these transducers be protected from these harsh environmental conditions in some way to enable the transducer to remain operational at high temperature over extended period of time, but the entire transducer structure, including: electrical contacts, lead-outs, interconnects and external wiring must also be protected.

Results are presented showing test data for latest high temperature "leadless" dielectrically isolated (SOI) semiconductor piezoresistive transducers. Data is presented at temperatures for up to 1075°F illustrating the excellent zero shift and low span sensitivity to temperature. Methods of construction of these devices are also discussed. The results indicate that ruggedized, high frequency, piezoresistive transducers are now feasible and can be manufactured for the kinds of environments that exist under the most stressful jet engine conditions.

2. INTRODUCTION

The modern aero gas turbine engine is generally considered to be a relatively mature device, having been the subject of intense development throughout the world for over half a century for both military and civil applications. Consequently the cost and difficulty of achieving further improvements to the gas turbine in terms of specific fuel consumption, weight and price have risen steeply. However the explosive growth in computing and microelectronics gives rise to optimism in achieving dramatic

improvements in the performance of gas turbines in the future when this technology is applied to engine control systems. Significant improvements have already been made in the performance, economy and handling of modern gas turbine engines by the use of Full Authority Digital Engine Control systems (FADEC). Many modern turbomachines, in particular multistage axial flow compressors, now rely on complex scheduling of stator vanes and bleed valves and monitoring of pressures, temperatures and flows to achieve stable operation. The ability of a FADEC to process the many sensor inputs from an engine, to apply sophisticated control laws and control a range of actuators simultaneously, enables many modern gas turbines to function economically and reliably. A return to the previously used hydro-mechanical control systems would, in many cases, be impossible without significant mechanical and aerodynamic redesign of the turbomachine.

The modern FADEC controls the starting, steady operation and transient conditions of a gas turbine and incorporates fault tolerant designs appropriate to a flight critical system. The next steps which are predicted to generate a significant improvement in efficiency of operation of a gas turbine have been identified as 1) the improvement in stability of compressors through the anticipation and suppression of surge and rotating stall and 2) improvement in stability of the combustion process. The natural aerodynamic instabilities of turbomachines often limit their performance, but increased stability potentially leads to lighter more efficient compressors with fewer stages and shorter airfoil chords, reduced fan noise from lower tip speeds, faster engine acceleration as the surge constraints have been removed and greater operating flexibility.

The subject of the control of stall and surge in turbomachines has been investigated widely with Ludwig's work in 1980 being the earliest identified reference [1]. However the phenomenon of stall and surge in the compression systems of gas turbine engines has been the subject of investigation since the 1950s. Twelve teams have been identified through a non rigorous review of the published technical data in this field [2] and in addition, there are other currently active teams who eschew publicity.

The subject of combustion related instabilities has also become the focus of much of the engine community. High performance gas turbine engines are often equipped with augmenters (also known as afterburners) to provide increased levels of thrust for relatively short periods of time. The level of thrust augmentation desired is determined by the aircraft requirement for specific excess power for maneuver. However, the augmentation level which can be supplied by the engines is limited by the oxygen in the air after the turbine, by cooling requirements for augmentor walls and downstream nozzle, and by the onset of the debilitating combustion instabilities of screech and rumble.

Screech (high frequency) and rumble (low frequency) are performance limiting instabilities which have proven endemic to high performance, augmented military aircraft since the dawn of the jet age. They are unacceptable in operation because the amplitude of these acoustic disturbances are often sufficient to rapidly induce fatigue and damage to the engine exhaust system. They have been troublesome in the design of almost all engines and remain so today. In fact, these problems are exacerbated in the newest designs since: (a) new engines have radically different augmentor geometries to meet strict new low observability requirements and (b) new engine augmentors are of very light weight construction to meet ambitious thrust-to-weight goals and thus can be even more susceptible to rapid acoustic fatigue than earlier implementations.

Rumble and screech problems appear during engine development and also in the field. A contributing factor to the long term persistence of this problem is that (a) these nonlinear instabilities have remained beyond the state the art of analytical modeling so that predictions are uncertain, and (b) the extraordinarily augmentor harsh environment has made comprehensive instrumentation difficult and expensive. It is for the avoidance of these instabilities that is the focus of the emerging sensor instrumentation needs.

3. SENSOR SELECTION

The selection of the sensor type and location(s) are critical factors in determining the effectiveness and practicality of an engine surge and stall control system, as is the selection of the actuator type and the algorithms used to process the data from the sensors. This paper will confine itself to the issues relating to the choice and design of the sensors, although similar importance needs to be attached to the selection of the actuators and signal processing software and hardware in order to create an engine control system which is both effective and safe.

A review of the most recently published material in the field of active control of surge and stall in axial flow compressors concludes that the most widely used physical parameter to monitor the stability of a compressor is pressure, although the measurement of gas flow using hot wire anemometers and the measurement of gas temperature using high response thermocouple probes have been used successfully.

The paper by Day, Breuer, Escuret, Cherrett and Wilson [3] assessed the generic features of stall inception using four high speed compressors. In the experiments on all four compressors, large numbers of miniature Kulite pressure transducers were used (MTU – 24, DRA – 24, SNECMA – 40, Rolls-Royce – 27). Similarly in the reported work by Freeman, Wilson, Day and Swinbanks [4] on the applied stall control of a Rolls-Royce Viper engine, 30 miniature Kulites were employed. In addition, the work by Eveker, Nett and Sharma on the demonstration of a non-linear control strategy on a high speed 3 stage axial flow compressor used 15 miniature Kulites. The paper by van Schalkwyk, Paduano, Greizer and Epstein [5] describes the first experimental validation of transfer function modeling and active stabilization on a 3 stage low speed axial flow compressor and is the exception in the use of 8 hot-wire anemometers, which measured the gas flow, as the sensors for the control system. DiPietro and O'Brien [6] and [7] report on the effects of transient inlet temperature fluctuations on the stability of a 2 stage subsonic axial flow compressor using medium response thermocouples and static and pressure tappings connected to Datametries and Omega pressure transducers.

In review of the combustion related instabilities, there appears to be three fundamental uses for dynamic instrumentation in augmentors. The first is for engine development. Here high frequency response transducers are needed in several locations to elucidate the spatial and temporal mode structure

of the oscillations. The second use is when in-service problems arise. Here the transducers must be readily retrofitted into existing engines to facilitate quick diagnostic of the problem. The third use is for realtime diagnostic, detection and control. In this case, transducers would be fit to production engines so that low cost, size, and weight of the complete measurement package (transducer plus electronics) is an important factor. In all three cases, the most useful measurement is that of static pressure, both steady state and time varying since these are thermo-acoustic disturbances. Pressure is the quantity of direct interest since it is the pressure perturbations which cause the damage. Also, the highly nonlinear nature of screech and rumble means the steady state pressure is an important determinant of the onset of instability.

The technical requirements for augmentor instrumentation are extremely challenging. Units must be physically compact so as to require minimum modification to an engine and so as not to disturb the measurement environment. The transducers must have wide frequency response, extending up to 3-5KHz for screech and, ideally, down to dc to capture startup transients and the steady state pressure level. They must be capable of long term, reliable service (2000 hrs) within the augmentor, which includes temperatures of 550F in the liner (and twice that through the liner wall) and vibrations levels up to several hundred g's. To simplify routine, rugged installation, the entire transducer package including leads must be capable of sustaining very high temperatures. For airborne application weight and power consumption of the transducer and signal conditioner must be kept to a minimum. Finally, the units should be of relatively low cost and ready availability, especially when multiple unit installations are called for.

4. SENSOR INSTALLATIONS

In the experimental work referred to in the previous section, the pressure transducers have been physically installed in a compressor in two configurations to sense the stability of operation of the machine by the measurement of high response pressure fluctuations. First the transducer can be attached to a total pressure pitot probe and can be either embedded within the probe or mounted remotely using a non-resonant pipe system, or semi-infinite line, as shown in Figure 1.

