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REVIEW PAPER

Emerging Trends in Instrumentation in Rocket Motor Testing Over Three Decades

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ABSTRACT

Rocket motors are designed, developed, and evaluated for its performance. After repeated tests, they are qualified for use in a launch vehicle or missile system. Comprehensive instrumentation measurement plan is made to record physical parameters during evaluation and testing. In the last thirty years, a revolution has happened in the field of electronics that has benefited instrumentation in terms of accuracy, bandwidth, capacity, reliability and analysis. This paper describes the improvements in instrumentation that have happened in the field of rocket motor testing over a period of last three decades.

Keywords: Test bed, static test, rocket motor, measurement chain, transducer, calibration, instrumentation amplifier, signal conditioners, performance indices, data acquisition system

1. INTRODUCTION

Rocket motor is the backbone of any aerospace vehicle or missile system that propels the payload to a desired location in the space or on earth. Rocket motors use liquid fuel, solid fuel, and hybrid fuel depending upon mission requirements and are designed for specific applications. After completion of design, during development phase, static tests of rocket motors are conducted to evaluate and qualify the performance of propulsion systems. A series of static tests are carried out to validate the performance parameters for aerospace applications. These tests are fully instrumented and the physical parameters recorded are pressure, thrust, flow, temperature, strain, vibration, shock and acoustic levels. The instrumentation sensors used are pressure transducers, load cells, thermocouples, flow meters, accelerometers, strain gauges, and microphones. As per requirement, the sensors are selected and mounted on the rocket motor at specified locations. The rocket motor is test fired and the data is recorded on recording systems. Detailed analysis are carried out on recorded data for performance evaluation. This paper describes the major components of data acquisition system and the improvements that have happened in terms of accuracy, bandwidth, and channel capacity over a period of last 30 years due to technological advancements in the field of electronics.

2. TEST BED

Test bed is the place of experimental setup where, rocket motor is static test fired. The test bed design is carried out according to the tonnage of thrust generated by the rocket motor. The test bed will be located in isolated area and far away from data acquisition facility for safety reasons. The distance between the test bed and data acquisition facility changes according to the type and capacity of rocket motor. The construction of test bed area along with thrust wall is monolithic. This means the entire test bed area along with the thrust wall has to be moulded and fabricated in one casting. Test bed will be designed for 30 T, for testing a rocket motor generating a thrust of 15 T, which amounts to a factor of safety of 2. The natural frequency of structure along the axis of test bed shall be $\leq$ 4 Hz. The rocket motor is mounted on the test stand, attached to the thrust wall through thrust frame. The test bed can be horizontal, vertical, single axis, or six-component test bed as per the testing requirement. Axial thrust can only be measured on single-axis test bed, whereas on a six component test bed thrust in three axes (x, y, and z) and three moments are measured. Single-axis test bed is calibrated for thrust frame absorption for estimation of correct thrust generated during the test. On six-component test bed facility, interaction coefficients between different components are generated during calibration and the same is validated by tri-axial calibration.

3. COMPONENTS OF INSTRUMENTATION MEASUREMENT SYSTEMS

Procedure followed to interface various types of signals to the data acquisition system is shown in Fig. 1. The major components of instrumentation measurement systems, undergone changes over a period of three decades are explained.

3.1 Cable

Cable is a very important component in the instrumentation measurement chain. Depending upon the type of sensor and

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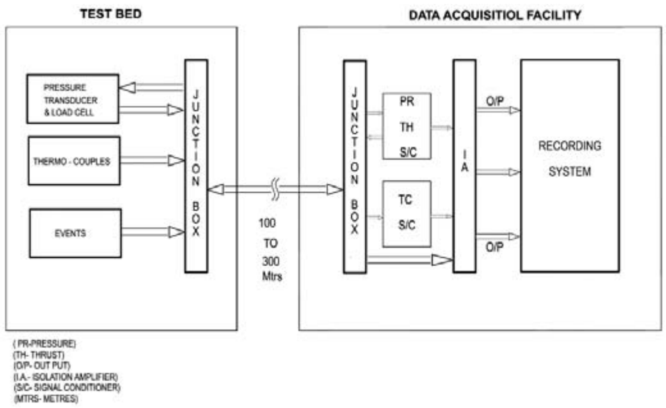

