Sensors and Networks for Aerospace Applications

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ABSTRACT

Sensors and networks are critical for realizing long, successful and safe operational lifespan of aircrafts and aerospace vehicles. They are used for structrural health monitoring; fuel quality and level monitoring, detection of leakage in fuel tanks, corrosion damage assessment, monitoring ice formation on windscreens, distributed temperature sensing of cabin and luggage bay, inspection of the luggage bay for hidden lethal and explosive items and navigational guidance etc. The aerospace sensors being used so far were mainly based on conventional technologies but in the recent times optics and photonics based sensor technologies owing to their various inherent advantages have become significantly important for these applications. CSIO has been working in the domain of sensors and instrumentation systems for aircrafts for the last more than two decades and several systems, devices & techniques have been investigated and develo0ped for different aerospace applications. They include, head up displays systems, panoramic cameras, fiber optic tail rotor control system for ALH, sensors for wind impact, cracks, strains, vibration, acoustic emission, temperature, fuel quality, level & leakage; corrosion, etc. The paper highlights the various emerging sensor and network technologies, trends and the current & future challenges for aerospace applications and discusses in detail the achievements made, technologies, developed and techniques investigated at CSIO for realizing different aircraft systems, sensors and networks.

1. INTRODUCTION

Aircraft structures are designed to accomplish their operational requirements at minimum cost. The ratio of life–cycle-cost versus operational capability has been significantly reduced over the past decades. This has been possible through the introduction of fracture mechanic analysis, better fatigue life evaluation concepts and improved non destructive testing, thus allowing to switch from safe life to fail-safe design. Fail safe conditions require a substantial amount of monitoring. This amount significantly depends on the failure criticality to be monitored. Advanced aircraft and spacecraft will thus require sensor technology to monitor the various aircraft parameters including the environment surrounding the platform as well as structural integrity of the platform itself. Size, weight, immunity to EMI and environmental ruggedness are the main drivers for usage of such a technology. Fiber optic sensor technology offers several advantages as compared to electronic technology for these types of applications including being lightweight and non-obstrusive, all passive configurations, low power consumption, immunity to EMI, high sensitivity and bandwidth, compatibility with optical data transmission and processing, long lifetimes and low cost.

In view of these salient features of fiber optics, for a number of years experts have been predicting a successful marriage of fiber optics and aircraft design. These days, the concept of smart skins is already making this prediction a reality. The term `Smart Materials and Skins' generally represent the structural fabric into which separate functions of sensing, actuation, signal processing and control are somehow integrated, while `Smart Structures' are an extension fabricated from smart materials to respond to the world around them – they will for example suppress vibrations or redistribute the load path in response to damage. The results of the efforts being made in the area of smart materials and structures technology may provide aircraft and space craft that are able to diagnose their status prior to take off, greatly reducing personnel requirements while increasing safety. It would also allow onboard systems to provide maintenance schedule information and diagnostic support thus reducing downtime and lowering costs [1].

Optical fiber sensor `nerves' possess the ability to monitor a variety of changes and combined distributed, multi measurand and networked sensing capabilities. They can be attached to materials or embedded within them in order to monitor materials during their fabrication, formation into a structures and use. During the lifetime of a smart material, fiber sensors could allow the integrated monitoring of a wide range of physical changes, including strain, temperature, vibration, ultrasonic waves and corrosion. The aerospace industry is a potentially important user of optical fibers, particularly as data links, which are considered a mature technology following a decade of intense development. Suppliers of military aircraft, such as Westland Helicopters, already use such components in their Lynx helicopters as pert of replaceable elements in their communication links, with projects such as the Boeing 777 and Eurofighter 2000 being potential candidates. Although research projects have shown that optical fiber sensors can operate within prescribed limits for use in aircraft, they are still considered as a technology under development. To date efforts are directed towards the sensor development for harsh environments unsuitable for conventional electro-mechanical sensors, taking advantage of radiation resistance and EMI immunity. The aerospace industry is very conservative and new sensors must undergo long testing periods before major changes in instrumentation systems can be accepted in both civil and military aircraft. Given the economy of scales, however, optical sensors can only be successful if they "buy" their way onto the aircraft. Practically this means a sensor system weight or cost reduction compared with electrical sensors. Increases in sensor reliability and ease of installation and maintenance with little training and without special handling are demanded, ideally leading to the so-called "fit and forget" systems. Finally, standardizing sensors and instrumentation reduces part numbers and overall costs.

Sensing strategies for aerospace applications (airplanes, helicopters, missiles, and space vehicles) broadly follow the same conditions. The most important requirements are to have passive, low weight, and ideally common sensors that may be multiplexed over optical links. By carefully defining sensor requirements, it may be possible to specify a range of optical sensors, satisfying the majority of avionics applications that are either interchangeable or at least use common interrogation instrumentation. Currently, many sensor types perform similar functions but are not interchangeable. Any new optical fiber sensors cannot exceed the size and weight of conventional electro-mechanical sensors; therefore, a sensor intrinsic to the core of standard fiber optic cable, e.g. a fiber Bragg grating, is highly attractive. The Bragg grating sensor solves one of the major drawbacks to optical fiber sensors: the lack of a standard demodulation approach, while maintaining a completely passive network. The largest class of sensors measures the position of flight control elements such as landing gear status, flap and rudder position, and so forth. When taking into account high levels of system redundance (triple level for key equipment functions), well in excess of 100 sensors are employed. As a result, size and weight savings become important. Flight control sensors monitor fuel levels, vibration, and so forth.. This is an area of high sensor density, in a critical application area where sensors are systematically exposed to harsh environments. There are a number of sensor categories, such as temperature, pressure, speed and proximity sensors, fluid level, torque and debris monitoring sensors.

Keeping in view the advantages offered by fiber optics for avionics, in 1976 the US Air Force replaced a wiring harness of an A-7 aircraft with an overall optical data link in its airborne light technology programme (ALOFT): 302 electrical cables, over 1,200 meters in length and weighing over 40,000 grams were replaced with 12 optical fibers, 76 meters in length, weighing less than 1,700 grams. In the ALOFT program, the principal design requirement was the reduction of size and weight. But one of the major ancillary benefits was the development of a safer aircraft. The ability to provide complete redundancy for all critical cabling is a major motivating factor in the introduction of fiber in avionic systems.

On July 17, 1996 at about 8.30 PM in the evening TWA 800 flight crashed into the Atlantic Ocean shortly after take off from JFK Airport. The evidence indicated that an in flight explosion occurred in the central fuel tank (CWT). After this event the FAA has adopted a lessons learned approach in its recommendations on preventing fuel cell explosions. The F-16 Fight Falcon was one of the earliest applications of explosion proofing in military aircrafts. In this aircraft, every available cubic inch of space is used to carry either fuel, ordnance or critical airborne system. Usable space is at such a premium that the cable harnesses used to transmit fuel quantity data, power the fuel pump, interconnect the fly by wire flight control system, and provide data links between critical avionics sensors and cockpit devices must travel directly through jet's internal fuel cells. Such ‘Total Immersion Fuel Tank Air Borne Cables (TIFAC)’ must exhibit extremely high integrity while fully immersed in jet fuel, lubricating oil, hydraulic fluid and other liquid chemicals. The cables must be able to withstand penetration and degradation from these caustic fluids for their entire life span, as any failure could potentially introduce an ignition source into the fuel cells and result in a dangerous flight safety condition. The total electrical isolation of optical fiber clearly makes it a safer, spark free media for use in hazardous environments such as aircraft fuel cells.

A vigorous effort is being made worldwide for research and development of optical fiber based sensors for aircraft and aerospace applications. Some of the important fiber optic sensors that have been developed and or investigated recently for these applications are based on extrinsic Fabry Perot interferometric (EFPI) configuration, fiber Bragg gratings (FBGs) & long period gratings (LPGs) and Raman scattering based distributed temperature sensor (DTS) [2]. In an EFPI sensor, two single mode fibers are aligned in a silica capillary tube leaving a small gap and it works as a low finesse Fabry Perot sensor. The schematic of an EFPI sensor is indicated in Fig 1.

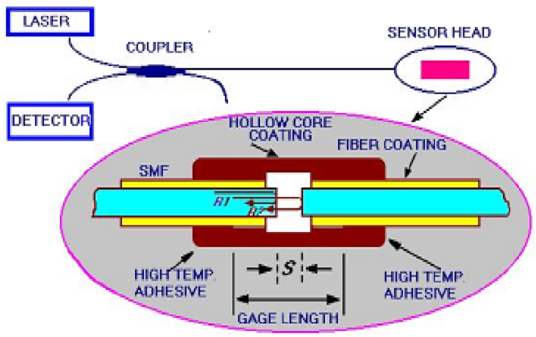
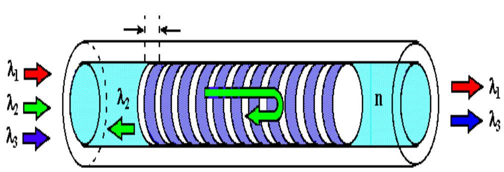
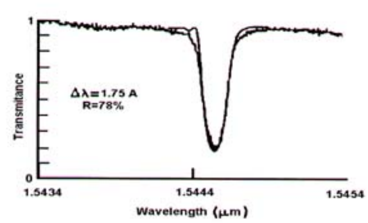


Fig 1. Schematic of EFPI Sensor

The change in the air gap of the sensor due to the measurand like temperature and strain is determined employing the technique of white light interferometry. This sensor offers excellent features like only axial and point sensing, extremely low apparent thermal strain and suitability for bonding & embedment in aerospace structures. This sensor has been developed at CSIO and it is extremely useful for health monitoring of structures. FBGs and LPGs are periodic perturbations in the refractive index of optical fiber cores created by exposing the germanium doped silica cores to UV radiations from either a KrF excimer laser (248nm) or a frequency doubled Ar ion laser (244nm) through a phase mask. FBGs can also be written holographically without using a phase mask but it needs a highly stable environment. Figures 2 & 3 illustrate an FBG and LPG.