The second configuration is referred to as a wall static installation with the pressure transducer either directly mounted in the wall of the compressor casing with a flush sensing diaphragm or remote from the

static tappings using a non-resonant pipe system similar to that referred to in the pitot probe configuration and is shown in Figure 2.

Both configurations have strengths and limitations; the measurement of dynamic total pressures using the pitot probe potentially generates the largest unsteady pressure signals under stall and surge conditions but is intrusive which may affect compressor efficiency and weight, especially if multiple probes are required. Additionally, a long experience of working closely with compressor designers suggests that they are likely to be unhappy with a significant increase in the quantity of intrusive gas path instrumentation from the perspectives of reliability and efficiency. The wall static installation typically generates dynamic pressures, which are approximately half the amplitude of the signals produced from a total pressure pitot installation under similar conditions. However the wall static installation is mechanically superior in that it is non-intrusive and hence is unlikely to affect aerodynamic efficiency or weight and will be more reliable.

On the basis of the above considerations, the authors are of the opinion that the wall static configuration is the one which is most likely to be selected for application to production gas turbine engines. A flush diaphragm arrangement is also likely to be more acceptable thus avoiding the additional cost, weight and complexity of semi-infinite line systems.

5. PRESSURE SENSOR SPECIFICATION

The high response pressure data, which is generated by the dynamic pressure transducers, is processed using one of many proprietary algorithms in order to predict or detect the onset of stall and surge. Although the operation and logic of the algorithms described in the technical publications vary considerably, the data requirements from the pressure sensors appear to be remarkably similar. The required characteristics for a stall and surge pressure sensor have been derived from both published technical papers and informal discussions with leading researchers in the field.

The pertinent characteristics which are required of a compressor mounted stall and surge pressure sensor are high sensitivity (ability to detect 70Pa (0.01psi) peak to peak fluctuations), stability of sensitivity with temperature and time ($\pm 5\%$ to 10% FS) and the ability to survive in an extremely hostile environment (operating ambient temperatures and transients between -54°C and 400°C (-65°F and 750°F) and acceleration levels of up to 200g peak between 1kHz

and 18kHz). The pressure transducer installation should also have sufficient bandwidth to measure frequencies between 100Hz and 1kHz for large gas turbines and between 500Hz and 8kHz for small gas turbines with negligible phase shift. During surge conditions, the pressure transducer must survive gas path pressure and temperature transients of up to 3.4MPa (500psi) and 1000°C (1830°F) for several seconds. Finally, if active surge and stall control systems are to be applied to production civil and military gas turbine engines in the future, the reliability and cost of the dynamic pressure transducers must be competitive with the pressure transducers currently used to measure oil, fuel, air and hydraulic pressures on airframes and engines.

6. THE SILICON-ON-INSULATOR (SOI) SENSOR

For the last 40 years, Kulite has supplied high performance pressure transducers to the aerospace industries for both research and development and for production applications. These transducers are based upon the piezoresistive silicon technology, which Kulite pioneered and developed to its current high levels of performance and reliability. The latest evolution of sensors at Kulite, including the “leadless”, use silicon on insulator (SOI) technology.

Piezoresistive silicon strain gauges are integrated within the silicon diaphragm structure but are electrically isolated from the silicon diaphragm as shown schematically in Figure 3. The piezoresistors measure the stress in the silicon diaphragm, which is a direct function of the pressure of the media.

There are two core elements of the current generation of devices which will be considered in turn: the production of a suitable deflecting diaphragm to turn applied stress into displacement, and the addition of piezoresistive strain gauge elements to the diaphragm to record the displacement.

The latest evolution of the patented Silicon on Insulator (SOI) Technology enables the piezoresistive sensing elements to be dielectrically isolated from, while being molecularly attached to, a silicon diaphragm (Fig. 4). The process for fabricating the composite dielectrically isolated SOI sensor structure requires the use of two separate wafers. The first “Pattern” wafer is specifically selected to optimize the piezoresistive performance characteristics of the sensor chip, while the second “Substrate” wafer is specifically selected to optimize the micromachining capabilities of the sensing diaphragm. A layer of the

best thermally grown oxide is then grown on the surface of the substrate, while the piezoresistive patterns are introduced onto the pattern wafer. The piezoresistive patterns are diffused to the highest level (solid solubility) in order to achieve the most stable, long-term electrical performance characteristics of the sensing network. Once the pattern and the substrate wafers are appropriately processed, the two wafers are fusion bonded together using a specifically developed and patented diffusion enhanced fusion technique. The resulting molecular bond between the two wafers is as strong as silicon itself, and since both the sensing elements and the diaphragm are made from the same material, there is no thermal mismatch between the two, thus resulting in very stable-accurate performance characteristics with temperature. The presence of dielectric isolation enables the sensor to function at very high temperatures without any leakage effects associated with the p-n junction type devices. Since the device is capable of operating at high temperatures, a high temperature metallization scheme is introduced to enable the device to interface with the header at these high temperatures as well.

The micromachining is performed using a combination of different wet (Isotropic and Anisotropic) chemical processes. The shape and performance characteristics of the micromachined-sensing diaphragm are modeled using finite element analysis at the initial design stage. The composite silicon sensor is attached to a pyrex pedestal, by an electrostatic bonding program, to form a pressure-sensing capsule as shown in Fig. 5. The pedestal material is selected to thermally match the physical characteristics of the silicon sensor.

The sensing circuit is electrically insulated from the metallic housing by virtue of the non-conductive pedestal in the pressure capsule. The insulation resistance and the dielectric strength are inherently very high. The reference pressure is accomplished between the diaphragm and pedestal, providing a true hermetic seal.

7. LEADLESS SENSOR DESIGN

Under extreme conditions of temperature and vibration, the ultrasonic agitation used to form the ball bonds causes abrasion to take place during the welding process and allows microscopic holes to develop in the platinum metallization through which, at high temperatures, the gold can migrate and form a gold-silicon eutectic which causes the leads to fail. In addition, the pressure media is in direct contact with the stress-sensing network, leadouts and interconnects which at high temperatures and in the

presence of aggressive chemical can fail. The key elements in the design of a ruggedized pressure sensor is the elimination of the gold bond wires and the protection of the sensing elements from corrosive environments at high temperatures, hence the reference to the new sensor capsule as the “leadless” design.

The leadless sensor capsule is comprised of two main components, the sensor chip and the cover wafer, which are eventually assembled to form the pressure capsule.

The sensor chip is manufactured from two separate wafers. First a carrier wafer is fabricated which forms the mechanical structure, the diaphragm. The second wafer is referred to as the sacrificial wafer on which is defined the areas which the high conductivity P^+ piezoresistive strain gauges occupy. After oxidizing the carrier wafer to form an electrically insulating layer over its surface, the two wafers are bonded together using a Diffusion Enhanced Fusion bonding (DEF) process [8], [9]. The bond is a direct chemical molecular bond between the P^+ regions and the silicon oxide and uses no adhesive or additional components. Once the bond is formed, the non-doped areas of the carrier wafer are selectively removed chemically. The piezoresistive P^+ are now permanently bonded to the dielectrically isolated carrier wafer in which the diaphragm is now micromachined.

Figure 6 shows a view photograph of the sensor chip with the four-piezoresistive gauges strategically positioned inside the sensing diaphragm region and connected in a Wheatstone bridge. The entire sensing network is P^+ and there are separations between the contact regions of the bridge, Metal is deposited to form ohmic contacts to the P^+ regions located inside the large contact regions. There is also a rim of P^+ material around the periphery of the sensor chip. When the cover wafer is assembled to the sensor chip, an hermetic seal is formed between the cover and this area of P^+ material thus protecting the stress sensing network and all the electrical interconnections from the harsh environmental conditions. The cover wafer is manufactured from a Pyrex glass to the same dimensions as the silicon wafer. Four holes are micromachined in the cover, one in each corner, which align with the metallized contact pad areas. A cavity is also created in the center of the cover wafer to allow the diaphragm to deflect freely when assembled. The sensor chip and the cover wafer are then assembled using an electrostatic bond. Figure 7 shows a top isometric view of the components just prior to sealing. Once

the two wafers have been bonded, only the metallized leadout pads are exposed while all the gauges and electrical interconnections on the sensing side of the silicon chip are sealed by the cover. Thus the active portion of the pressure sensor is hermetically isolated.