Figure 1. Components of instrumentation measurement system.

measurement bandwidth requirement, suitable signal cable is selected. The types of signal cable used during rocket motor testing are twisted pair signal cable, may be a single-twisted shielded pair or multi-twisted pairs, individually shielded or with overall shield, co-axial cable, low noise cable and compensating cable. Copper is the most preferred conductor for any signal cable even today. The copper wire is coated with silver, which has less resistance for signal and ideal for soldering the cable, with the pin of a connector.

Nowadays instead of silver-coated copper, nickel-coated copper is preferred in most applications. Though nickel-coated copper has slightly more resistance compared to silver-coated copper, the same is not suitable for soldering application but it is best for crimping application. There are two significant advantages of nickel-coated copper over silver coated copper:

(i) Nickel-coated copper is preferred for crimp requirement. For most defence and aerospace applications, crimping of cable is preferred over soldering of the cable.
(ii) Melting temperature of nickel is higher than silver. So for aerospace applications, where as higher temperature is a concern, nickel-coated copper cables are used.

Introduction of electron beam cross-linking of wire and cable in late eighties and early nineties, during manufacturing has helped the cable manufacturers and cable users to a great extent. Though the process existed in early seventies, the methodology was adopted by manufacturers during the time mentioned above. In this process, chemical bonds are formed between polymer molecules to produce a three-dimensional insoluble network without application of heat. Electron beam cross linked wire and cable insulation exhibits several desirable properties like:

(i) It will neither melt nor flow at higher ambient temperature due to which, connector will not get heated and also it protects conductor during soldering process.
(ii) Electron beam cross-linked ethylene tetrafluoroethylene wire is also used in aircraft airframes. It is thin, lighter and can be used from – 65 ^{o}C to 200 ^{o}C. which is a wide range of temperature[1].
(iii) As the thickness of cable sheathing is less for a required insulation, with electron beam cross-linking, the diameter of cable reduces for a given cable construction. It reduces the weight and size of the cable ideal for aerospace applications and also enables designers to accommodate extra conductors in the same diameter, resulting more number of channels. This is very useful for planning in underwater instrumentation system for submarine-launched missile during development phase, where minimum penetrations in the pressure hulls are preferred.

3.2 Connector/Terminal Strip Connector

Introduction of new manufacturing and inspection technologies has helped manufacturers to improve and maintain the quality and ruggedness of connectors. The significant improvement is miniaturization of connector, to accommodate more wires in a single connector.

Major improvements have happened in the field of cable harnessing to protect the cable-connector interface from stress due to atmosphere and mechanical effects. These improvements are made possible due to the development of new sheathing materials and innovative products like heat-shrinking tubes, cable boot, etc., which can withstand more harsher environment and mechanical stress.

The break in cable is essential for troubleshooting and maintenance. Terminal strip connectors are ideal for this type of requirement. In early seventies and late eighties, terminal strip connectors were widely used. At present, there are several manufacturers to provide terminal strip connectors with better design and conforming to military standards which has increased the reliability and repeatability of data measurement.

3.3 Sensors

Sensor is a very important component of instrumentation measurement system. During last three decades, many new sensors have been developed by agencies to meet specific needs and requirements. Miniaturisation, non-contact measuring principle, energy autonomous sensors with wireless communication, introduction of novel measuring processes for detection of spatially distributed measuring data, such as tomography for industrial application, coupling of physical, chemical, and biological sensors on a single sensor element[2], are a few types of sensors developed by agencies to meet the specific requirements. The recent advances of sensor have been powered by high speed, low-cost electronic circuits, novel signal processing methods and innovative advances in manufacturing technology. Online self-test, self-calibration are being embedded in the sensor structure during the design and these have advantages in terms of cost, reliability, installation, and maintenance[3].