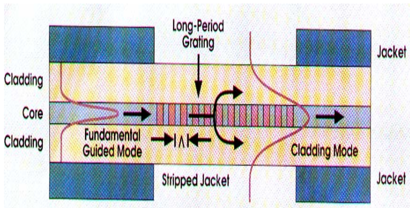


$\lambda_B = 2 n_{eff} \Lambda$ (Br



λ_B :Bragg wavelength,
n_{eff}.:Effective RI of the core ,
Λ:Grating pitch

Fig 2. Illustration of a uniform FBG



$\lambda_i=[n_{01}-n(i)clad]\,\Lambda$

(Phase matching condition)
λ_i : loss resonance wavelengths
n_{01} : Effective index of core mode
n(i)clad : effective index of ith cladding mode
Λ : Pitch of the grating

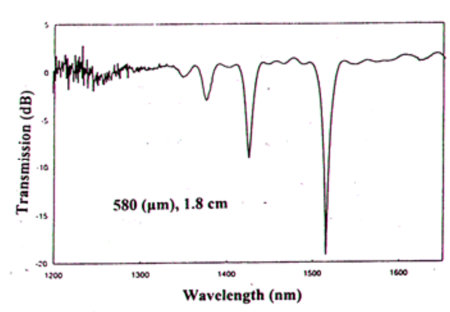


Fig 3 . Illustration of an LPG

The output of FBGs and LPGs basically involves measurement of shift of wavelength and the power loss at resonance wavelengths providing the salient features of self referencing and ease of multiplexing for realising distributed sensing. FBGs and LPGs have been investigated for structural health monitoring of aircrafts, as a fire safety sensor, fuel leakage and other sensing applications. A fiber optic distributed temperature system (DTS) functions on the basis of Raman scattering principle where temperature dependence of the ratio of upper and lower (anti Stokes and Stokes) sidebands of the Raman scatter signal is the basic physical property of the phenomena and it provides a temperature-sensing means with ranges of tens of kilometers and resolutions on the order of degrees Celcius in ranges on the order of a meter. Such a system has been developed for aircrafts and remotely piloted vehicles.

2. Aerospace Sensors and Systems Developed at CSIO

CSIO has been actively engaged over the years for the development of aircraft sensors and systems for different applications. They include panoramic cameras for reconnaissance, HUD system, temperature sensors, structural sensors, optics for RPVs, tail rotor controller for ALH, fire safety sensors. The details about these systems and sensos are briefly described below.

2.1 **Aerial Panoramic Cameras**

In the beginning, aerial panoramic camera (70mm) providing horizon to horizon scanning and mini pan (35mm) camera were designed and developed for reconnaissance application by fighter and unmanned aircrafts respectively. Both the cameras have undergone successful user trials. The developed minipan camera is shown in fig 4 .

Fig 4. Minipan Camera

2.2 **Head Up Display System For LCA**

Optics, Opto-mechanics and Opto electronics form an important part of a large number of instruments used for a variety of applications. R&D in the broad area of optical, opto-mechanical and opto electronic systems in general and avionics in particular, has been an active pursuit of the Institute over the years and as a result, expertise has been acquired and excellent infrastructural facilities created in the areas of optical design, aspheric optics, precision optics fabrication & testing, optical systems fabrication, assembly & testing, and thin film deposition & characterization. A Head Up Display (HUD) system for the Light Combat Aircraft (LCA) has been designed and developed. The prototype has under gone several successful flight trials and fully engineered eight numbers of the prototypes were developed in the first phase and delivered out of which three are airworthy units. Three HUD units are

Fig 5 HUD for LCA

installed in LCA-TD2, LCA-PV2 and are working satisfactorily. The developed HUD system is shown in fig. 5. and the technology has been transferred to M/s Bharat Electronics Limited (BEL) Panchkula. A batch production of 11 units has commenced at BEL, Panchkula as part of the second phase of development. The implementation of Night Mode feature in HUD is in final stages and the unit will be fabricated with both day and night mode features. The main features incorporated the system are: Total field of view 25 degrees; instantaneous FoV 18 degrees in elevation and 20 degrees in azimuth, high reflectivity for CRT display wavelength and at the same time high transmission for the outside world visible wavelength region, Brightness > 3300 footlamberts;capability to use it in night with FLIR camera and automatic brightness control for hand free operation. By adopting multiplayer selective coatings, peak reflectivity of 75% has been achieved and this has led to realization of minimum system loss. It is a matter of pride that this development enabled the Institute to bag the prestigious CSIR Technology Award for the year 2002 in Engineering Sciences. The first Successful Flight took place on 6th June 2002. HUD unit is also being fabricated for HJT-36 trainer aircraft of HAL (fig 6). This is an improved and compact version in comparison to HUD for LCA. The overall volume would be 60% of the LCA-HUD and weight would be 15 Kg. A new feature of electronic stand by sight (SBS) has been introduced which will guide the pilot for combating and landing, in case the mission computer of the aircraft fails. The synthetic SBS symbology will be displayed whenever the pilot demands.

Fig 6. HUD for HJT-36

2.3 **Relay Lens for RPVs**

Relay lens of 1.5 X & 2.3 X have been designed and developed for RPVs. Gimble due to space constraints to accommodate zoom lenses and CCD cameras. Both the systems are working in Visible Spectrum from 400 nm to 700 nm. Five units of each have been delivered to Aeronautical Development Establishment (ADE), Bangalore for integration in the Gimble of RPV. On successful field trials at Pokhran, ADE, Bangalore has sponsored another modified version of Relay lens 1.5X working in wide spectral range from 400 to 1100 nm. Number of lenses has been reduced from 12 to 8 in 2.3X system. Both types of systems are working 85mm of folding light path. The Relay Lenses are in fig. 7 having two right angled prisms one fixed type and another floating in order to achieve the image shift of 5mm while zooming for full zooming range. Limited Series Production has been initiated by ADE, Bangalore.

Fig 7. 1.5 X Relay Lens

2.4 Fiber Optic Tail Rotor Control System for Advanced Light Helicopter (ALH)

A fiber optics based Fly-By-Light Tail Rotor Control System has been developed and tested for Advanced Light Helicopter. The system enables transmission of control signals through optical fiber cables instead of using hydraulic system thereby providing immunity EMI large bandwidth and appreciable weight and space saving. This is a step towards achieving total fly-by-light capability in future advanced aircrafts. The schematic of the developed system is shown in fig 9 below.

Fig 8. Advanced Light Helicopter

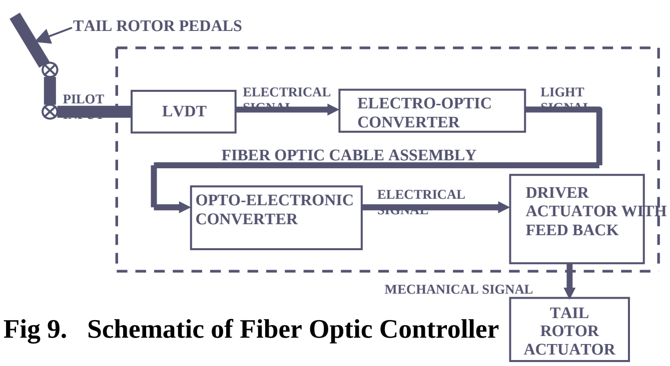


Fig 9. Schematic of Fiber Optic Controller

2.5 Structure Sensors

In the recent years, important application of fiber optic sensors has emerged for health monitoring of advanced existing and futuristic civil & aerospace structures and materials leading to the concept of smart structures and skins. Such structures and skins shall have the ability to sense their environmental changes within or around them, interpret and react to these changes and they will require development of materials with optical nerves. This form of resident inspectability clearly has both safety and economic ramifications, for it could lead to greater confidence in the use of advanced composite materials and weight savings through avoidance of over design. This should be of particular interest to the aerospace community because of the multiplier effect to weight savings in aircraft and space structures. This technology should lead to a reduction in maintenance, repair, and downtime of future aircrafts. CSIO has been engaged for the last more than 45 years in the area of Fiber optics and expertise have been acquired and infrastructural facilities created in the domains of fiber lightguide technology, fiber optic instrumentation, optical fiber measurements and fiber optic sensors. Currently an EFPI sensor for structural health monitoring has been developed and FGB & LPG sensors have been studied. and a state-of-the-art facility is being established for fabrication of fiber Bragg gratings and long period gratings for sensor applications based on phase mask and interferometric/ holographic writing technologies. Investigations and development carried out based on FBG, LPG and EFPI sensors in the realm of structures are as described below:

2.5.1 FBG Sensors Multiplexing for Strain and Temperature Measurement

FBGs offer all the advantages of optical fibers with some unique features of their own such as self-referencing and multiplexing capabilities in wavelength domain and thus have a distinct edge over other traditional devices.. Due to their inherent immunity to EMI, power fluctuations and radiation, FBG sensors have become quite promising especially in the field of structural health monitoring for different types of civil structures, nuclear power plants and for aerospace applications. In all these applications fibers with sensor arrays can be embedded into the materials to allow measurement of parameters such as load, strain, temperature and vibration from which the health of a structure can be assessed and traced on a real-time basis.. Investigations were carried out to study multiplexing of FBG sensors for multiparameter sensing in various situations and measurement of strain and temperature as applied to three spliced fiber Bragg gratings was undertaken. In most of the applications fiber Bragg grating sensors are used for point sensing of strain and temperature to provide quasi-distributed sensing. The strain response arises due to both the physical elongation of the sensor and the corresponding change in grating pitch and the change in fiber index due to photoelastic effects, whereas thermal response arises due to inherent thermal expansion of the fiber material and the temperature dependence of the refractive index. Typically, a wavelength resolution of ~ 1 pm (0.001 nm) is required (at λ_B~ 1.3 μm) to resolve a temperature change of ~ 0.1 ^{0}C or a strain change of 1 μ strain.

Three FBGs indicated as FBG1, FBG2 and FBG3 with different resonance wavelengths of 1549.576, 1548.426 and 1545.826 nm respectively are spliced together and connected to the interrogator in this order to demonstrate three different sensing elements. The three Bragg wavelengths are observed on the monitor under conditions of zero loading. The schematic and photograph of the experimental set up implemented are depicted in figures 10 and 11 respectively.

