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Department of Automotive, Combustion Engine and Railway Engineering

Piston Temperature Measurement for a Spark Ignition Engine

Master Thesis

Study Program: Master of Automotive Engineering

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Declaration

I hereby declare that this thesis work is my independent work, under the supervisions of

Ing. Jindřich Hořenín and Ing. Miloslav Emrich, Ph.D. and using the literature mentioned.

In Prague on: 11-01-2019   Signature: Sugesh Balasubramanian

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Abstract

Design an installation of thermocouples into various locations of the reciprocally moving piston in a spark ignition engine with cylinder bore of 74.5 mm and piston stroke of 85.9 mm. Design a flexible wire routing to the connector block of the telemetry system attached to a connecting rod. Prepare a manufacturing drawing and an assembly drawing of the entire installation. Prepare an installation documentation. Prepare integration of the telemetry data into the data acquisition system. Test the functionality of the measuring system.

Keywords: Spark Ignition Engine, Piston, Thermocouple, Data Acquisition System, Telemetry System.

TABLE OF CONTENTS

Nomenclature

q_z	Operating co-efficient of preload
Q_z	Operating preload
F_h	External applied load
S_3'	Minimum area of thread core
ν	Utilization rate of yield strength
σ_{KT}	Yield strength
κ_x	Co-efficient of influence of torsion
d'_3	Minimum thread core diameter
k_1	Co-efficient of bolt stiffness
E_{bolt}	Young's modulus of bolt
L_b	Length of bolt
k_{21}	Co-efficient of tube stiffness
E_{tube}	Young's modulus of tube
d_2	Outer diameter of tube
d_1	Inner diameter of tube
L_{g2}	Length of tube
k_{22}	Co-efficient of holder stiffness
E_{grip}	Young's modulus of holder
d_{nom}	Nominal diameter of hole
A	Frustum angle
L_{g1}	Thickness of holder
k_2	Co-efficient of joint stiffness
k_m	Joint stiffness factor
Q'_0	Mounting preload
Q_{1m}	Central operation force
Q_{1a}	Amplitude force
F_{1h}	Change of force in bolt due to applied force

F_{2h}	Change of force in Joint due to applied force		M_k	Bolt torsion when reaching preload
			T	Torsional stress
			k_τ	Torsion safety factor
Q_Z	Clamping force in Joint			
			σ_{red_max}	Maximum reduced stress
Q_{1max}	Total tensile force in Bolt			
			k_{red_max}	Maximum static stress
σ_{Q0}	Tensile stress from preload			
			$\sigma_{c(-1)}$	Fatigue limit for pulsating stress
σ_m	Tensile stress from central operating force		σ_{pt}	Tensile strength
			ϕ	Overall reduction in fatigue coefficient
σ_a	Tensile stress from amplitude force			
			ψ_σ^x	Influence factor of σ_m [-]
σ_{1max}	Maximum stress			
γ	Thread pitch angle			
			k_σ	Dynamic safety co-efficient
P	Thread pitch			
i	Number of threads		k	Resulting safety factor
βn	Flank angle profile			
			d_{wire}	Diameter of thermocouple wire
B	Thread angle			
f	Friction of co-efficient		A_{wire}	Area of thermocouple wire

ρ_{wire}	Density of thermocouple wire	V_{wire_02}	Volume of thermocouple wire at position 02
V_{wire_01}	Volume of thermocouple wire at position 01	L_{wire_02}	Length of thermocouple wire at hanging position 02
L_{wire_01}	Length of thermocouple wire at hanging position 01	m_{wire_02}	Mass of thermocouple wire at position 02
m_{wire_01}	Mass of thermocouple wire at position 01	α_{wire_02}	Maximum acceleration of wire at position 02
α_{wire_01}	Maximum acceleration of wire at position 01	σ_{wire_02}	Stress on wire at position 02
σ_{wire_01}	Stress on wire at position 01		

1 Introduction

1.1 Motivation

In the last decade the mechanical power output of the internal combustion engine has been increased significantly. This has been possible through injection systems that brought to an optimization of the combustion and to an improvement of the turbo charging. Moreover, alternate fuels techniques have been getting more attention to the reduction of exhaust emissions and an increasing the engine efficiency. Furthermore, the fuel injection pressure and the pressure peaks into the combustion chamber have been increased to the aim of emission reduction and higher engine efficiency.