The two most important parameters namely pressure and thrust are measured to evaluate the performance of the rocket motor. Nowadays most of the sensors are available with built-in signal conditioning, display and also a 4-20 mA current drive. Testing of rocket motors is very costly in terms of money, time and logistics. Failure of rocket motor during testing, demands information from recorded data to find possible cause of failure. If data is converted to current and re-converted to voltage for analysis, useful information associated with signal will be lost and possible cause of failure might not be identified.

For rocket motor instrumentation it is preferred to record raw data from conventional transducers for subsequent analysis. For thrust measurement, load cells are used. The weight of load cell increases with the tonnage/capacity of the load cells, and it becomes difficult to handle the load cell of higher capacity in the field. In the late nineties, manufacturers came up with a new type of load cell, which is lighter, compared to the conventional load cells. Calibration of load cell is done before and after the test to ensure data integrity and correctness by a universal calibrating machine or dead weight calibrator. Pressure transducer experiences heat generated by hot gases during the testing. Strain gauge pressure transducers are available, compensated for higher temperature. The other factor that transducers should withstand is the transient pressure encountered during ignition of rocket motor. Pressure transducers are calibrated before and after the test by dead weight tester using nine-point calibration method. The calibrated data is taken to improve the accuracy during the test which is much lower than that specified by the manufactures. Field calibration and shunt calibration are carried out to further improve the accuracy of measurement chain. Shock tubes are used for calibration of dynamic sensors. Thermocouples are preferred for temperature measurement as these cover wide range of temperature. Thermocouples are calibrated using hot bath temperature calibrator. Turbine type flow meter is more popular for flow measurement and it is calibrated with water at required flow rate.

3.4 Signal Conditioner

Signal conditioner is another important component in the measurement chain. It provides excitation to the passive sensors, bridge completion circuit for resistance measurement and provides shunt calibration facility. The voltage output of transducer is of the order of 0 mV to 30 mV. Signal conditioner also amplifies the signal to a level suitable for recording. The most commonly used signal conditioning system works on 4 wire system. In late seventies and early eighties, manual operation was needed through series of toggle switch and values read on a digital voltmeter were noted in a book for future reference. In late eighties and early nineties, manufacturers started producing computer controlled signal conditioning unit where all adjustments were manual but readings were directly recorded on the computer. This was made possible due to development of general purpose interface bus (GPIB). National Instruments of United States of America came up with an intelligent signal conditioning system on personal computer interface extension for instrumentation (PXI) in early nineties, where all operations were carried out by computer itself. At present, PXI-based systems are used, supporting online self-test, self-calibration features.

Earlier for temperature measurement, thermocouples along with compensating cable were used from test bed to data acquisition facility and cold junction compensation was provided by ice box kept in the test bed. Amplified data was recorded on UV chart recorder. Analyses were carried out by look-up table for the type of thermocouple used. During late eighties and early nineties, electronic cold junction compensation was provided in signal conditioner itself with linearization and requirement of ice box in test bed and look-up table during analysis no more exists. Use of compensating cable is restricted from thermocouple to signal conditioners.

3.5 Isolation Amplifier

Isolation amplifier (IA) is another important component in the measurement chain. The basic purpose of this device is to provide input/output ground isolation, impedance matching, and amplification. IA will have very high input impedance and very low output impedance. Like signal conditioner, there is no change in the basic electronics. Amplifiers were available as single channel, all control and adjustment were by knob. Thereafter control and adjustments were done by computer through GPIB interface. In late nineties, amplifiers have become intelligent and can directly interface to PXI chassis. This has happened due to development of various types of databus.

3.6 Recording System

This is the most important component of measurement chain, Data is recorded on these devices and used offline for performance analysis. This component of measurement chain has most benefitted by advancement of technology in the field of electronics and data communication.