The first grating FBG1 is bonded to a metallic cantilever (39.5cm x 4.2cm) at a location of 12cm from the fixed end using

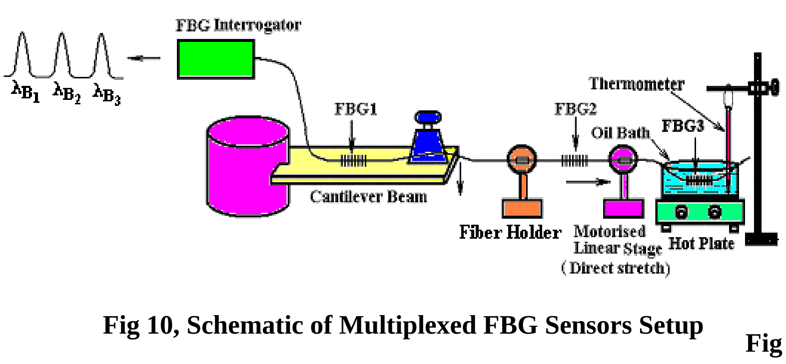


Fig 10, Schematic of Multiplexed FBG Sensors Setup

Fig 11. Experimental Setup of Multiplexed FBG Sensors

araldite epoxy. It acts as a pressure sensor with different weights applied on the cantilever tip and the results obtained for different loading are quite linear as shown in figure 12. The second grating FBG2 is used as a strain sensor and it is held tight between two fiber holders and stretched longitudinally using a motorized linear precision stage with a pitch of 0.5 mm i.e. one complete rotation of the motor screw results in 0.5 mm movement of the linear stage which is the change in length of the fiber (Δl as in equ.5.3). A 30 cm length of the fiber with a grating element located in the middle position is stretched by the movement of the stage. Thus, for each rotation value of the screw Δl is known and resulting strain is calculated using the simple formula for strain $\Delta l/L$, where L is 30 cm in this case. A maximum strain of ~2333 με was thus produced using this technique. The effect of the pulling strain on the Bragg wavelength is quite linear as shown in figure 13. The third grating FBG3, which demonstrates the effect of temperature on Bragg wavelength, is immersed in a glycerol bath kept in a second bigger bath containing water. The grating is heated indirectly to avoid rapid temperature rise. The temperature of the glycerol bath varied from 15^{o}C to 70^{o}C is measured using thermometer immersed in the glycerol bath and the corresponding Bragg wavelength shift was recorded which has also shown a good linearity as depicted in figure 14 [3].

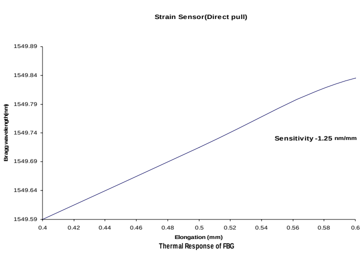


Fig 12:Pulling Strain response of FBG 1

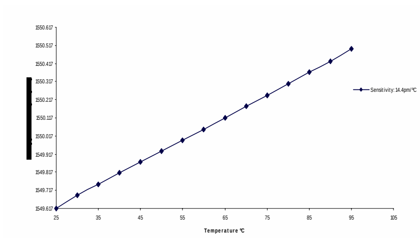


Fig 13 Temperature response of FBG 2

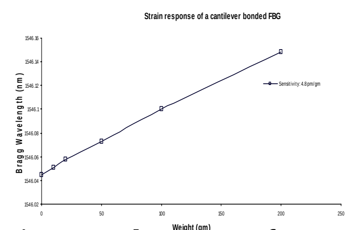


Fig 14 Load response of FBG 3

The performance of multiplexed FBG sensors, realized by splicing three fiber Bragg grating elements, is demonstrated for simultaneous measurement of strain and temperature. The three sensors have exhibited a good linear performance as expected. The experiment has been performed in a controlled temperature laboratory environment but in actual applications, suitable compensation technique will have to be employed for variation in environmental temperature to obtain the realistic mechanical strain data. For the second FBG sensor, strain results from the direct pull, and its sensitivity has been estimated to be approximately 0.39 pm/με. The third grating which is used as temperature sensor has exhibited a sensitivity of 11.1 pm / 0C. The first grating bonded to a cantilever has exhibited a response of 4.8 pm/gm. In this case bending the cantilever with pressure applied at its free end produces strain in the grating. Apart from being lightweight, low cost, immune to EMI/RFI, chemically inert; this device offers other advantages as well. For example, a good linear response is obtained in all the three cases and the sensed parameter namely strain and temperature are wavelength encoded, and hence they are independent of fluctuations in the light source, connector or fiber losses etc. Another point that is crucial for structural health monitoring and sensing in hazardous environment is the feasibility of remote sensing.

2.5.2 Wind Impact Measurement

Wind speed has an impact on the health of structures which include buildings, vehicles, aircrafts and ships. Keeping this aspect in view, investigations were carried out in the Lab by simulating wind impact with the help of an air compressor. An FBG was bonded to an aluminum plate and it was located at a distance of about 5.0 cm from the outlet of an air compressor and exposed to impact of different air pressures. A linear performance is observed between the


Fig 15. Experimental setup for wind impact of FBG Sensor

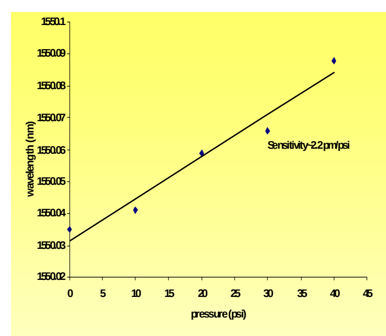


Fig 16. Wind impact response of FBG

pressure and the wavelength shift as expected. The experimental set up realized and the results showing good linearity are given in figures 15 and 16 respectively. The air pressure was varied from 0 to 45 psi and a measurement sensitivity of about 2.2 pm/ psi was achieved. There was, however, a little error caused by cooling of the grating due to water vapours coming out from the compressor**.** This experiment is further planned in a moving car where the gratings shall be mounted on the wind screen.

2.5.3 Extrinsic Fabry Perot Interferometric (EFPI) Sensor for Strain Measurement

An extrinsic Fabry Perot interferometer (EFPI) sensor has been developed for measurement of strain & temperature and detection of cracks in concrete, composite and metallic structures. Techniques have also been developed and investigated for safe embedding and bonding of EFPI sensors to structures The performance of the indigenous EFPI sensor was studied and was found to be satisfactory and comparable to the conventional strain gages.

As the area of structurally embedded optical fiber sensors is evolving quite rapidly, it is important to reduce the number of leads required and to eliminate the sensitivity of various leads. The Fabry-Perot optical fiber sensor provides a system in which a single optical fiber acts both as the lead-in and lead-out fiber. The extrinsic Fabry Perot Interferometer (EFPI) has evolved recently as an extremely useful embeddable and bondable sensing configuration for health monitoring of structures and materials. Operation of an EFPI basically depends on an air cavity which works as a low finesse 2-beam Fabry Perot interferometer. This important indigenous EFPI sensor has been designed, fabricated and its strain measuring characteristics were investigated. Techniques have also been developed for bonding of EFPI sensors to metal and concrete specimens and the sensor was bonded alongwith conventional strain gages to an aluminum strip and loaded in a cantilever configuration. The performance of the sensor has been found repeatable and comparable with that of the conventional strain gages.

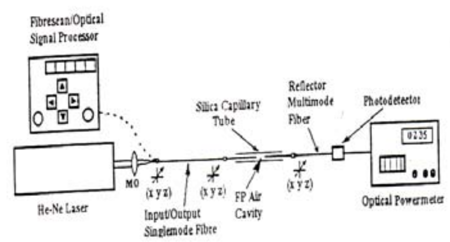


Fig.17 Schematic of EFPI Sensor Fabrication

Besides the advantage of simple construction, single-ended operation, high resolution & accuracy and low cost, EFPI sensor also offers several other novel features for applications in the domain of structures. Under a given situation of an arbitrary set of applied loads, the ability to measure the full three-dimensional state of internal strain is important for quantitative assessment of the damage of materials and structures. Such measurements have traditionally been accomplished through the use of surface mounted resistance strain rosette gages. However, these gages are limited to external applications and the Fabry Perot fiber optic strain sensor which offers the unique ability to be suspended within the matrix portion of the composite system, could provide a viable alternative to them for assessment of internal strain state of a structure. The EFPI output is not affected by transverse strains and the sensor only monitors axial strain components, since the cavity consists of only an air gap formed between two fiber end faces. The strain measurements by EFPI are also not affected by surface shears. Since one must contain a sensor in the smallest surface area to make a constant strain assumption reasonable, a small size sensor makes possible the acceptance of this approximation. The EFPI sensor can be manufactured with a very small gage length and meets the requirement of essentially providing a point measurement of the strain.

Fig.18 Experimental Setup for EFPI fabrication

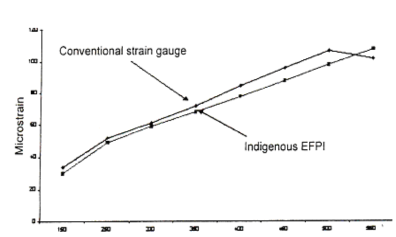


Fig. 19 Performance comparison for EFPI sensor

Embedded Fabry Perot fiber optic sensors can provide accurate and reproducible measurements of three-dimensional strain within a material containing complex damage states and offer a tool to interrogate the health of structures and an instrument to study the basic physical behavior. Such strain measurements would facilitate enhanced understanding and detection of composite failure modes (such as de-lamination), sensing for adaptive structural control, and structural health monitoring systems for civil structures. The latter application could involve remote monitoring of structural integrity during and after an earthquake. These embedded sensors can be subsequently used for in-situ characterisation of the host material or structure.

A fiber optic extrinsic Fabry Perot interferometric sensor was designed, fabricated and investigated in the laboratory for strain measurements. Figures 17-19 show the experimental set up realized for fabricating the sensor.