The car manufacturers are following the way of the engine downsizing that means to have the same engine power by a lower engine displacement. The downsizing has main effect of a thermal risks particularly for the hot parts of the combustion chamber (Piston, exhaust valves, spark plug body) due to these parts have an increased thermal stress and high heat load. These temperatures could have effect to the risk of engine damage by irregular combustion due to surface ignition by deposit or by hot spot of the combustion chamber.

One of the main tasks of modern engine building is to further improve the technical and economic indicators of internal combustion engine. However, this leads to increase of mechanical and heat loads on the cylinder-piston group. Increase of temperature of the engine parts leads to early wear of Piston ring sticking, piston seizure, burnouts of the piston heads, etc. Engineers nowadays are using single cylinder for research and development where duel fuels are used. That give different heat release of combustion for different fuel compositions and different temperature distribution of piston. The typical distribution of temperature in Piston are shown in Figure 1-1. One of the most challenging components to analyse is the piston due to its reciprocating motion. However, the accurate measurement of piston

temperature is difficult task with the limitations of current measurement systems. The difficulties are mainly due to piston speeds over 6000 rpm, accelerations over 2000g, temperature more than 300 degrees Celsius. Piston contributes on the order of 50% to 60% of the mechanical losses of the engine.
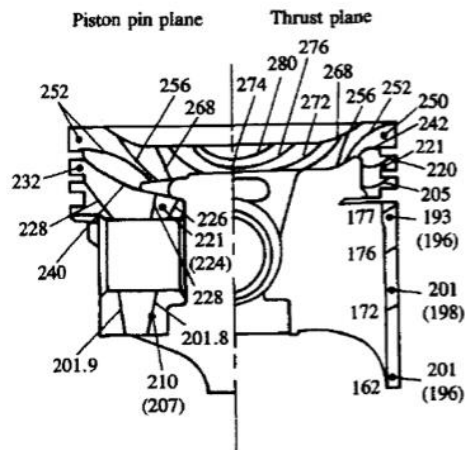

Figure 1-1: Typical temperature distribution of SI piston [33]

However, piston remains one of the most important components of small engine with respect to durability. The piston, as the key part of internal combustion engine, is always running with the large thermal load by converting the thermal energy from the fuel into mechanical energy and transfers it to the crankshaft. Piston durability has a major influence on the reliability, emission performance, lifetime and economy of the internal combustion engine, and the piston temperatures are useful information for the development of the engine. The performance of piston and its life are greatly influenced by the thermal conditions in the engine combustion chamber. The temperature distribution in piston are basic aspect in determining the piston stress, material requirements, friction, expansion and distortion, oil consumption. Piston temperature is influenced by many factors including engine speed, load, ignition and injection timing, air/fuel ratio, piston cooling, combustion chamber design. The impact of engine speed on the temperature of piston is shown in Figure 1-2.
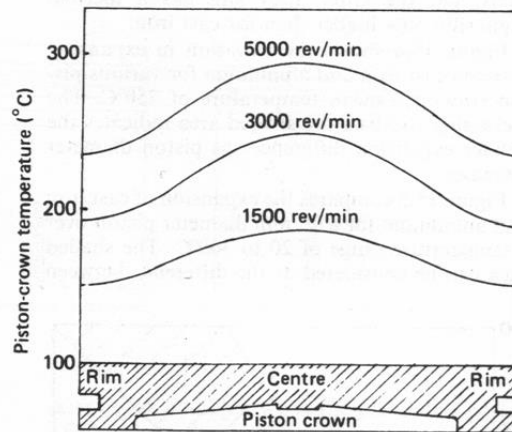
Figure 1-2: Change in temperature of Piston with speed [11]

1.2 Objectives of Work

This work is a part of a larger project that deals with the design of new single-cylinder Spark ignition engine that will be used in the laboratory. The engine will be used for many experimental measurements. This thesis work will majorly focus on the design of temperature measurement method using thermocouples and RF telemetry system that to be installed on to the piston and to the connecting rod. The main motivation of the work is to experimentally study the time averaged temperature of piston of single cylinder spark ignition research engine at steady state full load condition (6000rpm).