Earlier UV recorders and analog magnetic tape recorders were the only devices used for long duration data acquisition. Though magnetic tape recorders provided higher bandwidth, recording on UV recorders was possible with lower bandwidth which was still adequate for required information. The maximum bandwidth possible on UV Recorder was 200 Hz. The other limitation was the number of channels. For static testing of rocket motors, multiple recorders were used for more number of parameters and one common channel in each recorder was recorded as reference signal to co-relate data of all recorders used during a test. The traces of UV on the chart fades away over a period of time. A special chemical spray was used to protect the traces to stay permanently, for future reference. Data acquisition on computer was not very popular and had limitation with memory (RAM) and number of channels and throughput of ADC systems. At Defence Research and Development Organisation, Hyderabad, TDC-312 real time computer system developed by Electronics Corporation of India Limited was regularly used during static testing of rocket motors. Computer was based on valves, tubes and transistor. The onboard memory, RAM was 20 K, input data programming was through punched cards and magnetic tapes, and output devices used were display, teleprinter and magnetic tapes. The entire computer was occupying a room size of 15' x 10'. The throughput of ADC was 3 KS/s and used for limited channel. Later, UV recorders were replaced by chart recorders and thermal recorders.

In the eighties, emergence of computer system brought revolution in the field of recording systems. Most of the scientific institutions started using computer, supporting multi-terminal facility working on UNIX-based operating system for simulation and analysis of the data. Real-time data acquisition with limited throughput and stand-alone analog-to-digital convertor (ADC) was possible by computers working on real-time operating system. Most of the scientific and research organizations were using computer for data acquisition purpose. A centralised mainframe (computer) was made operational at DRDO, Hyderabad in 1989 with 512 channels and 512 KS/s throughput. The accuracy and bandwidth of measurement chain improved significantly, and the only limitation was with other recording systems. The accuracy and bandwidth of the components in the measurement chain is shown in Figs 2 and 3. The bandwidth of transducer was increased to 5 KHz which was suitable for transient pressure measurement. It may be noted that the accuracy of measurement chain has improved from 0.56 % to 0.27%. This calculation is based on manufacturer's specification. The accuracy can be further improved using actual calibration data of the lab. The throughput of ADC has also increased significantly for measurement of higher bandwidth signals.

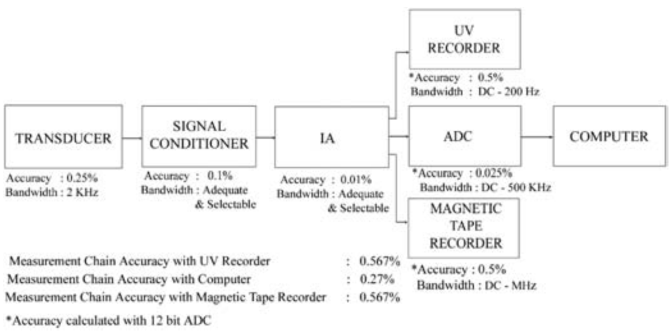

Figure 2. Measurement chain and data acquisition during 1970s and 1980s.

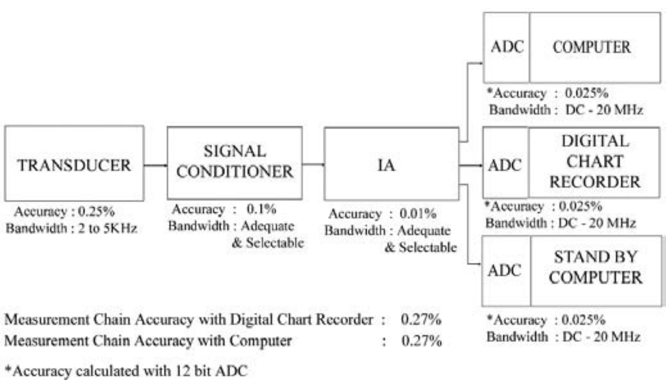

Figure 3. Measurement chain and data acquisition in early 1990s.