8. THE LEADLESS PACKAGING

To avoid the use of gold ball bonds and fine gold wires, a high temperature metal frit is used to provide the electrical connection between the sensing chip and a specially designed header. The frit is a mixture of high conductivity metal powders in appropriate physical form and glass and is used to fill the holes in the cover wafer after it is attached to the sensor chip (Figure 8).

The specially designed header contains a group of four hermetically sealed pins protruding from its surface, which are spaced so as to fit the holes drilled in the cover wafer. The leadless sensor is bonded to the header at a high temperature using a non-conductive glass frit, during this process the metal frit in the cover wafer holes melts and creates low resistance electrical connections between the header pins and the metal contact pads on the sensor chip. Figure 9 shows the mounting process of a leadless chip on to a header and also shows a section of the pressure capsule mounted in the header.

Previous work [10] described transducers made by essentially these methods that were evaluated up to 900°F. However, by varying the composition of the metal frit and its firing characteristics, significant improvements in high temperature reliability was obtained. This method allows the tip of the transducer to operate in excess of 1075°F. Once the chip is mounted on to the header, and the interconnections are established, only the non-active side of the diaphragm is exposed to the pressure medium. The small ball bonded gold leads have been eliminated and the entire sensor network and contact areas are hermetically sealed from the environment and the pressure media.

The hermetically sealed pressure-sensing capsule bonded to the header is the starting point for the assembly into a pressure transducer. Typically most transducers must be attached to a mounting surface, which is exposed to the pressure media, frequently by means of a threaded port. In addition, the header pins must be electrically connected to a high temperature cable assembly without the use of solder joints, which may fail at high temperatures. The high

temperature cable assembly must also contain material which will provide electrical insulation between individual leads, while the interconnects between the header and the cable as well as the cable itself must be strong enough to withstand the mechanical stresses of handling. The package is completed using a building block approach and Figure 10 shows the assembly of a typical ultra high temperature leadless pressure transducer.

A sleeve is welded between the first header and a second header. A high temperature (HT) cable containing nickel wires is used to interconnect the pins from the first header and the exposed leads from the first header are welded to the second header to ensure low resistance electrical connections between the leads of the HT cable and the header leads.

The header/ HT cable assembly is then inserted into a port and welded to the port. At the end of the port is a tubulation, which is crimped to retain the HT cable.

A cover sleeve is then assembled over the HT cable to give additional support and is welded to the rear of the cover, which in turn is welded to the port.

This design of assembly results in the transducer being totally hermetically sealed from any atmospheric contamination or oxidation. Every single internal metallized surface such as metal to silicon and metal to glass frit, header pins to header tubes, header pins to HT cable wires are hermetically sealed from the atmosphere. In addition, the welding of the sleeve to the port together and the addition of a cable relief and crimp ring greatly increases the structural integrity of the entire electrical interconnect system and reduces the chances of any damage in severe environments.

9. STATIC PERFORMANCE

Test data from the latest generation of leadless transducers manufactured have confirmed the original results and, in fact, has demonstrated operability of these sensors up to and above 1075°F. The latest sensors reconfirmed the previously reported data [10] where devices were shown to have the following characteristics: less than 0.02% F.S. non-linearity and no measurable hysteresis up to temperatures of 482° C (900°F). At temperatures of 454°C (850°F) the non-linearity increased to around 0.1% F.S. but a static error band of better than 0.15% F.S. was demonstrated. All units tested exhibited only minor changes in performance characteristics after repeated exposure to high temperatures. The

compensated units exhibited span and zero shifts of less than 1% F.S. over the *temperature range from room temperature to 480°C (900°F)*. The latest evolution of leadless SOI sensors were tested at 150 psi up to 1075°F. The data was extremely stable and repeatable and is shown in Figure 11.

10. DYNAMIC PERFORMANCE

The design of the high temperature sensor is such that it should have high frequency response characteristics similar to those of more familiar, low temperature capability Kulite sensors. To verify this experimentally, a pulsed air apparatus was set up in an oven. The frequency response test configuration is shown in Figure 12.

Large-scale pressure primary pulsations at frequencies up to 400-500Hz were generated by a water cooled, motor driven rotary valve with an 1/4" port. The valve was close mounted externally to an oven containing the test transducer. About 15 cm of 1/4" stainless steel line connected the valve to the transducer, which was mounted on one leg of a T-piece inserted in the line. A second, standard, lower temperature capability transducer (model XTC-190) was mounted in the opposite leg of the T. The air flow, after passing by the transducers, exited the oven through 15 cm of line to a manual throttle valve.

The response of both transducers was first established at room temperature. The high temperature unit and low temperature reference unit had essentially identical waveform shapes and frequency responses. This verified that the transducers and test arrangement were responding as expected. The reference unit was then removed and the test repeated at elevated temperatures, after an appropriate soak time.

An example of the transducer response at 650 F when subjected to a nominally 250 Hz sinewave excitation is shown in Figures 13 and 14.

The amplifier gain used was 200. At the higher frequency of 400Hz, the waveform is less sinusoidal due to resonance in the flow system. The second harmonic response is clearly visible at 800Hz. These tests are greatly constrained by the limitations of the excitation mechanism and so do not fairly illustrate the frequency response capabilities of the sensor, which is in excess of many tens of kilohertz. The data do however, demonstrate nearly ideal ac response through the range of interest for many gas turbine active control applications.

Additional Dynamic Response Time Testing was performed using a shock tube. A block diagram of a shock tube set-up is shown in Figure 15. The shock tube is an apparatus where a pressure medium is separated into two chambers that are isolated by a Mylar diaphragm. The device under test is mounted to the end of chamber #1 with its pressure-sensing element exposed to the inside of the chamber. A specified pressure level is applied to chamber #2 and the Mylar diaphragm is ruptured using the shock tube control system. This produces a square wave pressure pulse that travels through chamber #1 and excites the pressure-sensing element of the device under test. The dynamic response of the device under test is captured on the digital storage oscilloscope.

To test the dynamic response time of the latest leadless sensor, a high temperature XTEH-7L-190-200A was mounted to the end of chamber #1. A pressure level of 200 psi was placed in chamber #2. The shock tube control system pierced the diaphragm, which sent a square wave pressure pulse to the device under test. The dynamic response of the device was captured on the digital storage oscilloscope, which was recorded to be 4.0 microseconds with a natural frequency of approximately 800 KHz (Figure 16).

Additionally, in order to evaluate the robustness of Kulite's transducers, Kulite has developed and established its own testing and evaluation technology. Using standard vibration test apparatus, accelerations to 50Gs can be achieved, in the 100 Hz to 3000 Hz range. In order to test components to significantly higher G levels, a resonant beam apparatus is used to achieve the high acceleration levels on standard vibration test equipment.

The beam is designed (Fig. 17) to amplify the acceleration level around the beam's resonant frequency with an amplification essentially being the Q of the system. The resonant frequency is chosen based on design requirements at the high acceleration level. Typically, aircraft structures have the highest G requirements at about 1,000 Hz and the beam dimensions, such as length and cross section, are selected to achieve the frequency and amplification required. The beam is fastened to the vibration table (fig. 18), allowing the low acceleration levels to act as the system input. The device under test, which will experience the amplified G level, is placed at the end of the beam. The amplification can be on the order of 10 to 250 times.

Two accelerometers were used on the beam to measure the vibration (acceleration levels). Accelerometer #1 was used to sense the shaker-produced vibration, while accelerometer #2 was used to measure the amplified vibration levels. The leadless transducer was mounted on the beam next to the measuring accelerometers (#2) and the beam was vibrated at its resonant frequency (at approximately 1650Hz) with a G of 37 in the shaker and a Q of 7.3. The transducer itself saw a G of 271 and the transducer was held at this vibration level for two (2) hours with no sign of degradation. By increasing the G level of the shaker to 62 and at the same resonant frequency, it resulted in a measured G level of 617 (Table 1). The transducer was held at that level for two (2) hours. Once again the units survived with absolutely no sign of degradation.