The Preliminary design of the geometry of the engine piston, connecting rod, connecting rod bolts and crank shaft were available at the beginning of this thesis. Few factors must be considered while designing this measurement method that enough space for placing the telemetry module on to the connecting rod, the engine will work in laboratory conditions and due to various testing and measurement, the engine will be often disassembled. The geometry of the piston has been little modified to fix the type-J thermocouples into it. An additional component called holder for holding the telemetry transmitter module which is attached to the bottom side of the connecting rod with two small sized bolts to screw it to the connecting rod

bolts. A flexible wire route of thermocouple wires from the piston to the telemetry module along the connecting rod has been made. Software has been developed for the Integration of telemetry data into Data Acquisition system using LabVIEW software.

1.3 Outline of the Work

In the following chapter a review of the literature on various methods used for the measurement of temperature of piston are discussed. Also, the method of temperature measurement of piston using thermocouples through telemetry system is discussed with background on the technique used in this research. A detail information and setup of the equipment used for this thesis and calculation of bolt are given in chapter 3. Details of development of the software are discussed in the chapter 4. The discussion and conclusion that are obtained from this work are given in Chapter 5.

2   Literature Review and Background

2.1   Piston Temperature Methods

The first attempt was done to measure the piston temperature in internal combustion engine by Gibson in 1926 [1]. The engine was run until the desired conditions were attained, then the engine was stopped. The piston been inserted with thermometer into a small cavity. Temperature versus time was plotted and extrapolated back to the time when the engine was stopped to estimate the temperature of running piston.

Another attempt has been made by thermocouple wires were attached to the piston and a two-bar link mechanism were used to guide the wire outside the crankcase by Baker [2]. Positive of this method are its ability to measure both steady state and transient conditions. With this measurement technique could withstand 1400 RPM and need more modifications of engine.

To avoid the breaking of thermocouple wire investigators invented a new measurement technique called contact method in which the electric circuit is to be completed at one end of its stroke [3] [4] [5]. This contact method has two groups: Sliding contact and Impact contact. The sliding contact method uses the contacts that rub each other while sliding of piston. This method appears better suited for high speed engine as noted by Underwood. The impact contact method as the speed increases, fails because of bouncing of the contact point as the spring used to ensure electrical contact with movement of piston. However, this contact method has major disadvantage is that for only short period of time the electric contact is made and occurs only if the piston is at engine cycle when the least temperature and pressure are in the combustion chamber. Due to internment of the crankcase, this contact method is limited to number of contacts. The contacts were places higher in the stroke, because of reciprocating motion of piston, the contacts would interfere with the engine operations.

To work on two stroke engines and smaller engines with limited space in the crankcase led to use the thermocouple wires being routed outside the combustion chamber through tube with the wires. But for this method sealing is required for combustion gasses and cooling system to cool the wires inside the tube for preventing the insulation of wire. However, this method was limited to 300 RPM due to fatigue of wire at high engine speeds.

One of the latest method developed to measure the temperature of piston using thermistor and electromagnetic induction. A set of transmitter coils and receiver coils are combined and fixed to the cylinder block. Resonator coil with thermistor coil is installed in the piston. When alternating current passed to the transmitter coil, the same frequency of alternating current flows through the receiver coil. When the piston reaches the bottom dead center, via electromagnetic induction the current flows through the resonator coil, which cause the current flows to decrease to resonator coil due to resistance of thermistor. By the reduction of current flow due to resistance of thermistor, the piston temperature was measured reported by M. Suzuki and S. Ueda [6].

Another method was proposed [7] to measure temperature of piston using Voltage memory. This method comprises the usage of thermocouple, compensation, cycling circuit and voltage memory. The main works of voltage memory: was to record the data of voltage with the clock and the timer. This method of measurement is limited to slow speed.