The recorded data was used to be analysed on UNIX-based multi-terminal system. Use of magnetic tape recorders was confined to higher bandwidth and longer duration tests. Also, PC-based systems were becoming more popular with features like throughput and numbers of channels with multiple ADC cards in personal computer interface (PCI) slots. Though it never matched in terms of number of channels of stand-alone ADC used along with the mainframe computer, but flexibility, ease of operation and analysis helped PC-based system becoming more popular and powerful. In 1990's PC-based computer system replaced the mainframe-based data acquisition system. The concept of distributed data acquisition system with centralised control was more acceptable to users and most suitable to carryout remote data acquisition. Chart recorders and magnetic tape recorders became digital from analog. In chart recorders data was stored on hard disk and in digital magnetic tape recorder on digital tapes. Basically these digital recorders are PC-based systems with built-in displays for specific requirement. In late 1990, PXI-based systems became more popular and users started configuring the data acquisition system requirements based on PXI. At present, PC-based and PXI-based data acquisition systems are used. Chart recorder with features like computers are also very popular and presently also used for data acquisition.

The change in recording systems has not happened overnight. It has happened due to development of several technologies in the field of hardware and software over a period of three decades.

3.7 Visual Instrumentation

Though visual instrumentation is not a part of measurement chain, it is important for post- test analysis of rocket motors. In early seventies till late nineties, high speed cine photography camera in 16 mm and 35 mm format were extensively used during rocket motor testing. The limitation of recording was the length of the film. The use of photography in ballistic works extends over a period of more than 140 years. Photo-Sonic Inc had built 16 mm, 35 mm, and 70 mm intermittent-action pin-registered camera for National Aeronautics and Space Administration. Kodak Limited manufactured the first rotating prism type high speed cine photography camera in Europe and had higher speed compared to the pin-registered intermittent cameras. Wolleensak and Hitachi from USA and Japan, Weinberger AG of Switzerland and Sweden, Red Lake of USA, were the other manufacturers of high speed cine photography cameras[4].

High speed still camera was also used to get good resolution photographs for documentation and publicity. In late eighties, video camera was available with higher frame rate of shorter duration. This limitation was due to onboard solid-state memory, and due to this limitation, high speed photography camera was preferred over high speed video camera. With development of technology, solid-state memory was available in larger capacity. With features immediate playback like on screen, re-usability of memory, variable frame rates, and absence of moving parts, video cameras fully replaced high speed cine photography cameras in late 1990's. The manufacturer of cine photography cameras diversified to high speed video cameras.

3.8 Data Reduction and Analysis

Recorded data is used to carry out performance analysis of the rocket motor. Until late eighties, UV recorders and magnetic tape recorders were used for data acquisition, study of chart and measurement on chart was essential to calculate performance indices and performance parameters. It was a laborious task and used to take days for data reduction. Even data recorded on analog magnetic tape recorders was required to playback on chart recorder or computer system to retrieve data. The accuracy of measurement was also getting affected during data reduction in case of UV recorders and magnetic tape recorder. The quick look data was possible to see in storage oscilloscope. After arrival of computers, data reduction and analysis became much simpler and more accurate. It became possible to get performance analysis within minutes after completion of a static test.

To calculate the performance of rocket motor two important parameters namely specific impulse and characteristic velocity, also called performance indices are required to be calculated by measuring data on the UV records. To calculate area under curve (Integral) Trapezoidal rule, Simpson's 1/3 rule formulae were used to find out integral thrust and pressure.

Performance indices of rocket motor are characteristic velocity (C*) and specific impulse (Isp). Characteristic velocity (C*) is the property of the propellant and is a function of nozzle / injector geometry of rocket motor.

$$\text{Cee star } (C^*) = \frac{A_t * \int P\,dt * g}{\text{Wt. of propellant}} \tag{1}$$

where specific impulse (Isp) is the total thrust generated by the rocket motor per unit weight of the propellant

$$\text{Isp }(\text{delivered}) = \frac{\int F\,dt}{\text{Wt. of propellant}} \tag{2}$$

where A_t is throat area of the nozzle and g is acceleration due to gravity and P is chamber pressure measured, and F is thrust force measured during the test[5]. The other important parameters, viz.; action time, test duration, web burn time, and ignition delay are also measured. In SI unit C^* is expressed in m/s and Isp is expressed in seconds.