11. CONCLUSIONS

The latest generation of leadless sensors have been designed, fabricated and evaluated within Kulite with very encouraging results. The key features of the leadless design, which are protected by U.S. Patent Number 5,955,771, are the elimination of the gold ball bonding and gold lead wires and the hermetic sealing of the pressure capsule and the transducer assembly which will enable these transducers to operate reliably in the most hostile environments.

These sensors have been demonstrated to (1) operate up to and above 1075°F, (2) perform well through dynamic time response testing and (3) withstand very high G-level (acceleration) without any signs of degradation.

Currently these next-generation leadless dynamic pressure transducers are being evaluated both in laboratories and on gas turbines by the majority of the US and European aero engine manufacturers and many aerospace industry test organizations. The results of this test program will be the subject of further technical papers.

12. REFERENCES

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Massachusetts Institute of Technology, MA
MTU, Munich
NASA Lewis, Cleveland, OH
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Rolls-Royce, Derby, UK
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Figure 1

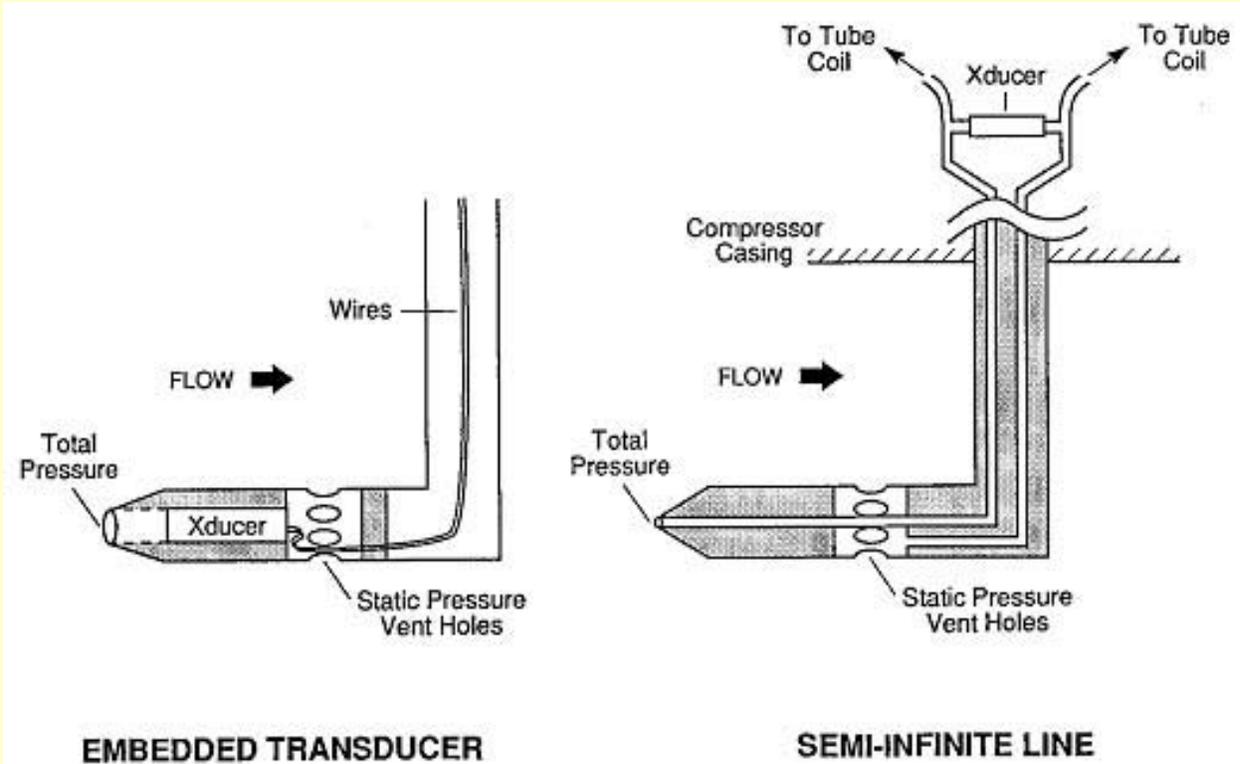


Figure 2

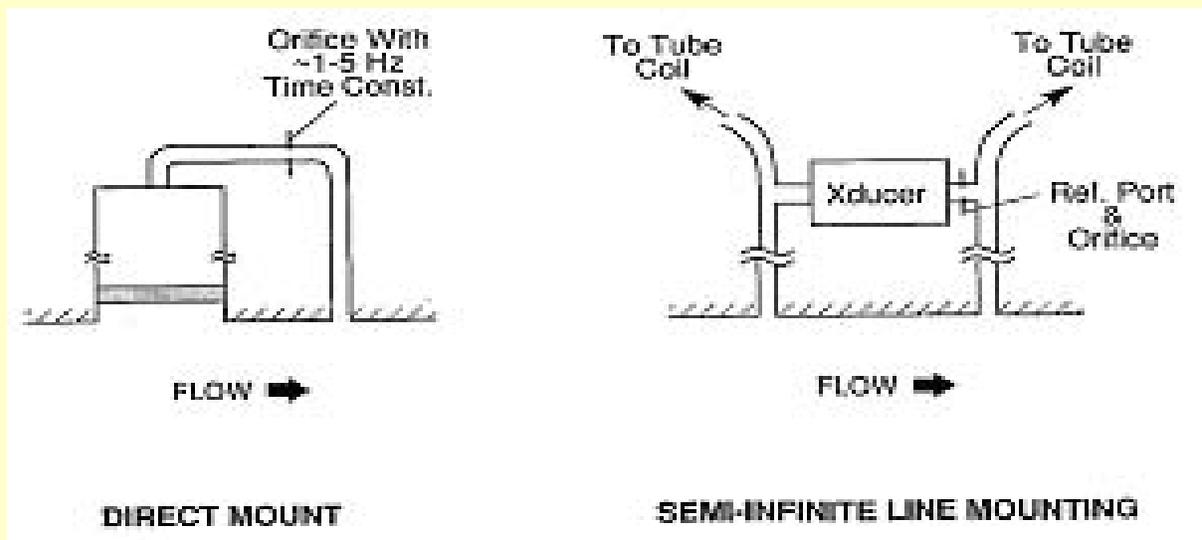


Fig. 3
Silicon Integrated Sensors

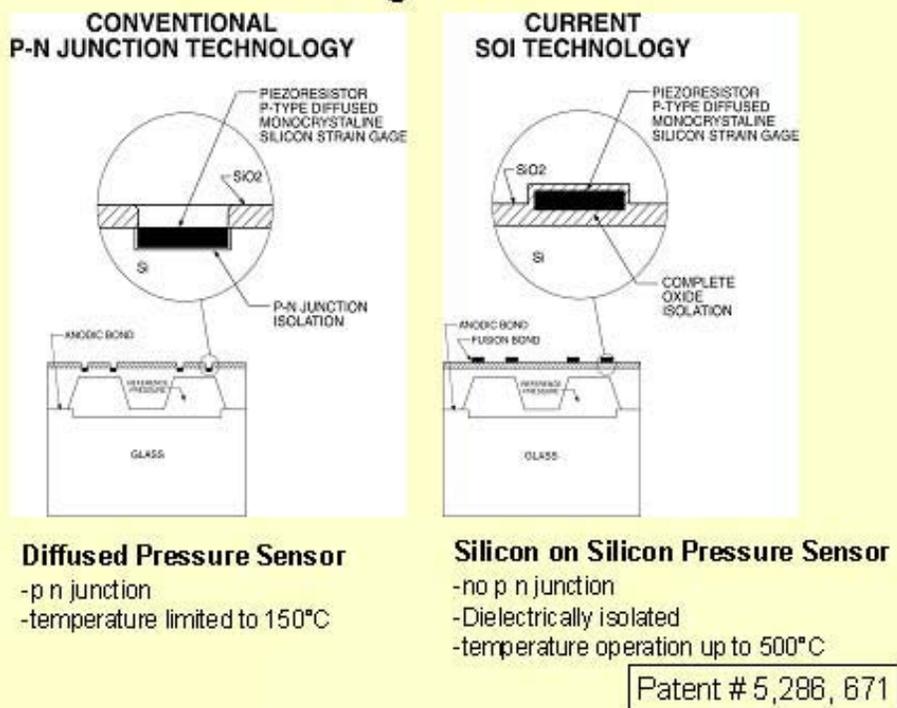


Fig. 4
Dielectrically Isolated Sensor

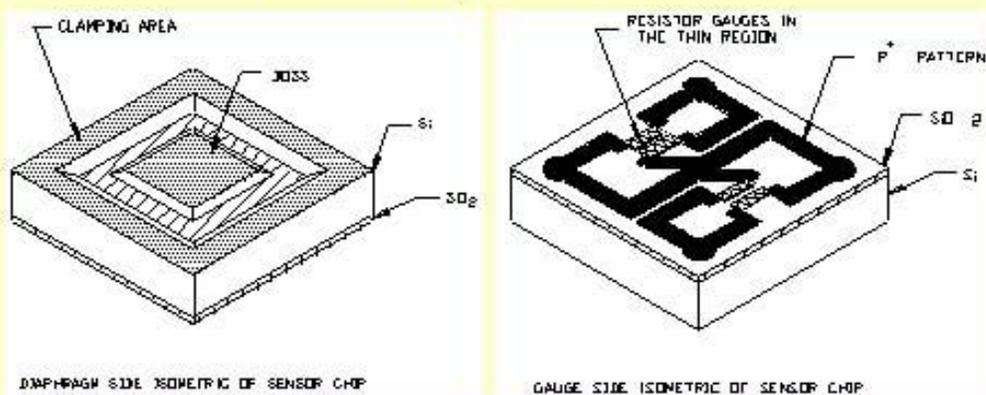


Diagram showing Isometric View of the Sensor

Figure 5

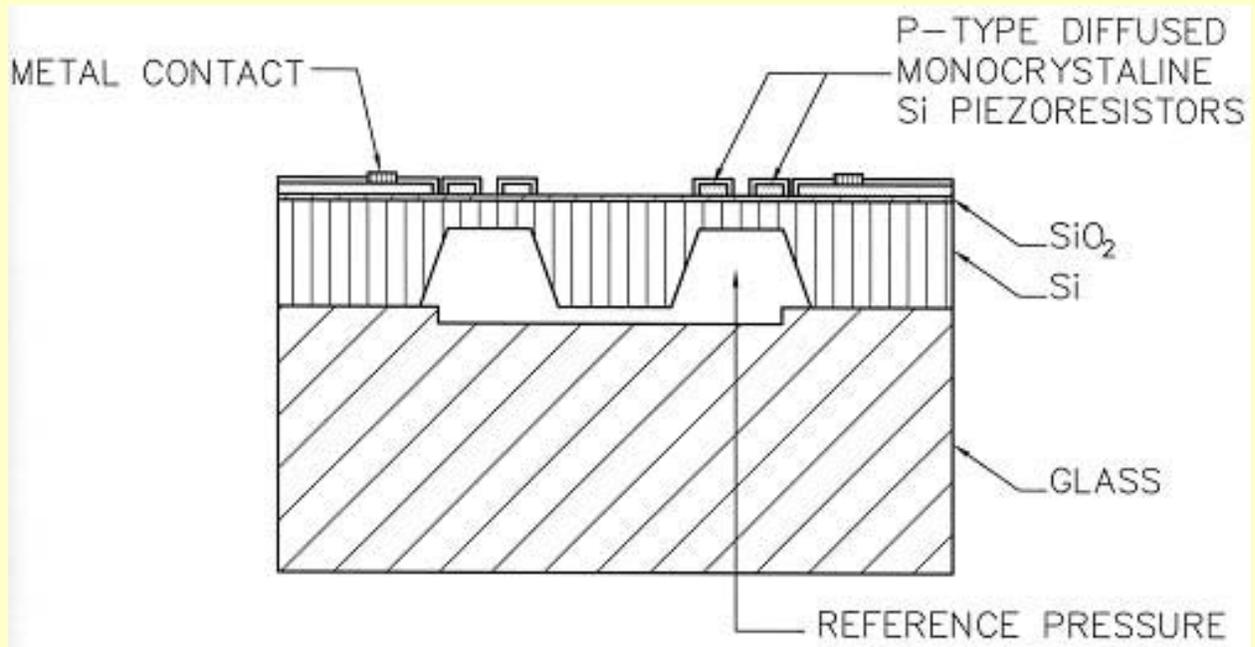


Fig. 6
Leadless Sensor

- Leadless Silicon on Silicon Sensor with Cover Glass Attached

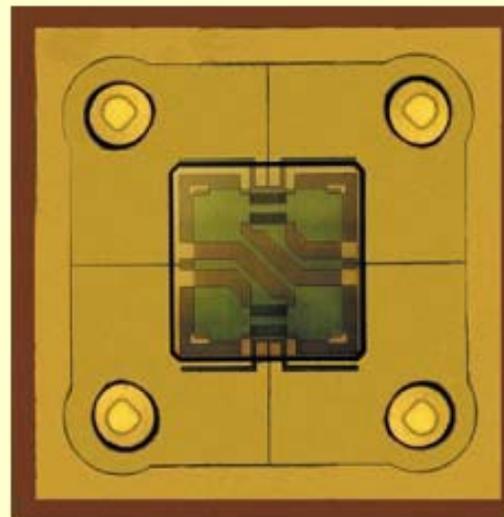


Fig. 7
Leadless Sensor

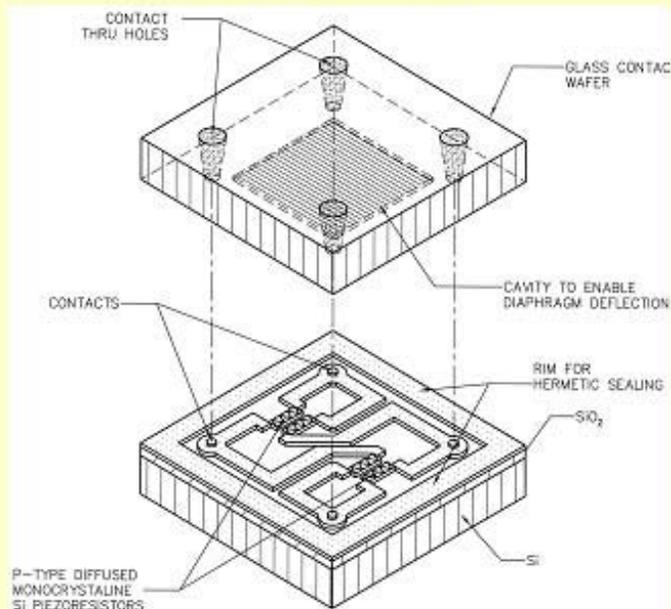
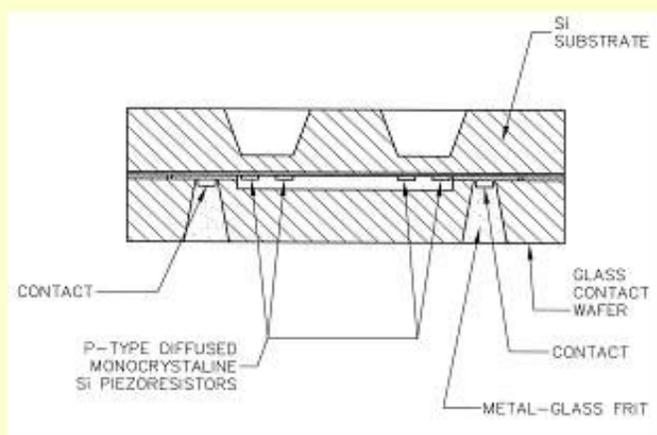