Experimental arrangement for EFPI fabrication

Light from a He-Ne laser (632.8nm) was launched into an input/output singlemode fiber (7/125 µm) using a fixture comprising a microscope objective and a X-Y-Z fiber positioner. The sensor was realized by first inserting the cleaved end of a reflector multimode fiber (50/125 µm) into a 15 mm long silica capillary tube with an inner diameter of about 150µm and an outer diameter of about 250 µm and permanently bonding the fiber to the inside of the capillary by means of an epoxy. Further, the opposite end of the capillary is carefully slipped over the input/output single mode fiber using a precision micropositioning stage leaving an air gap of typically 45-55 µm between the two reflecting fiber end faces forming the air cavity. The far end of the single mode fiber is aligned with respect to the multimode fiber and the photodetector signal is maximized. Once it is achieved, the near end of the single mode fiber terminated in a suitable connector is hooked to the input port of a Fiberscan signal processor which has an in-built LED source (850nm) and a fiber coupler for tracking the interference signal. The single mode fiber is then attached to the capillary while actively modulating the air gap to ensure that the sensor is set close to quadrature for achieving sensor sensitivity. The gap separation for maximum sensitivity was achieved by moving the translation stage carrying the single mode fiber and monitoring the output intensity corresponding to the signal having greatest modulation depth. When maximum sensitivity is obtained, the single mode fiber is bonded to the capillary. The air cavity so realised, works as a low-finesse FP interferometer, because higher order multiple reflections do not contribute significantly. The resulting interference signal was detected at the output of the coupler using an optical signal processor which can directly display displacement, strain and temperature.

In this case, the cantilever was loaded at the tip. The sensor has shown a good repeatable and linear performance and a typical comparison between strain measurement by the EFPI sensor and conventional gage under loading is shown in figure 19. It is clear from the results that the indigenously developed EFPI sensor (air gap = 46µm, gage length = 12 mm) has performed as good as the conventional strain gage and exhibited a typical strain measurement sensitivity of about 0.5 $\mu\in$ gm[1].Development and investigations of EFPI sensor bonding techniques for health monitoring of structures were pursued and experimental investigations undertaken and techniques investigated & developed for bonding of EFPI sensors to concrete and metal structures and their performance compared with conventional strain gages. EFPI sensors were bonded to concrete and metal structures and their basic credibility for strain measurement was studied by comparing the performance with conventional strain gages in different configurations. [4,5]. Fig. 20 indicates compressive strain testing of the EFPI Sensor.

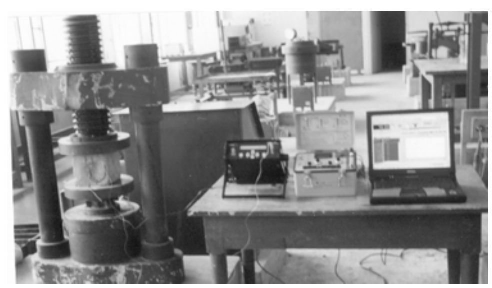


Fig 20 Compressive Strain Testing of the EFPI Sensor

2.5.4 Mechanical Long Period Gratings (LPGs) as Bend Sensors

Long period gratings are mode coupling in-fiber devices which couple guided core mode to different cladding modes, thus attenuating the transmission spectrum of the fiber. Since coupling involves cladding modes, their sensitivity to external perturbation is much higher than that of their Bragg grating counterparts. Any change in external parameters, which directly influence the optical properties of cladding, strongly attenuates the transmission spectrum that can be measured. This property can be used in a vast area of sensing applications. Both, the loss resonance wavelength and the strength of the coupling process are sensitive to axial and transverse strain, temperature and ambient refractive index. These changes in attenuation bands and wavelengths can be easily measured and therefore, LPGs may be used in a wide-range of sensing applications. Typically, these LPGs have been fabricated by inducing periodic refractive index perturbation in optical fiber core by exposing it to UV radiation. However, this is not only time consuming but also requires capital-intensive equipment; the tuning ranges are limited, and the central wavelengths are difficult to control with sufficient accuracy. For a number of applications, it would be worthwhile to also develop a non-UV type of LPG that provides more flexibility and simplicity in the method of fabrication and usage. In an LPG, the index modulation period can vary from 100 to 1000 μm, and so it is possible to induce it mechanically and using other techniques. Investigative studies undertaken on mechanically created LPGs are described below.

The inherent sensitivity of the mode-coupling to small perturbations in the core and cladding modes makes the magnitude and the central wavelength of LPG attenuation bands highly sensitive to bends. While this sensitivity requires the use of rigid packaging in applications in which a stable wavelength is required, it also provides a unique opportunity for shape sensing in smart structures. Conventionally, the shape of a structure is inferred from strain data. In contrast to FBGs, an LPG exhibits direct bend sensitivity, and it can be used to measure curvature regardless of distance from the neutral axis (with a small correction necessary if the sensor is not at a strain free location), making it a more versatile device. Although direct bend sensors based on dual-mode fiber and bend sensitized plastic fiber have also been demonstrated, LPGs provide the advantages of localized sensing (typical LPG length is 2.5 cm) and wavelength-encoded and self-referencing readouts. In this paper, the resonance loss splitting with curvature in a mechanically created LPG are observed and quantified for the first time to the best of our knowledge, and the application of these gratings to shape sensing from curvature analysis is investigated and suggested.

The experimental setup developed for the present study is shown in figures 21 and 22. The setup comprises of a high-resolution (HR) monochromator, a light launcher into the fiber, a fixture for bending the mechanically created LPGs, and a high-sensitivity optical power meter. LPGs were fabricated using graphite rods of 500 μm diameter in the middle portion of an aluminum strip (38x5.5x0.2 cm) supported at two points separated by a given distance typically about 25 cm, which is varied to realize different curvatures. The surface of the sheet was properly prepared and a total of 42 graphite rods were then pasted on it adjacent to each other along the direction perpendicular to the length of the strip, and in this way a 25-mm-long periodic structure with a periodicity of 588 mm was realized. A single-mode (SM) fiber was laid on the structure such that the fiber axis is perpendicular to the length of the graphite rods. To realize an LPG, the fiber and the periodic structure combination is covered with a glass microslide and a suitable weight is applied onto it, but in the beginning, a support is kept below the aluminum sheet to arrest its bending such that a grating is created in the fiber with a no-bend situation.

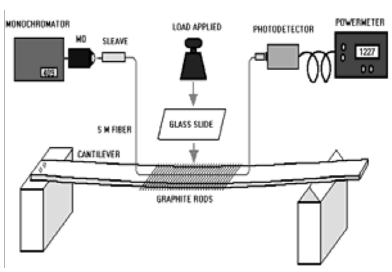


Fig 21Experimental setup for bend sensing using mechanical LPGs

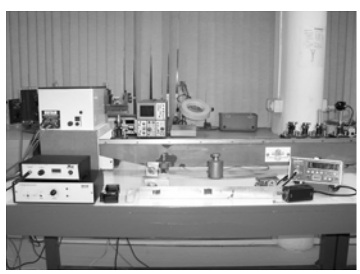


Fig 22 Experimental Set Up

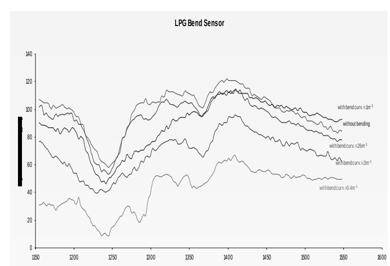


Fig 23Transmission spectrum of mechanical LPG for different bend curvatures

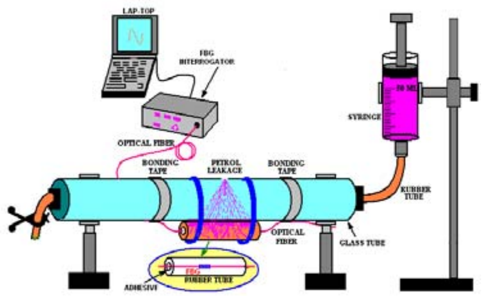
Optical wavelengths in the range of 1150 to 1600 nm in steps of 3-nm were launched in this LPG and the corresponding output optical power was monitored for a no-bend case. The data obtained are indicated in figure Further, by applying increasing loads on the aluminum sheet and with no supporting platform below it, bend curvatures of 0.1, 0.26, 0.3, and 0.4 m21 were created, and for each case, the corresponding output power of the grating was again monitored for the wavelengths in the band: 1150 to 1600 nm. Evidently, there is a split of the loss resonance peak into two peaks and as the bend curvature increases, the resonance splitting becomes more pronounced and clear.

Mechanically created LPGs are quite simple, inexpensive, and very promising devices for bend-sensing applications. They have been demonstrated to sense bend curvatures of 0.1, 0.26, 0.3, and 0.4 m^{-1}, and a clear split of 10 nm for the maximum bend curvature of 0.4 m^{-1} giving a bend sensitivity of 25 nm/m^{-1} has been realized. Note that bend curvature higher than 0.4 m^{-1} could not be produced with the present setup, but even with this modest bending, there is a clear indication of the split in the attenuation band, which can be utilized in various bend-sensing applications such as sensing of shapes and warping in smart structures. The experiment is reproducible with the minimum risk of fiber damage at least for the level of bends reported here [6].

2.6 **FBG Sensor for Petrol Leak**

An FBG based transducer was designed, fabricated and its characteristics investigated for detection and location of petrol leak in pipelines and storage tanks FBG sensors are very functional in such situations because they are insulators, chemically inert and perform multipoint sensing within a single fiber. A fast detection system of petrol leak along with its location is possible using FBG sensors. To detect petrol leak, a specialised rubber tube as a transducer is suitably attached to an FBG. This rubber has the ability to swell by absorbing petrol or even vapours from a close distance without being dissolved in it and to shrink to its original state in drying condition. This swelling and shrinking is converted into a mechanical force which acts on the FBG and is detected by measuring the Bragg wavelength shift. It was mentioned above that FBG sensors have vast application potential in diverse areas and for detection of wavelength shift quasi-static methods are employed and an interrogator falling in this category has been used in this study. This system as described earlier takes advantage of tunable wavelength shift which is a typical tuning in and reading out system. The FBG sensor in a single fiber is illuminated with a broadband swept fiber laser source (wavelength range =1520-1570 nm) with a sweep frequency of 50 Hz through a fiber pigtail and the reflected light is returned via a coupler to a scanning Fabry Perot filter and detector.