With the emergence of computers and powerful analysis software, performance analysis used to be carried out immediately after the test and results were presented within 5 min. The input parameters like propellant weight, throat diameter and gravity of the place of test was entered in the database of a computer. The software packages used are DADISP®, WINDAQ®, MATLAB® and LABVIEW® etc. Thrust and pressure profile of a rocket motor is shown in Fig. 4, generated by computer immediately after the test. The complete performance analysis of a rocket motor, carried out by a computer is shown in Table 1. The data analysis time has been significantly reduced compared to earlier days.

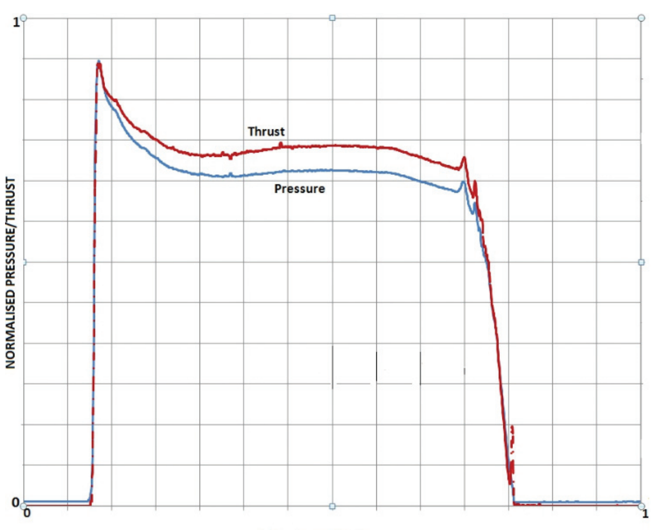

Figure 4. Thrust and pressure profile of a rocket motor.

Table 1. Performance parameters of a rocket motor

Input parameters		
Propellant weight (N)	436.56	
Avg. Throat dia (m)	0.048	
Booster weight (N)	174.62	
Sustainer weight (N)	261.93	
Gravity (m/s^2)	9.8105	
Performance analysis		
	Booster phase	**Sustainer phase**
Web burn time (s)	2.589	4.362
Maximum pressure (N/m^2)	9808038	
Maximum thrust (N)	26874.8	
Integral Pdt (web) (N/m^2-s)	23088816	14492313
Integral Fdt (web) (N/m^2-s)	621593973	382819554
Average Press (web) (N/m^2-s)	8918271	3322647
Average Thrust (web) (N)	24010.22	8776.66
Combined performance		
Cstar (m/s)	1510.71	
ISP (del) (s)	226.79	
Integral Pdt (act) (N/m^2-s)	37074933	
Integral Fdt (act) (N/m^2-s)	990039915	
Total web burn time (s)	6.951	
Total action time (s)	7.016	
Total duration (s)	7.133	
Ignition delay (s)	0.095	

3.9 Technologies

The development of semiconductor technology has given boost in the field of electronics and computers by providing products like hard disk, flash drive, application-specific integrated circuits (ASICs), programmable logic devices (PLDs) and field programmable gate arrays (FPGAs) along with other advanced manufacturing and inspection technologies.

Field programmable gate arrays (FPGAs) and ASICs arrived in 1984 as an alternative to programmable logic device (PLDs). FPGA, as the name suggests has benefit of being readily programmable unlike PLDs, FPGAs can be programmed again and again providing designers multiple chance for optimal design of the circuit[6]. The development of Internet has also brought revolution in the field of software technologies. Software technology developed for Internet is also used for data acquisition and instrumentation. The rise of cloud storage and computing has helped, data acquisition in remote places where access to data is very difficult. It has not only saved in terms of time and ease of operation, but also in terms of money. The emerging software advancement in the field of mobile technology is also influencing the data acquisition, specially in the area of hand-held instruments. The future developments in software technology in the field of mobiles may also influence the software in the area of data acquisition. The features like remote triggering and web publication are very helpful and are used for display of real-time data at several locations during the testing of rocket motors.