Fig. 8
Leadless Sensor



SIDE VIEW OF THE "LEADLESS CHIP COMPOSITE" AFTER FILLING WITH GLASS-METAL PASTE FOR CONTACTING

Figure 9

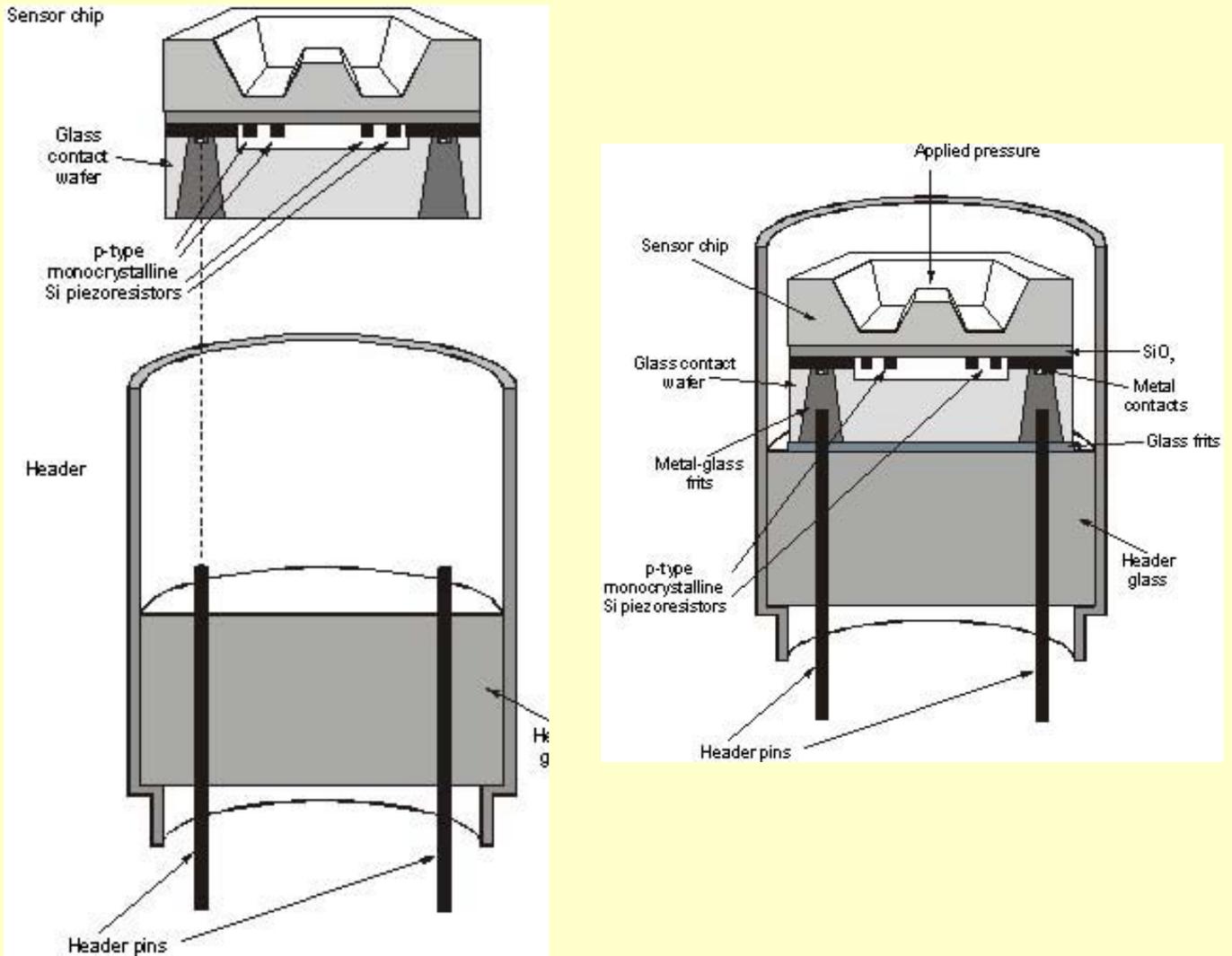


Figure 10

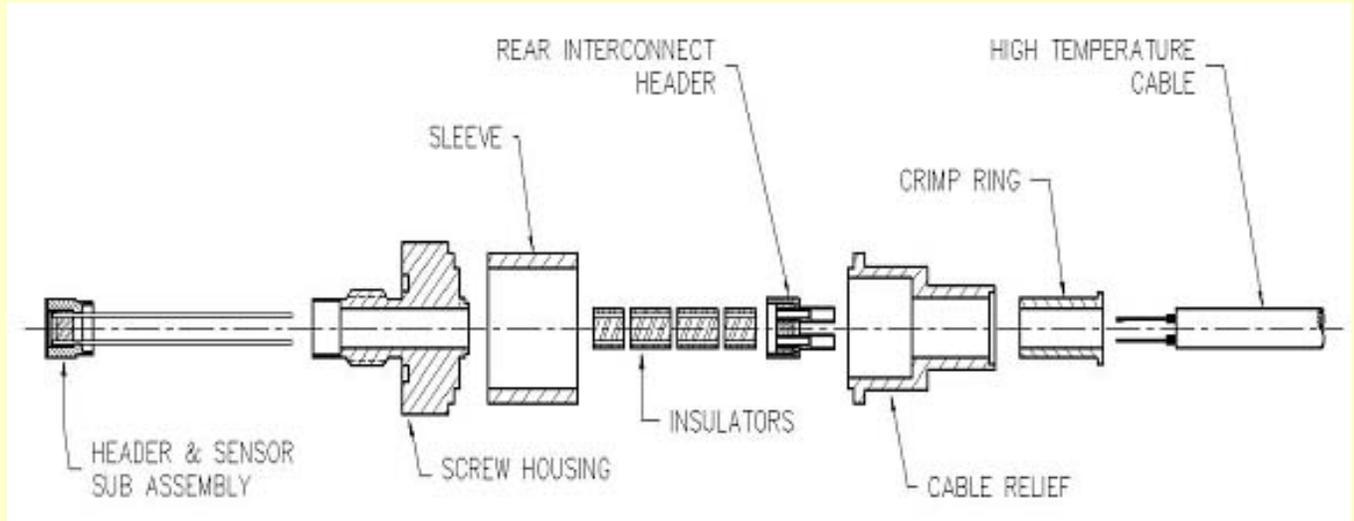
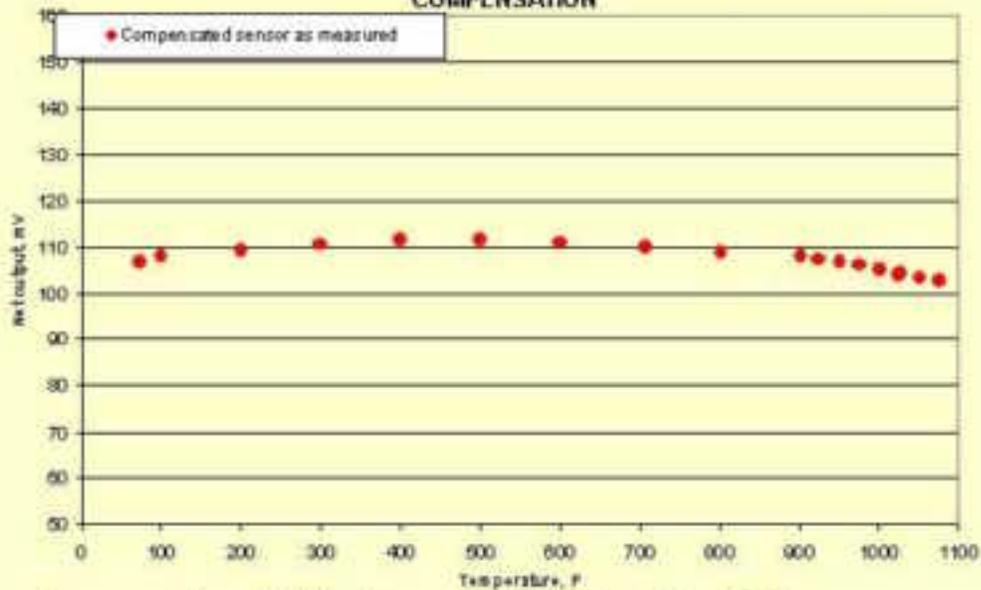