Optical temperature measurement [8] [9] to measure the surface temperature of piston. They implemented the detector (InGaAs) in a special spark plug and conducted measurements. Sapphire windows have been inserted in the liner of the cylinder. Sapphire is transparent to both thermal infrared radiation and to the visible light. Infrared thermal microscope used to measure the temperature of piston surface.

Memory Test System [5] method is one another method to measure the temperature of piston. MTS consist of thermocouple as the temperature sensors, the storage unit and the data acquisition unit. The Data acquisition unit send the signal to the storage unit by regulating signals from thermocouples. The data stored in the storage unit would be read out by computer for post processing.

A method using Surface Acoustic Wave (SAW) to measure the piston temperature has also proposed [10]. The SAW sensor and antenna with trans receiver unit were mounted on potential positions and the signal were measured.

Another attempt was made by Dennis [11] using optical fiber sensor embedding into a metal piston. The embedded sensor was calibrated by measuring the wavelength shift of the fiber Bragg grating and comparing it the temperature as measured by thermocouple. The wavelength scanning lasers were used to measure piston temperature in a non-contact manner. This method also limited to low speed.

Few industries are commercially selling the wireless devices for piston temperature measurements. A study conducted by Prathik [33] says that the Scania are commercially selling three types of piston temperature measurement system where they design and developed by their own. Their three types of measurement system are Templugs, Telemetry system, Thermographic paints. They are using microwave telemetry systems from different manufactures. Thermographic paints are heat sensitive paints that change color when exposed to certain temperature limits. A thin layer of irreversible temperature sensitive paint is applied on the piston surface and allowed to stabilize. After the piston is run under steady state condition for a set duration. Once the piston is cooled to atmospheric condition it is examined and compared with calibrated color range to obtain the surface temperature profiles.

3   Selection of Appropriate Solution

3.1   Test Engine

The engine is single cylinder research spark ignition engine. The specification of the engine is shown in Table 1. In this thesis the design of the temperature measurement system for piston is made for full load steady state condition at 6000rpm. The Figure 3-1 shows the model of the engine. The engine is dimensioned for maximum combustion pressure of 130 bar and a maximum speed of 7000 rpm.

Table 1:Experimental Engine Specification

Cylinder No.	1
Bore	74,5 mm
Stroke	85,9 mm
Displacement	374,5 cc
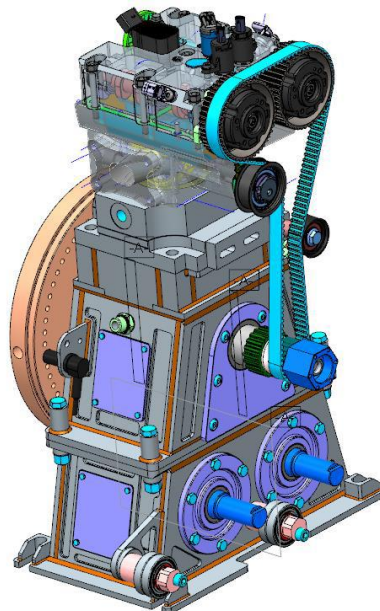
Figure 3-1: Engine Model
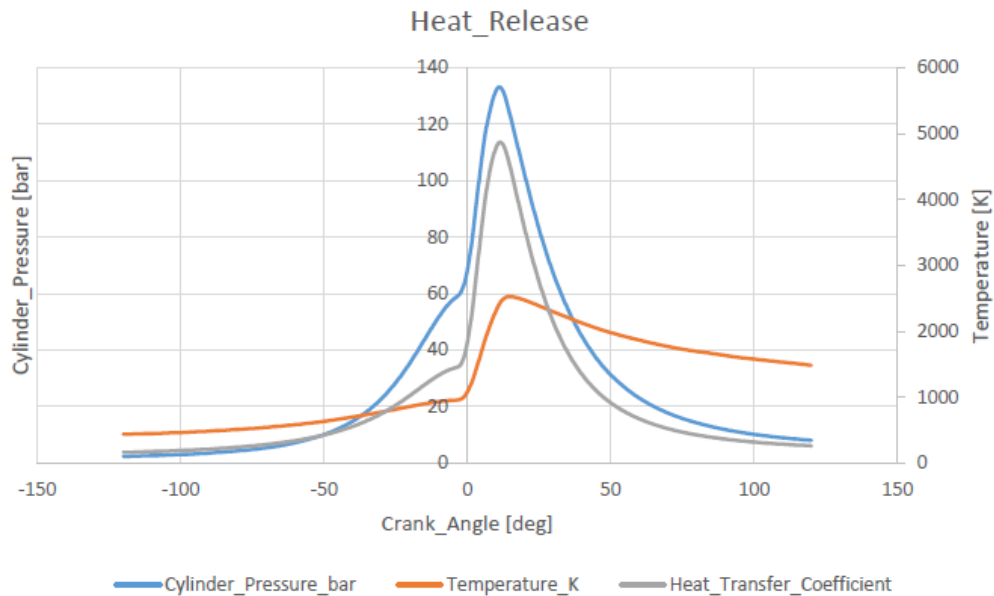
Chart 3-1: Heat Release [21]