The interconnect bus, mostly used for communication of data from computer to instruments are serial communication (Serial Port), GPIB, the PC bus and VXI bus. GPIB was the first industry standard bus for connecting computer with instruments. A major advantage of GPIB is that the interface can be embedded on the rear of a standard instrument. This allows dual use of the instrument as a stand-alone manual instrument and as a computer controlled Instrument.

Development of data bus and network technologies also has helped the computer technology to grow. PCI express 4.0 introduced by Intel in 2004 is the most common bus interface in desktop computer. Compared to PCI, with a bandwidth of 132 MB/s, PCI express provides 4 GB/s per device. PXI express system is based on PCI express technology. Similarly, USB 3.0 has become one of the most popular bus interface used for computer. This bus made it fundamentally easier to connect external devices to computer including data acquisition device. Compared to USB 2.0 which has a maximum throughput of 35 MB/s, USB 3.0 uses additional wires and implements full duplex communication to achieve much higher transfer rate up to 625 MB/s. The maximum power provided by a single bus port has increased to 900 mA, allowing more devices to be powered of the bus instead of external power source. Thunderbolt is new technology developed by Intel and Apple that aim to merge multiple cable by combining data, audio, and power into a single connection. Power over ethernet (PoE) is method for safely passing electrical power along with data over on ethernet cable. Specialised equipment is used to supply power in common mode over four or more differential pairs of wires found in ethernet cable. PoE +, provides up to 25.5 W of power and can be run 100 m. PoE is widely used in the field of networking. 802.11 AC, i.e., wi-fi is one of the most popular ways to connect computing device to local area network and for internet. With wi-fi based data acquisition engineers can eliminate use of signal cable, however high performance data acquisition application that requires continuous streaming may not be suitable. Compared to other bus it is slow and depends up on the quality of the wireless signal. WI-FI direct is a standard that connects wi-fi device without a wireless router or access point. It works by embedding a software access point in the device[7].

Virtual instruments represent a fundamental shift from traditional hardware-centered instrumentation system towards software-centered systems. The basic components of all virtual instruments include a computer and display, the virtual instrument software, a bus structure and the instrument hardware. It exploits the computing power, productivity, display and connectivity capabilities of popular desktop computers and works stations. Although PC and integrated circuit technologies experienced significant advances in the past three decades, it is the software that makes virtual instrument possible. Engineers and scientists can build measurement and automated systems that suit exactly their specific need. A virtual instrument can be defined as an integration of sensors by a PC equipped with specific data acquisition hardware and software to permit measurement, data acquisition, processing and display[8]. In the field of rocket motor Instrumentation manual controls are replaced with virtual instruments on the computer monitor.

4. CONCLUSIONS

(i) As enunciated in this paper, the limitation of accuracy and bandwidth during measurement was due to recording systems. The other components of measurement chain were having adequate bandwidth and accuracy for measurement.

(ii) Electronic and computer field is flooded with new technologies. As an engineer and a scientist or any user, one should be very careful while configuring the system for a specific application. As stated in this paper, though several advancements have been made in the field of sensors, but for rocket motor application, transducer developed three decades earlier are found most suitable for the application. Glamour of new technology should not distract and tempt while configuring new systems. The other important factors one should consider are the cost of total system, maintenance, and availability of support, for future. Failure of one component should not call for design change and procurement of a new system.

(iii) Advancement in technology is good for mankind and for the scientific community. One should change with technology rather in different words we should use technology. Normally, Engineers and scientists have shown reluctance for change in their existing systems. Introduction of new technology provides an opportunity of learning for scientists and engineers.

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