An FBG is kept inside a swellable rubber tube of length 2.5 cms and diameter 0.1 cm both ends of which are bonded with the fiber using a suitable epoxy. One end of this fiber is connected to the interrogator while the other end is kept free. The FBG used in the present investigations has been manufactured at IFAC, CNR, Firenze, Italy during Collaborative Research Programme. This FBG with the rubber tube as transducer along with interrogator put together, a sensor system is realised. The transducer is attached to a glass pipe of length 31 cm and diameter 0.7 cm, through which petrol is made to flow.



Schematic

Experimental setup

Fig 24 FBG sensor for petrol leak

The schematic of the experimental setup implemented is depicted in figure 24. Bragg wavelength of this sensor system is observed on a laptop monitoring the interrogator. The petrol is made to leak through a hole using a syringe As soon as the rubber comes into contact with leaked petrol, it starts swelling immediately. Since the rubber tube is bonded on both sides of FBG, this swelling causes the FBG to get stretched resulting in Bragg wavelength shift. The Bragg wavelength shift is monitored every minute for some time and then the sensor setup is left for drying. The tube attains its original form i.e. the

Bragg wavelength attains its dry-state value typically after 4 hrs of it being left in drying state. This complete wet-dry cycle was repeated after a gap of about 5 hrs. The behavior of the typical Bragg wavelength shift observed for initial 18 minutes is shown in figure 25.

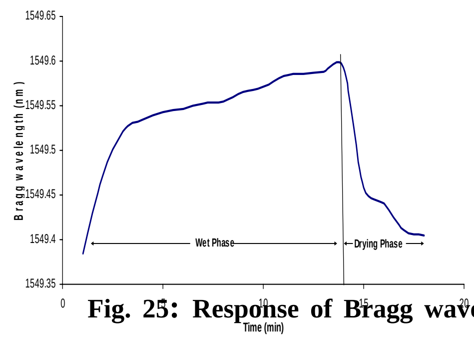


Fig. 25: Response of Bragg wavelength to petrol leak

As evident from the figure above, the Bragg wavelength of the grating with the swellable rubber tube as transducer increases rapidly once the sensor comes in contact with petrol. However, the increase is not linear because the petrol was made to leak just for an instant and the drying commences immediately. A Bragg wavelength shift of 0.2 nm is recorded even for this short duration of petrol leak which can be improved easily either by increasing the petrol contact time or by manipulating the size of the rubber tube. The experiment has been performed repeatedly in a controlled laboratory environment where the timing and extent of petrol leak is controlled manually, but this sensor should work equally well in actual field applications. The properties of transducer rubber tube do not change after repeated (up to 10 times) use [7]. This technique could be beneficially exploited for detection of fuel leak in aircrafts.

2.7 Fuel Contamination Sensor

Due to their sensitivity to refractive index of the ambient, LPGs are quite useful sensors for determining the fuel contamination. Experimental investigations have been carried out using LPGs for determining the presence of kerosene in petrol and diesel as a contaminant. This study could also be used for detecting the contamination of aviation fuel. The schematic and experimental set up realized and the results achieved are indicated in figs. 26-27

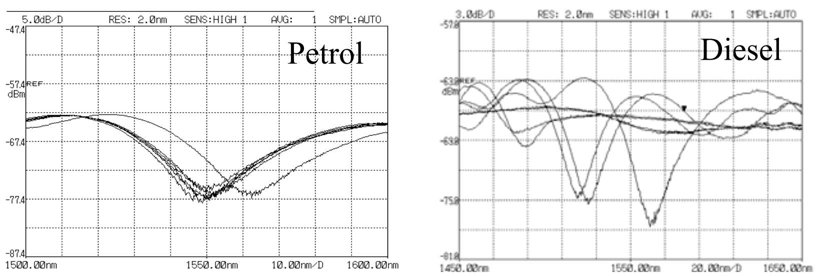


Fig 27 .Transmission Spectra of LPFG with different % of kerosene in Petrol and Diesel

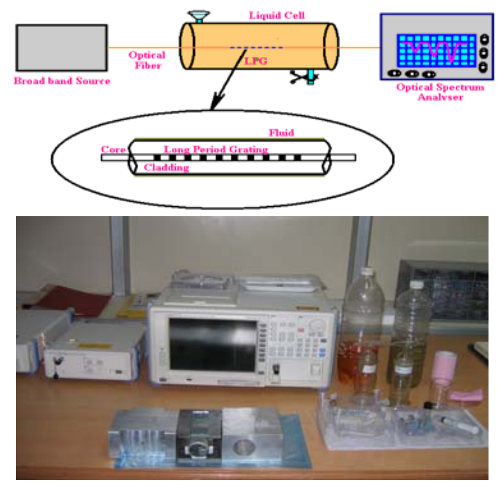


Fig 26. Schematic and Experimental Setup of LPG based fuel contamination sensor

For petrol, a 10% addition of kerosene resulted in 0.6 nm shift in resonance wavelength while change of 10 to 20% of kerosene resulted in a maximum wavelength shift of 1.2 nm. Though the max sensitivity obtained in this study is small [0.12 nm/ % of kerosene] yet it is possible to detect the presence of 10% kerosene in petrol. For diesel the behaviour of the LPFG is drastically different. Increasing percentage of kerosene resulted in red shift in contrast with the case of petrol. A maximum wavelength shift of 31 nm for 20 to 40 % change of kerosene observed indicating a sensitivity of 1.02-nm / % change

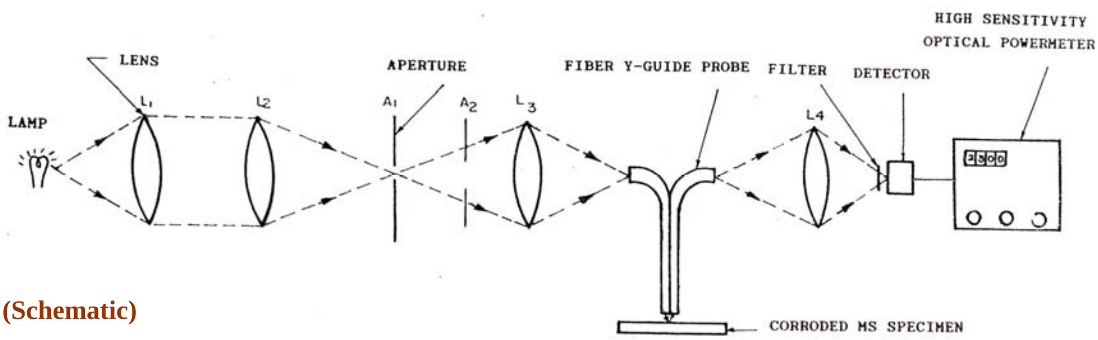
2.8 Corrosion Sensors

Technique based on colorimetry has been studied for corrosion sensing while another technique based on LPGs has been studied for refractive index sensing which also has potential for corrosion sensing. Both the techniques are described below.

2.8.1 Colorimetry Technique Damage due to corrosion in aerospace structures is huge taking into account the losses in time, labour, materials and systems and the down time that results from disassembly procedures necessary to locate corrosion damage in remote location Optical fiber corrosion sensors are being developed to address the high service costs associated with the current structural maintenance procedures for civilian and military assets. A distributed optical fiber sensor system will help reduce such costs and extend the lifetime of existing assets.

Fiber optics based direct absorption spectroscopic techniques investigated by some research groups, for the estimation of corrosion have relied on using single fiber elements for recording the light signal reflected off the specimen at different wavelengths. However, the present corrosion measuring technique investigated reports a simple and alternate method based on the color matching principle of colorimetry for detection of corrosion induced color changes. In contrast to single fiber elements, it employs a thin Y-shaped optical fiber lightguide/bundle, which increases the quantity of light energy coupled from a white light source resulting in ease of optical signal processing and a simple measurement set up. The technique actually involves detection of the brown color of rust formed both on steel members and reinforced concrete in structures. .

The schematic and photograph of the experimental arrangement realized in the laboratory for detection of corrosion in structures are depicted in Fig 28.The set up employs an indigenously built thin Y-shaped fiber optic bundle as described earlier. Light from a 50-watt quartz halogen lamp driven by a 12V (DC) stabilized power supply was coupled to the source arm of the bundle using suitable optics.



(Schematic)

The corroded specimens were prepared in the laboratory using mild steel (MS) sheets dipped in water solution containing varying concentrations of sodium chloride (NaCl). The specimen is located very close to the common end of the Y-guide at a displacement of 5 mm which corresponds to the peak sensitivity of the response of the lightguide and the reflected light picked up by the other arm of the bundle is made to pass through a complementary filter (Greenish-Yellow) before it is incident on a photo-detector. The detector signal is processed and displayed by a high sensitivity optical power meter. Corrosion measurement on the MS specimens was thus carried out both for ambient and concrete embedded conditions. Data was recorded for a fixed displacement between the fiber end and sample surface both for the case of corrosion under ambient and embedded conditions and the result were found to be reproducible. A typical variation between concentrations of NaCl in the water solution and the reflected optical power is shown in Fig 29. It clearly indicates that at low concentrations, there is a linear increase in absorption (e.g. a decrease in reflected optical power) of the complementary color with an increase of concentration of NaCl, which tries to saturate at relatively higher concentration. An increase in NaCl, concentration means more corrosion in a given time period. Also, on highways and bridges, it is the penetration of chloride used for deicing in the structures that causes corrosion and its state can be assessed from measurement of chloride ion concentration present in the structure and or by employing the present colorimetry based technique.