The Chart 3-1 show the heat release curve of the experimental engine where the maximum temperature of the ignited mixture in the cylinder is calculated at 2525 K. The peak of the combustion pressure is 11 degrees behind the top dead center. The engine will be used in the laboratory where the lowest ambient temperature will therefore be around 20 °C. The engine will be used for research and development of combustion process with various fuels which gives various heat release curve which leads to various piston temperatures.

3.2 Piston Modifications and preparation

As mentioned in the Figure 1-1, the maximum temperature of typical piston would be on its top surface, as it is directly exposed to the combustion explosion and it drops down towards to the skirt of piston. Thus, for our case to measure the piston's maximum temperature, the interest is the top surface of the piston. There are totally 7 places of the surfaces were selected to locate the thermocouple wires in the piston. These locations almost cover the entire area of piston top surface. The 7 locations of the holes are in 2 different perpendicular planes of the piston: thrust plane, piston pin plane as shown in Figure 3-3. The holes (1,2,3,4,5) are in thrust plane of the

piston and the holes (6,7) are in the piston pin plane of piston. The tip of the holes is approximately below 1mm from the top surface of the piston to get maximum accurate temperature measurement.

To fix the thermocouple wires in underside of the piston, some modification like drilling has been made. The proper size of the holes has chosen after a trial has been made to check the more suitable dimensions of the thermocouple wires. The trial process includes, a cylindrical model with many holes of 1,5mm inner diameter and outer diameters 2mm, 3mm, 4mm, 5mm and 6mm of depth 8mm and 9mm was designed and manufactured. Then thermocouple wires were installed into the various dimensioned holes of the model and analysed that the hole size of 3mm of outer diameter and 1.5mm of inner diameter is more suitable for gluing and easy installing the thermocouple wires. The trial installation of wire is shown in Figure 3-2 as the left picture is a sample piece with different holes and the right picture is the sample piece with installed thermocouple wires in it.

Figure 3-2: Trial installation of thermocouple wires
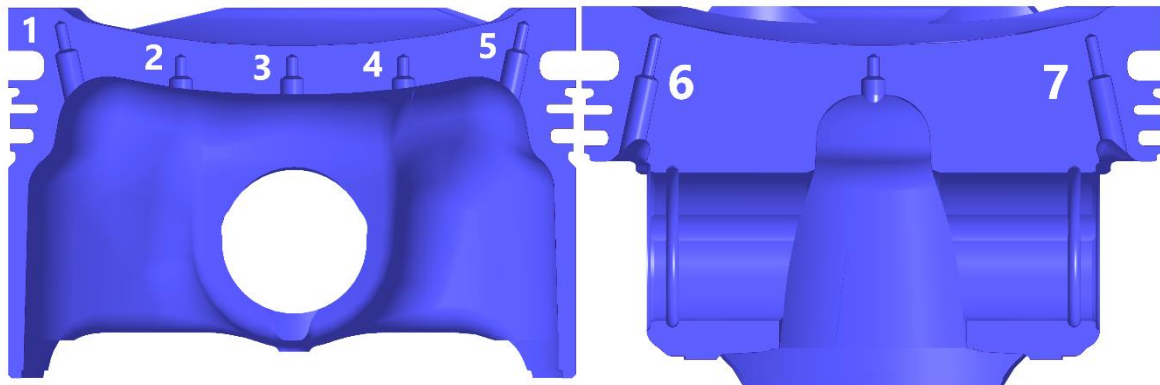
Figure 3-3.Thermocouple location in thrust plane and in piston pin plane