Fig. 11
SOI SENSOR PERFORMANCE UP TO 1075 °F WITH SPAN TEMPERATURE COMPENSATION



- Span compensation calculated and measured with 10 VDC excitation at 1500.
- wafer lot # 6837-3D4

Figure 12

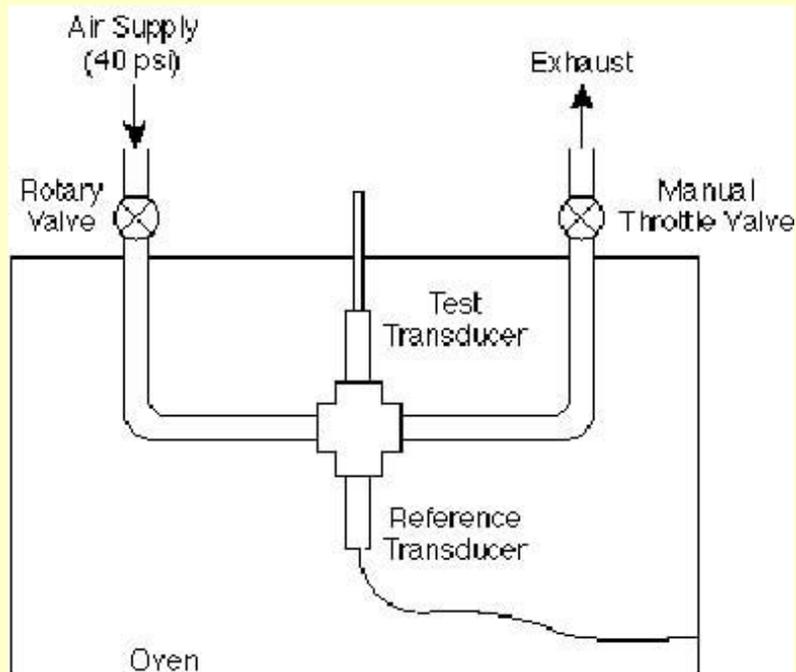


Figure 13

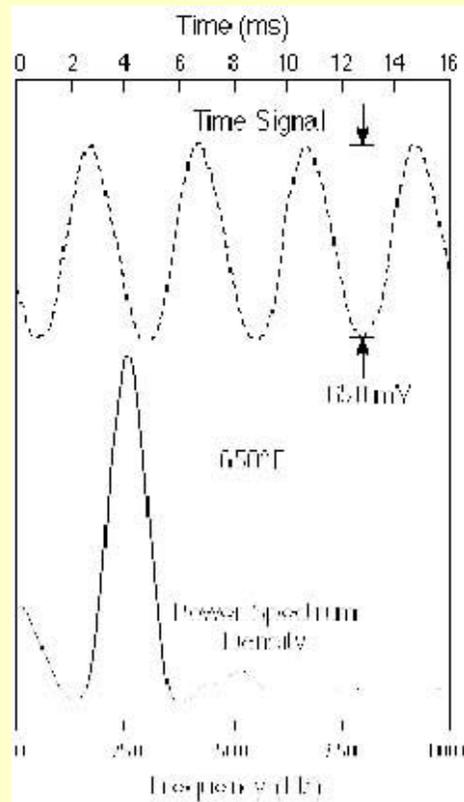


Figure 14

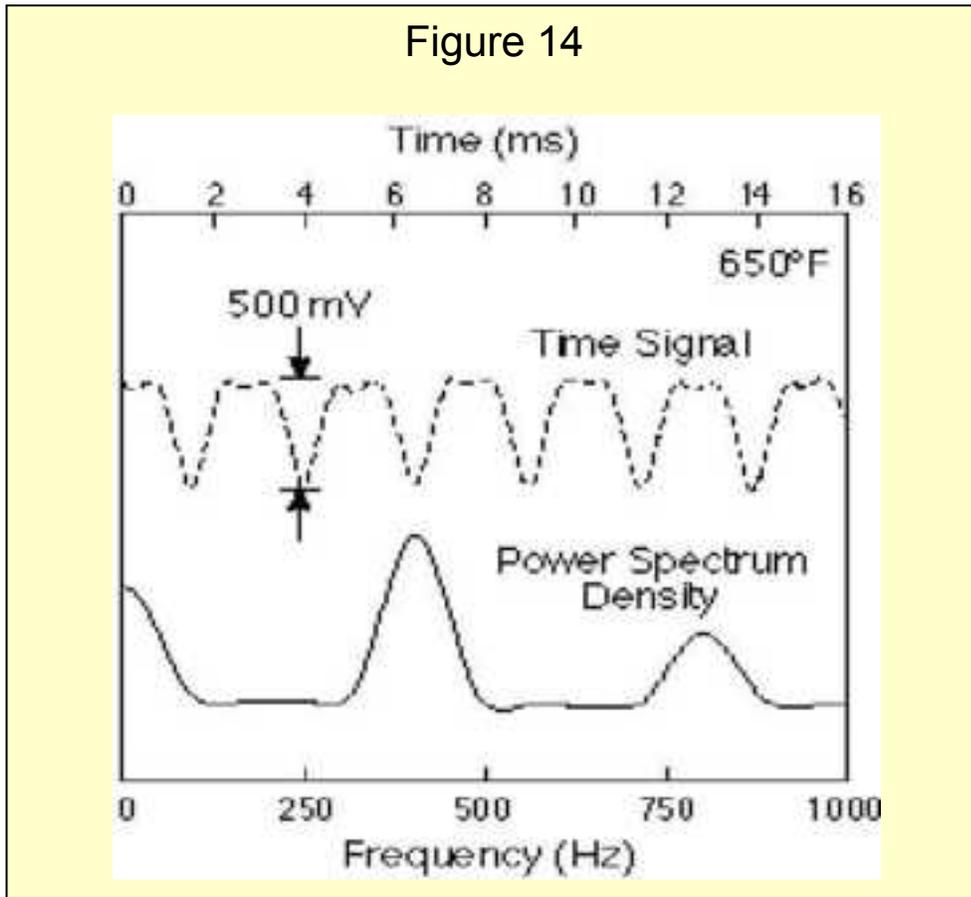


Fig. 15
Block Diagram of Shock Tube Set-Up

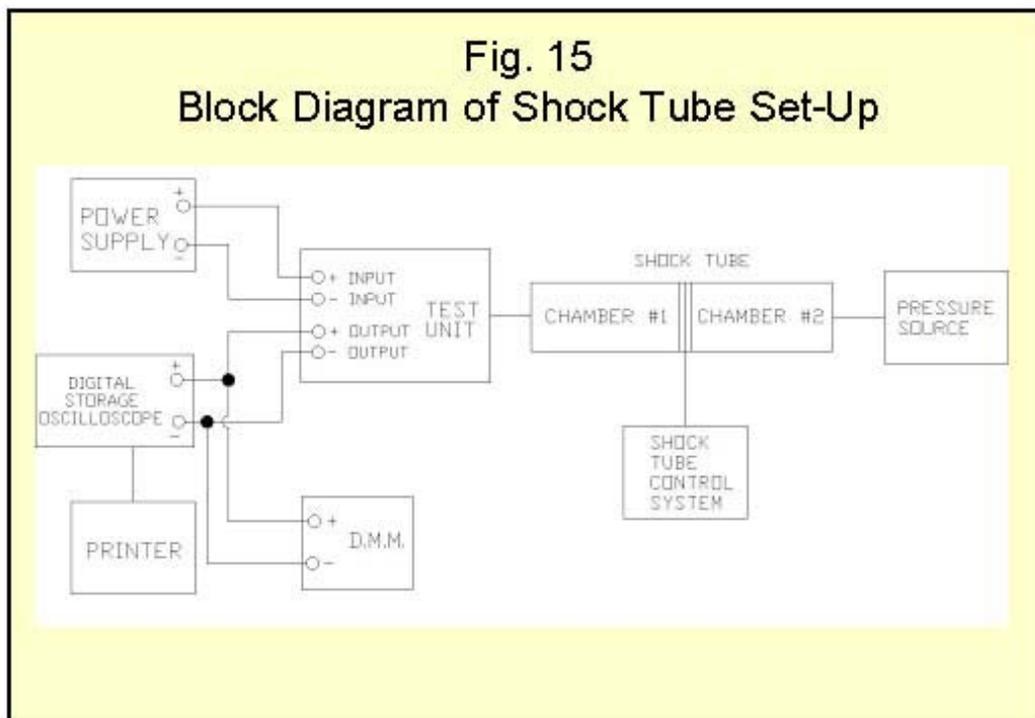