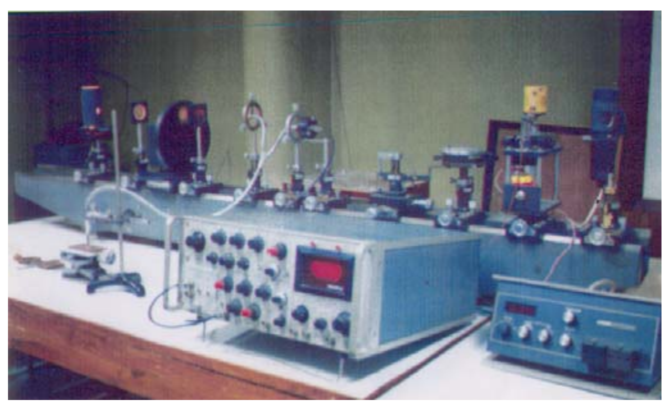


Fig.28 . Experimental setup for in-situ fiber optic colorimetry for detection of corrosion

This simple technique based on the principle of colorimetry employing fiber optic bundles, enables in-situ monitoring of the onset of corrosion and its further growth in aerospace structures. Such colorimetric fiber optic probes can be embedded into surfaces or attached to the structures at pre-determined sites for conveniently monitoring the state of corrosion from a remote location. This technique is very useful to study the kinetics of corrosion [8].

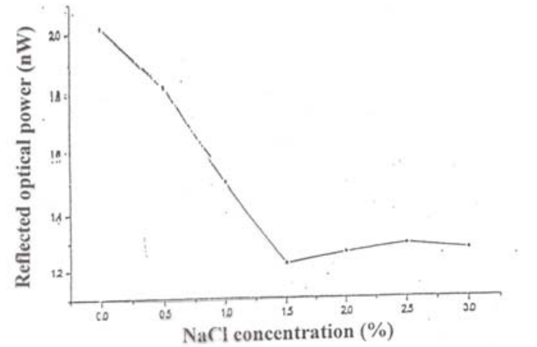
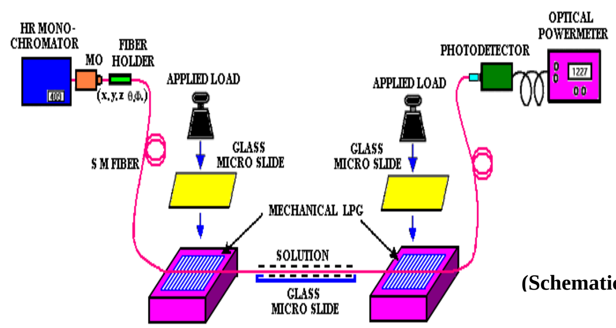


Fig. 29 Typical variation of reflected optical power with concentration of NaCl solution for corroded MS specimens

2.8.2 Refractive index and Concentration Sensing using Mechanical LPG pair

LPG based sensors are very useful for online monitoring of concentration and refractive index of liquids. These sensors have special utility in case of hazardous solutions or solutions that are not easily accessible. LPGs are more useful in such cases as compared to fiber Bragg gratings (FBGs) because, (i) the loss resonance wavelength is directly influenced by the ambient and (ii) there is no need to remove the fiber cladding as is the case with FBGs and hence mechanical strength of the fiber is not compromised. Although LPGs are advantageous, but their use as sensor is limited because the transmission spectrum is quite wide to get a good resolution. To achieve a better and narrower spectral response, two similar LPGs can be cascaded in series. The use of cascaded LPGs serves two purposes: (i) the spectral response is better as compared to that of a single grating and (ii) the fiber region without protective polymer coating is not under the direct influence of grooves and weights thus making the sensor less prone to damage.



(Schematic)

The two cascaded LPGs used act as a Mach-Zehnder interferometer. One part of the incident beam guided along the fiber core is coupled to a cladding mode by the first grating and is guided along the cladding while the remaining part of the beam is guided along the core unperturbed. These two different optical paths make two arms of the interferometer while the gratings functions as two couplers. The second grating recombines both these parts resulting in interference fringes. Adjusting the fiber lengths between the LPGs can control the wavelength spacing and the line width of the loss peaks. If this length is comparable to the grating length, cascading effect will be absent; and the grating acts as phase-shifted one with a pass band within the stop band. If the grating length is negligible with respect to grating separation, very sharp interference fringes are obtained. When a section of the fiber between the two gratings is exposed to different solutions, the coupled mode will be directly influenced.

Fig. 30 : Experimental setup of mechanical LPG sensor for refractive index and concentration

The experimental set-up implemented consists of a high resolution (HR) monochromator with a quartz halogen lamp as a light source, a light launcher into the fiber, two identical brass plates of size 3.5cm x 3.5cm x.3.5mm each and with fine grooves of periodicity 500 μm and an optical power meter. The set up schematic and photograph are shown in figure 27.

The two brass plates were kept 16 cm apart to keep the separation between the gratings greater than the grating dimensions. Sharp fringes are obtained when the separation between the gratings is much larger than the grating length [36], but the detector system used in this experiment has an inadequate resolution to detect them. Taking the separation not so large results in multiple dips in the transmission spectrum of the grating. The SM fiber was pressed between the grooves and plane glass micro slide and a suitable weight is applied onto it. A length of 1.5 cm of the fiber in between two gratings was stripped of its protective polymer coating and laid on a glass micro slide. To prevent any bending effect, the unstripped portion on either side of the stripped portion was fixed on the slide using an adhesive tape. To study the effect of concentration, NaCl solutions of different concentration were prepared by dissolving measured amount of NaCl in 100 ml of distilled water. The uncovered portion of the fiber was dipped in the solution. Optical wavelengths in the range of 1150-1550 nm in a step of 3nm were launched in this LPG pair from the monochromator and the corresponding output optical power was monitored for different concentrations.

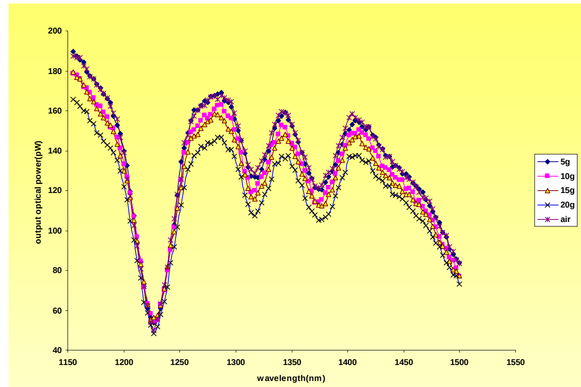


Fig. 31: Transmission spectrum of the mechanical LPG pair as a concentration sensor

To study the effect of refractive index, certified refractive index liquids of different values, obtained from M/S Cargille Laboratories, USA were used and the above-mentioned experimental procedure was repeated. The variation of output power with wavelengths for concentration and refractive index sensing is plotted in figures 31 and 32 respectively.

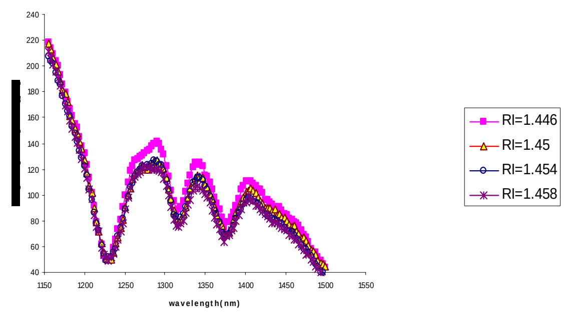


Fig. 32: Transmission spectrum of the mechanical LPG pair refractive index sensor

In the study for concentration sensing, NaCl solution with concentration of 5g, 10g, 15g and 20g per 100 ml of distilled water has been used in this experimental set up. As evident from results shown in figure 28, there is a distinct variation in the optical power corresponding to the loss resonance dip. However, there is no apparent shift in the wavelength values or the shift is too small to be detected by this experimental setup but intensity variation is obvious and the intensity loss increases with increasing concentration. A maximum variation of 20 pW is observed as the concentration is increased from 5g to 20g per 100 ml. For refractive index sensing, liquids with refractive index values of 1.446, 1.45, 1.454 and 1.458 are used and again loss increases with increasing value of refractive index. A maximum variation of 11 pW is observed as the refractive index changes from 1.446 to 1.458 as shown in figure 32. It may be mentioned that the experimental technique presented here provides a simple and inexpensive means for measurement of refractive index and concentration of solutions and it has a vast application potential in chemical, biological and process control industry [9]

2.9 Fire Safety Sensors

Fire safety sensors have been developed based on ceramic material wires and fiber optic microbend privciples. The details of the developed sensors are as below:

2.9.1 Ceramic Material based Wire Sensor

Fire safety sensor has been developed (Fig.33)under a project with the main objective to develop Fire Safety Sensor of 20' and 50' long along with end connectors, which have kilo ohm resistance between sensing wires or wire to body at 2250 C and this resistance value must drop 200-300 ohm at 3300C (± 6% of the temperature) The fire safety sensor should work on the principle of continuous thermocouple (CT2C) and ceramic material must have NTC properties and must provide ultra fast response to overheat of any portion when installed in bay of the engine system of the aircraft.

The developed sensor consists of outer sheath of 316 SS. (Inconel) of dia 2.8mm wall thickness 0.25mm, annealed & seamless. Two sensing wires Chromel & Alumel in annealed condition (K Type) and of dia 0.3mm run parallel inside the pipe and are at equidistant from the centre of the pipe and inner walls of the sheath. These wires do not touch each other, nor the inner body of sheath. The pipe is filled with an insulating ceramic material (which is 95% Mn_3O_4 + 5% La_2O_3). 10' long sensor have been fabricated after carrying out thermo mechanical treatment. Each 10' sensor was characterized for thermal behaviour by keeping the 6" pipe for keeping whole sensor in coil form inside the muffle and measuring the resistance drop between Chromel & Alumel, Chromel & outer sheath, Alumel & outer sheath. Flame test has also been carried out in different portion of the sensor. Each 10' sensor has been welded with plug & socket at the extreme end of the connector. Seven sensors were joined together to get 50' length & 20' length. The total length of the sensor was characterized for thermal as well flame test. A complete set of sensor was submitted to ADA Bangalore for evaluation & testing.