Moreover, the underside surface of the piston is not more sophisticated for machining purpose. While making drilling process the drill bit may be subjected to broken or damage and may not be precisely locate the location in the piston. To make the drilling process easy and to prevent the damage of the drill bit, an additional Jig component has been developed. The jig part helps to hold the piston and make the guide path for the drilling process. It extends from bottom of the piston skirt to almost near to each location of the holes in piston. This jig prevents the small size drill bit from damage while drilling process. The Figure 3-4 shows the cross-section view of the jig (cyan color) component for machining of piston. The jig can also be used for piston with similar dimensions.
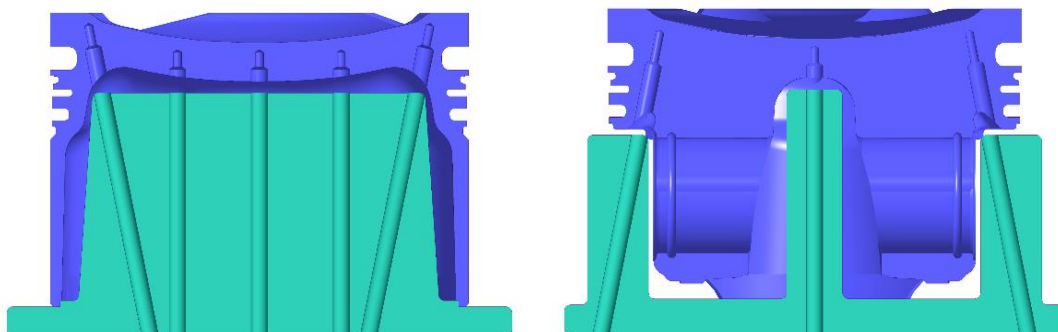
Figure 3-4: Jig for Piston

3.3 Thermocouple system setup

A simple thermocouple system is comprised of two wires and a voltmeter. Each thermocouple wires are sheathed with different colours of sheath to prevent any contact along the wire and it also allows to identify the positive and negative leads of the wire. This sheath also acts as electrical insulation. The wires are welded using the thermocouple welding machine in such a way that initially the plastic sheaths are removed at one end of each wire for small distance, then made a little twist of both wires together. Then proper voltage is set in welding machine and the weld is made at the tip of the bare wire to make a junction.
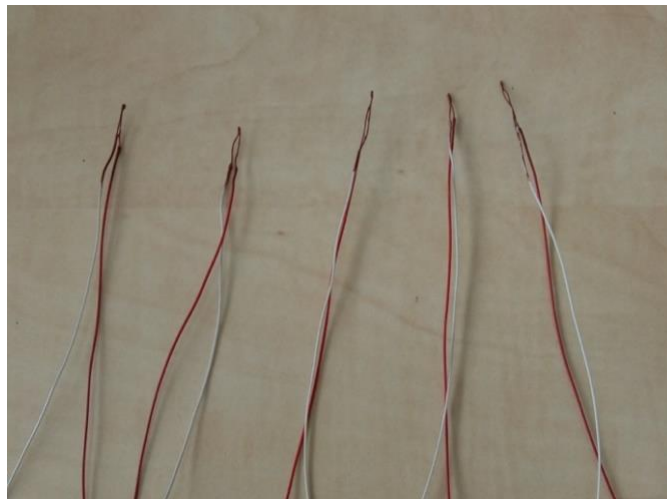
Figure 3-5: J type Thermocouple

Figure 3-5 shows the J type thermocouples with welded tip at one end and other end of the wires are subjected to interfaced into telemetry transmitter module. The white colour wire is positive (Iron) and the red colour wire is negative (Constantan). Each wire has diameter of 0.38mm. As J-type thermocouple possess high range of measurement, it is well suited for our measurement process. These pair of thermocouple wires are twisted and are again to be wrapped using copper braided cable as shown in Figure 3-12 for extra protection and for the purpose of reduction of stress on the wire at high speed of revolution. The total diameter of the

wire is 3mm. This size wire can withstand the high force in the engine as calculated the stress of wire in section 3.6.1 and 3.6.2 Table 2 shows the specification of J type thermocouple.