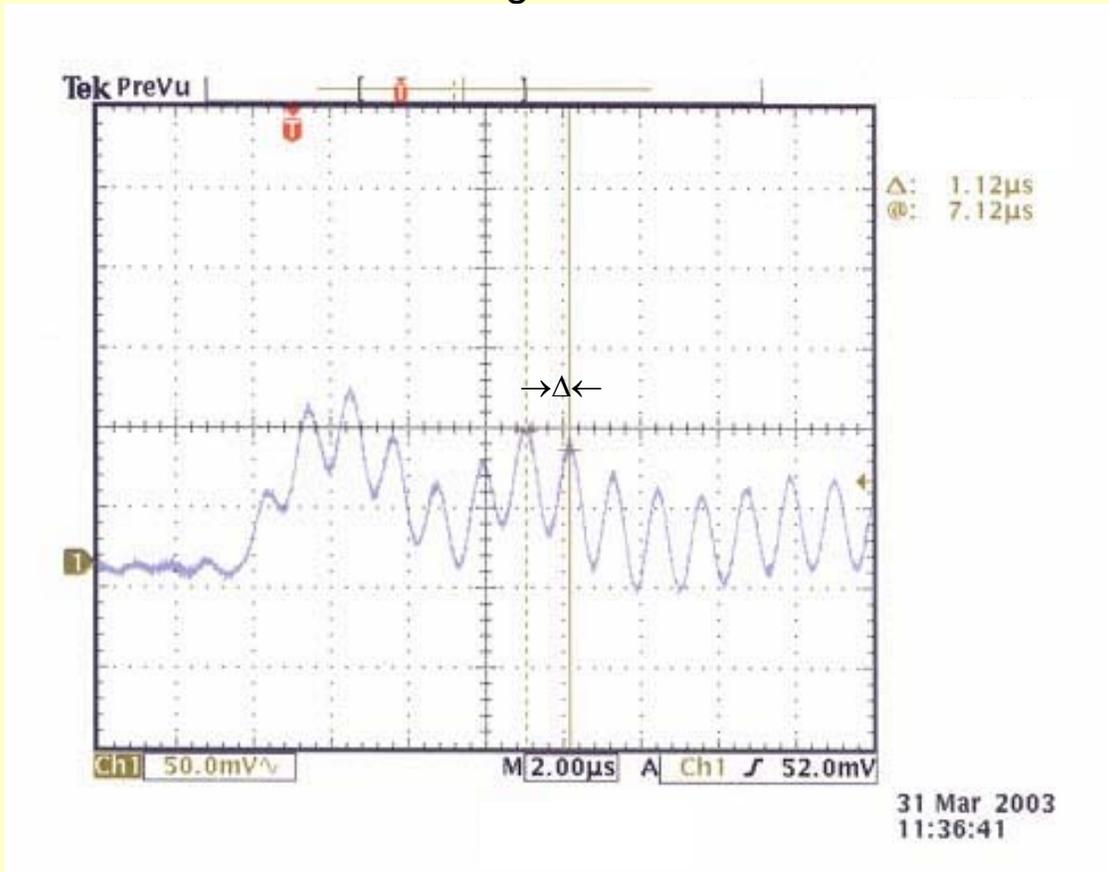


Figure 16

OUTPUT (50 mV/DIV)



TIME (2 μS/DIV)

Fig. 17
Resonant Beam Apparatus

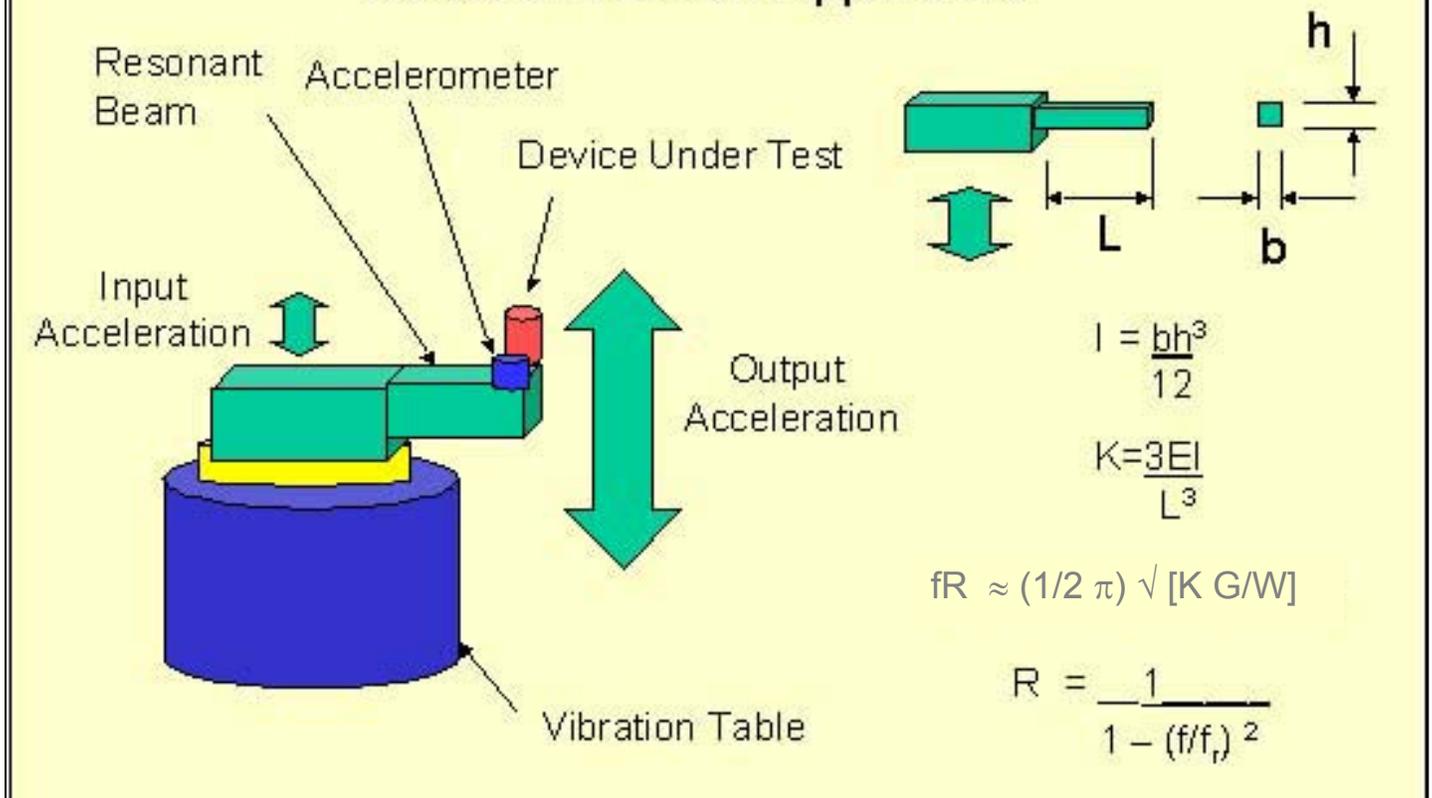


Figure 18
Vibration Set-Up

Control
Accelerometer



Response
Accelerometer



Resonating
Beam

Table 1

Control (Shaker G)	Beam (Resonating Frequency Hz)	System (Q)	Response (Output G)
37.42	1649.49	7.26	271.7
65.52	1623.90	9.87	617.1