As regards functional requirements, the sensor element should have high resistance (Mega to kilo ohms) under normal temperature among sensing wires and the resistance should drop to the desired value once it senses high temperature (above 330° ± 6% Celsius). When any portion of the sensor gets heated suddenly at 1100oC the desired resistance drop should happen in 5 seconds. The sensor wire should be in the annealed condition so that it has a bend radius of 1 inch. The sensing wires must be coupled through plug and socket in such a way that there should not be any deviation in the properties of the sensor element on exposure to heat. The environmental condition for the sensor include temperature range: -55° Celsius to +250° Celsius, acceleration: -3.5 g to 9 g, altitude: up to 18 Km above sea level. min expected MTBF: 1000 hours. The conditions for Shock include, functional**:** 20 g sawtooth/15 g sinusoidal –11 ms 3 shocks in each of 6 directions. Transit Drop**:** 122 cm drop at each face, edge, and corner (with packing) totaling 26 drops. The unit shall confirm to MIL-STD-810 D and LCA environmental map. ADA/LCA/110027/1 dated 27/12/89. MIL-B508 7B for bonding class R for general bonding of electrical unit MIL STD 785 reliability programs for system and equipment development and production. MIL F 7872 C for fire and over heat warning systems continuous Aircraft test and installation of.

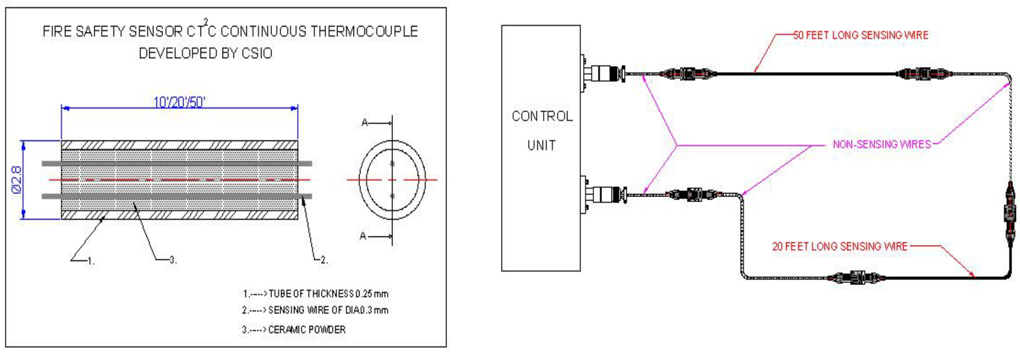


Fig33. Wire based Fire Safety Sensor

The ceramic materials with the desired properties were synthesised in the Lab for developing the sensor. The desired characteristic of ceramic material is that it should have negative temperature coefficient of resistance, so that in case of overheat or fire, the resistance of the filled ceramic material should fall to ohms level so that appropriate signal is sent to the control unit. To ascertain the exact objective for ceramic material given imported sample already being used was studied for different characteristics and its composition. The imported sensor wire characteristics, the rate of fall of resistance with increase in temperature was established and was found that resistance is in the range of Mega Ohms at room temperature and it drops to 100-200 ohms between 320-360º C. To develop the ceramic material having the desired characteristics a internet/literature survey was carried out. It was found that in most of the compounds oxides of manganese mixed with oxides of one or two transition metal or alkali earth metals are the major constituents present in them. A number of experiments were conducted to synthesize different combinations of these compounds to get the desired characteristics.

Mn_3O_4 mixed with La_2O_3 was found to be the best combination giving the desired characteristics. Mn_3O_4 is not available as such so it was prepared by reducing MnO_2 at 1000oC in the muffle by keeping it for three hours. The complete conversion was confirmed by spectrochemical analysis. This powder is grinded and sieved through a 250 mesh (60µm). This powder was mixed with lanthanum oxide La_2O_3 in the ratio 95:5 for this work, grinded the powder again sieved through 250 mesh. This composition is mixed with 0.5% stearic acid and 0.5% wax along with 1% ethanol to make it uniform. However, alcohol gets evaporated. Pellets were made from this material and two sensing wires were inserted inside the tablet and characterized for temperature resistance behavior continuously for few months to make workable material as per requirement. As per MIL grade two types of piping materials are used inconel and SS 316 or SS 310, In the present sensor SS 316 has been used with following dimensions: Pipe in coil form, Outer Dia 3.5mm Wall thickness 0.25mm seamless and annealed, polished and uniform diameter from inside the pipe. Sensing wires chromel, alumel of dia 0.3mm in annealed condition.

For filling of ceramic materials in SS tubes a number of methods were tried to put the sensor wire and the ceramic material inside the SS tube. Among them two methods were given importance: Wet Method (Extrusion Method), Dry method (with mechanical tapping and electromechanical vibration). The Wet Method basically involves pushing the paste of ceramic material and thermocouple wires together in to the tube. It consists of two assemblies. One of the assemblies pushes the paste of ceramic material with force and second assembly guide the thermocouple wire at desired distance and move along with the paste. The purpose of this method is to create infrastructure so that the tube with longer length can be filled with ceramic material along with wire. It was observed that there is change in the resistance characteristics of the paste. So efforts were made to evaporate the solvent liquid by heating, but this lead to creation of voids in the tube. In the dry method the tube is filled with the dry ceramic mixture with the thermocouple wire already kept in position. The method involves following steps: (1) Positioning of thermocouple wire in the tube and (2) Filling of the ceramic mixture in the tube.

The sensor wire was given thermo-Mechanical treatment as described below**:**

(a) Cold Reduction:

The filled up sensor pipe is cold drawn straight from diameter 3.5 mm to 2.8 mm through tungsten carbide die using grease as lubricant. The reduction percentage is around is 35 %. Initially die of size 2.8 mm diameter is gripped in a bench vice & pointed end is inserted into the die. The pointed end is projected about 30 to 40 mm from other end of the die. It is then gripped with specially designed fixture. This fixture is attached through the chain and hook to the wire rope. The other end of wire rope is attached at distance of 10 meters to a drum of cold drawing machine. It is then straight drawn through the 2.8 mm diameter die very slowly, smoothly, without jerks or interruption by rotating the drum of drawing machine manually. The pipe and the grip are held manually to avoid twisting of sensor pipe. The wires from the rear end are held taut and fed gradually into the pipe. Small length capillaries inserted at the rear end are pulled out. Reduction of diameter of tube takes place whereas length of the sensor tube is increases by 1.5 to 2 feet. Cold drawing compacts the powder and fixes the position of the wire in the pipe. Both ends are then cut and unwanted portion of sensor tube is rejected.

(b) Heat Treatment:

The sensor is then coiled to about 1 feet diameter roll and kept in furnace between 400 to 450˚C for 3 to 4 hours and air-cooled to drive away the volatiles and sinter the ceramic powder. It is then reheated at 680 +20˚C for 10 to 15 minutes and then cold water quenched. It is then dried at 200˚C for about 30 minutes to remove moisture entrapped in the sensor tube. The ends are cut till the wires are concentric and powder inside the tube is compacted. The final length of the sensor is around 10.5 to 11 feet. Characterization of the Sensor. The outer side of sensor is cleaned manually with the help of emery paper and wires are taken out by peeling 30 mm of sheath from both the ends with the help of file. It is then checked with multimeter for continuity and resistance. Time response is then checked with flame test. These sensors are then characterized for properties and end connectors are welded.

To study the temperature coefficient of resistance (TCR) and response time of the sensor infrastructure involving. Electric furnaces with facility to monitor temperature Burner with flame length 10cm and control knob for fuel flow, and thermocouple setup for study of temperature of flame were developed,. Data acquisition for temperature coefficient of resistance (TCR) and response time was carried out for the developed and imported samples simultaneously. Initially characterization was carried out for smaller lengths, then six inches sample of 10 feet sensor inside the furnace, whole sensor inside the furnace, interconnecting the five sensors together. Study for resistance change between wire to wire and wire to body for all the sensors was carried out. Potential drop measurement was carried out between wire to wire. Measurements of parameters were made with rise of 20ºC from room temperature. Efforts were also made to study the behavior of the resistance with fall of temperature. Response time measurement was carried out for sensors whose TCR was near to imported sensor wire. In this experiment, the indigenous sensor wire was exposed to air-acetylene flame so that flames heats up 10cm sensor length and the time taken for the fall of resistance to desired value was noted . The response time of the final sensor wire for the flame test is around 5 seconds

Plug and socket type end connectors have been designed and fabricated. These connectors have been fabricated from 316 Stainless steel of 12 mm, 16mm and 20 mm diameter rods. The male and female pins have also been designed and fabricated from brass rods of 3.0 mm diameter. A fixture has been designed and fabricated for filling of plugs and sockets. Initially two pins (male & female) are placed into the fixture after applying silicone grease to the die. Then plug and socket are fixed in the relevant fixture ensuring alignment of slot and key. The annular gap between pins and interior of plug / Socket is filled with mixture of sieved quartz and 5% sodium silicate. Care is taken to avoid mixture getting entrapped into the holes of the pins. The mixture is rammed with the help of specially designed ramming tool. It is compressed leveled and cleaned. This tool also helps maintaining distance between the two pins. The whole assembly is heated in a furnace at 250˚ C for 2-3 hours. Then the plug and socket is ejected from the fixture and are checked for alignment of pins by coupling each other. The male and female pins project out of plug and socket from rear end (3.0-4.0 mm). End caps of the connectors are initially inserted into the sensor pipe in appropriate direction. The plug and socket are separately taken, sensor wire are cut to the desired length. The wires are then inserted into male and female pins from the back side of plug/socket and crimped with a crimping tool ensuring proper position and direction of wires. Chromel wire is marked red in the plug and socket, The space between wires and pins is insulated by inserting insulating fibre, End cover is then slided/Pushed on the plug and socket, These connectors are TIG (Orbital) welded in the argon atmosphere at two places in plug and socket as shown in diagram. The welding of sensor wire to end connector cap is critical. These connectors are then cleaned and the sensor is then checked for continuity. It is then characterized for resistance, milli volts and time response. Each ten feet long sensors are then coupled through connectors to make 20 feet and 50 feet long sensors. Welding portion of wire gets heated & as such there is possibility of the adjoining areas / length of sensor becoming hard. It is advisable to not to bend 3"-4" of the sensor wire adjoining the connector. Alternatively 3"-4" portion adjoining the connector should be kept straight.