*Table 2: J-Type Thermocouple specifications*

Type	J
Wires	• Positive – Iron • Negative = Constantan
Colour	• Iron – White • Constantan – Red
Range	-196°C to 800 °C
Accuracy	+/- 2.2°C
Diameter	0.38mm

3.4   Module Holder Design

A holder is designed to hold the telemetry transmitter module and to attach the module in bottom side of the connecting rod. The holder is designed in such a way to give space for transmission of RF wave from the transmitter module to receiver which is placed outside the engine crank case. The holder is attached to the bottom side of the connecting rod to its bolt. A desired size bolts were selected after analysis to screw it into the connecting rod bolt.

The material of 304 Austenitic stainless steel has chosen for the holder. Stainless steel 304 has excellent corrosion resistance property in wide variety of environments and in contact with different corrosive media. It is also having good property of resistance to oxidation in intermittent service up to 870°C. The thickness is 1mm and the overall weight of the holder is 49 grams. Initially the Stainless-steel is cut using laser cut process and then it is bended to desired dimension to hold telemetry module of dimensioned (14×26×45) mm. The Figure 3-6 shows the 3D design view of module transmitter holder with telemetry module attached to it.

In this figure the violet color indicates the telemetry module and the dark cyan color indicates the holder.
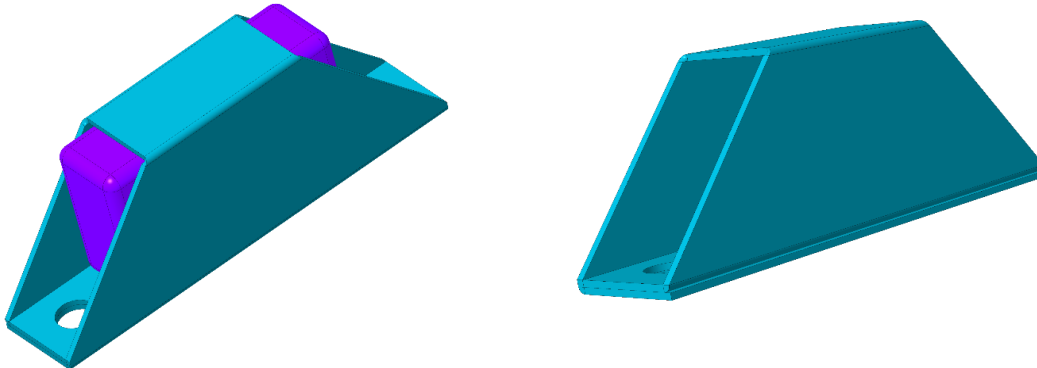

Figure 3-6.Telemetry module with module holder
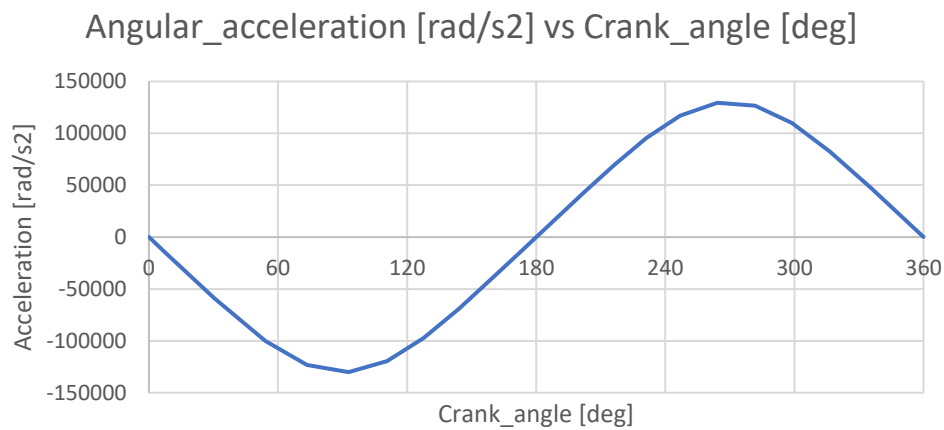
3.5   Calculation of Bolt

The module holder must be mounted to the connecting rod bolts. To do that a desired bolts size must be find. It must be considered that the maximum forces that apply on the bolt at full load condition (6000 rpm), high strength, less weight and with at least minimum safety factor while selecting the bolts.