Different combinations of Mn, La, Sr, and Ca were made as suggested earlier and their characterization was studied. It was found that although all the combination has negative temperature coefficient of resistance (TCR) but the rate of fall of resistance is different for each case. It was found that mixture of Mn_3O_4 (95%), La_2O_3 (5%), has a better negative TCR. A comparison between characteristics of imported piece and best compound developed in our laboratory was also made. It was found that negative TCR is within 1% of imported piece. Various methods have been tried for filling the compound with thermocouple wire in the tube. It was found that the mobility of Mn3O4 is better. Efforts were also made to find the binder which can enhance the mobility of the powder in the tube. For this glycol was tried. Although mobility improved to some extent the presence of glycol created void on heating the tube. Then stearic acid, for flowability wax as binder mixed with ethanol was added in small proportion and was found that the flowability increased remarkably. Also stearic acid & wax escapes at low temperature, with little heat they were removed from the tube. The presence of these binders did not affect the characteristics of the sensor. Different techniques like, Extrusion method and Dry filling method were tried for the filling of the ceramic mixture in the tube along with thermocouple wires. It was found that in the wet method the presence of the paste affected the characteristics of the sensor, also it created voids on the tube. Finally it was decided to fill the tube with dry ceramic mixture and the vibrations were created either manually or electromechanically to increase the flowability. In this method 10ft sensor wires have been developed and tested for their characteristics and found satisfactory. Efforts are also being made to develop 20 ft long sensors by using this method [10].

2.9.2 Hot Air Leak Detection System

The primary purpose of the Hot air leak detection system(Fig. 34) is to detect the hot air leak in the hot air pipe of the ECS, and to protect the lives of individuals by issuing a timely warning signal The fire wire sensor solves the problem of detecting such hazards quickly The sensor continuously monitors the temperature and offers the best possible protection against fire Discrete sensing ability is completely independent of rate of heating The design of the system is based upon the principle that fire/overheat conditions on aircraft must be detected quickly during the initial build-up state of the condition The control unit senses the change in impedance of the sensor element and actuates an alarm through an inbuilt relay.

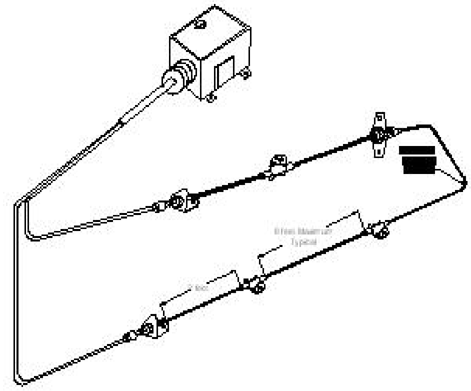


Fig.34. Typical single loop installation

The main objective of the project is to develop Hot air leak detection system consisting of 2 meter long sensor wire (7 no's for each aircraft) and Control Unit.2 meter long sensor along with end connectors, which have Mega ohm resistance between sensing wire to body at normal temperature and the resistance should drop below 10 ohms once it senses high temperature i.e. above 300° Celsius The design of the system is based upon the principle that fire/overheat conditions on aircraft must be detected quickly during the initial build-up state of the condition These sensor must provide ultra fast response to overheat of any portion when installed in the Dossel spine of ECS of the aircraft. The sensor wire consists of solid nickel conductor insulated with porous Aluminium oxide ceramic and encased in Inconel / stainless steel tubing (less than 3 mm O.D) hermetically sealed at both ends. The voids and clearances between the tubing, porous ceramic insulators and the center conductors are saturated with an eutectic salt mixture. During over-heat condition the impedance between the center conductor and the outer sheath conductor drops sharply as the temperature reaches the eutectic point or alarm temperature. The environmental conditions for the system are: Temperature Range: -55° Celsius to +250° Celsius, Acceleration: -3.5 g to 9 g, Altitude: up to 18 Km above sea level**.** The unit shall confirm to environmental severities normally confirming to MIL-STD-810D and LCA environmental map. ADA/LCA/110027/1 dated 27/12/89. The functional Requirements are such that the sensor element shall have high resistance (in Mega ohms) under normal temperature and the resistance should drop below 10 ohms once it senses high temperature (above 300° Celsius). It should have the **o**perating temperature of 300 ± 5° Celsius and above with a **m**in expected MTBF of 1000 hours The other specs include, Acceleration Procedure II (Operational) 9 g in all directions, Procedure I (structural) 13 g in all directions; Shock **:** 20 g sawtooth /15 g sinusoidal –11 ms 3 shocks in each of 6 directions and Transit Drop**:** 122 cm drop at each face, edge, and corner (with packing) totaling 26 drops.

2.9.3 Fiber Optic Fire Detection and Warning System for Aircrafts

A fiber optic temperature sensor for detection of fire and hot spots in aircrafts has been developed using optical fibers and shake memory alloys (Figs. 35-36). The system would enable quasi-distributed and fully distributed sensing inside aircrafts.

The existing imported systems for fire detection and warning consist of fire wire type sensing cables filled with a material sensitive to temperature changes. The present developed system uses optical fibers which has increased level of protection against Electro Magnetic Interference (EMI), Electro Magnetic Pulse (EMP) and High Intensity Radio Frequency

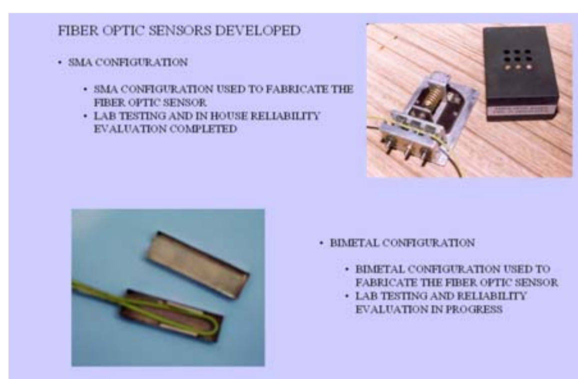
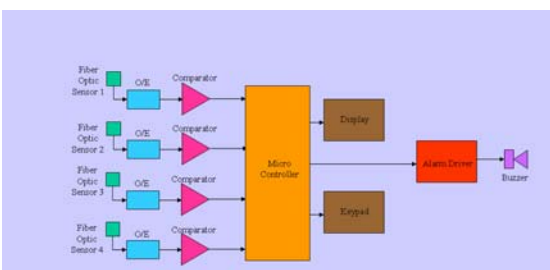
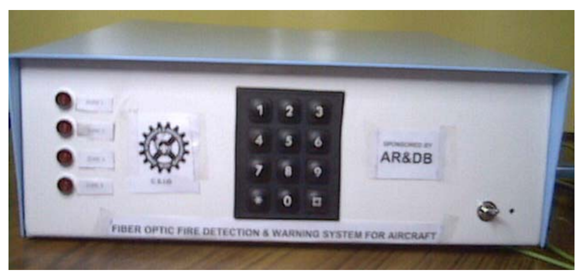


Fig. 35. Microbends in fiber on heating for sensing fire

(HIRF) and has less overall maintenance. Moreover the system is light-weight, flexible and easy to route. Being intrinsically safe it is possible to route the sensing fiber in close proximity to critical areas like fuel tanks, armaments etc. The fiber optic sensor designed is based on intensity modulation in a multimode fiber induced by temperature change. The fire safety sensor developed not only gives fire detection warning but also narrows down the zone where the fire hazard is located. The Mean Time Between Failures (hours) estimated for the sensor typically are: 1,95,814 (E/O) and 2,74,602 (O/E). The system comprises of modules: (1) Optical Fiber Fire Sensor Cable Assembly which involves a multi-mode optical fiber with core/clad of 80/125 micron and Graded Index profile terminated with standard SMA (Sub Miniature Amphenol) or FC (Face Contact) connectors; (2) Sensors which work on the principle of producing microbends in the fiber where the microbends induce excess transmission loss in an optical fiber and this property is exploited to detect/measure displacement, pressure, strain, temperature etc. If a portion of fiber is deformed, the fiber would exhibit excess light loss. Such sensors can be made very sensitive being capable of measuring displacement down to 10-3 microns and strains to 10-7 microstrains and pressure upto 10-6 Kg mm; (3) E/O and O/E Modules and Control Unit converts the electrical signal into light signal. Actually an LED (840 nm) is driven electrically through direct modulation of its current and the light generated is launched into the fiber. The optical to electrical (O/E) module uses integrated circuits and photo diode as detector to convert the optical signal coming out of optical fiber cable into an electronic signal; (4) ADC Circuit which converts the output voltage signal into digital signal using Analog to Digital Converter (ADC) circuits. The 8-bit A/D converter uses successive approximation as the conversion technique. The 8-channel multiplexer can directly access any of the 8-single ended analog signals. It operates on single supply of 5 V DC and consumes low power of the order of 15 mW. ADC resolution is defined as the voltage input change necessary for a one bit change in the output. It can also be expressed as a percentage. Resolution in terms of voltage is the full scale input voltage divided by the binary total of the number of bits, i.e. total number of levels. Thus an 8-bit +5 V ADC would have a resolution of 5/2^8 – 1 = 0.0196 V = 20 mV per bit. This represents the smallest input voltage 20mV per bit, which the system will resolve and is one of the important factors in deciding the specification; (5) Embedded Software using Microcontroller has been implemented in native assembly of MCS 51 and the code is optimized so as to accommodate in the on-chip memory of 89c51. After hardware IC directives and software register directives, the ports are reset to 0 so that all alarm and keyboard lines are cleared. Depending on the initial conditions of the optical fiber sensors, the initial thresholds are set after interrogating all the ports of the ADC by sequentially giving the address and ALE signals and storing the outputs. The program keeps on interrogating the eight inputs and sets the alarm flags if any one crosses the threshold values. This project was funded by Min of Defence.



Block Diagram of Microcontroller Unit



Electronic Controller

Fig 36. Fiber Optic Fire Detection & Warning System for Aircraft

3. Conclusion: The emerging technological scenario of aerospace sensors and networks based on the new and passive technologies like fiber optics has been presented and the achievements made at CSIO in the realm of aerospace sensors and systems and future programmes planned in this domain have been highlighted..

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