3.5.1   Maximum Force applied

Since, the module holder bolts are attached to the bottom end of the connecting rod with the connecting rod bolts, the centrifugal force act on the bolt. The mass of the telemetry module is 38 [g], the mass of the telemetry module holder is 49 [g]. The Chart 3-2 shows the maximum centrifugal force applied on one bolt is $F_h = 2206$ [N] which are obtained from the dynamic simulation of PTC Creo 4 for the full load condition (6000 rpm). The angular acceleration at the position of bolt for the same full load condition (6000rpm) is obtained from the dynamic simulation using PTC Creo 4 is shown in Chart 3-3.
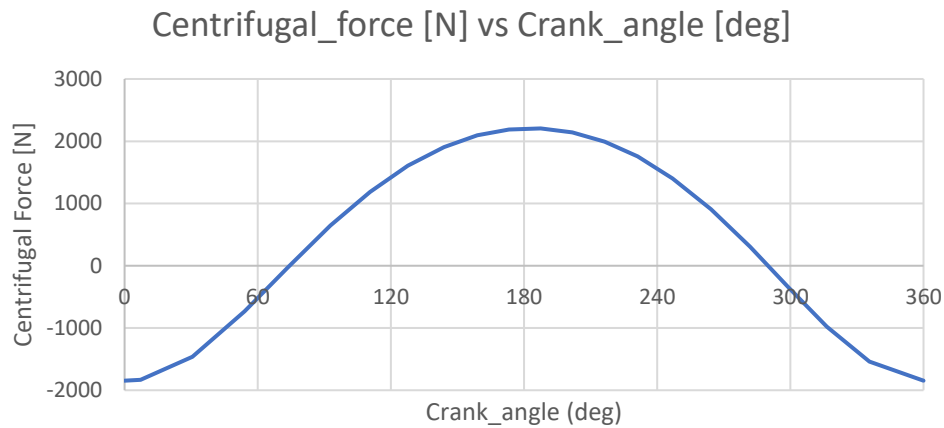
Chart 3-2:External Force Acting on Bolt

Chart 3-3: Angular Acceleration of bolt

3.5.2   Bolt design and thread calculation

The operating coefficient of preload q_z [-] is selected. Q_z [N] is the operating preload.

$$q_z = \frac{Q_z}{F_h} = 1,3$$

(3.5.1)

The metric thread M6 is used in the connecting rod head. The strength class of these screw is 12.9. The tensile strength of this class is 1200 [MPa] and the yield strength is 1100 [MPa]. The

proof load is 935 [MPa]. The thread core diameter d$_3$ = 4.773 [mm]. The minimum thread core diameter d'$_3$ [mm] is

$$\frac{F_h}{S_3'} \leq \frac{\nu . \sigma_{KT}}{\kappa_x . (1 + q_z)}$$

(3.5.2)

$$S_3' = \frac{\pi . d_3'^{2}}{4}$$

(3.5.3)

Where, S_3' [mm^2] is the minimum area of thread core

ν [-] is the utilization rate of yield strength,

σ_{KT} [N/mm^2] is the yield strength,

κ_x [-] is the co-efficient of influence of torsion.

$$d_3' = \sqrt{\frac{4 . F_h . \kappa_z . (1 + q_z)}{\pi . \nu . \sigma_{KT}}} = \sqrt{\frac{4 . 2206 . 1,2 . (1 + 1,3)}{\pi . 0.85 . 1100}} = 2,88 \, [mm]$$

(3.5.4)

$$S_3 = \frac{\pi . d_3^2}{4} = 17,9 \, [mm^2]$$

(3.5.5)

3.5.3 Calculation of Stiffness constant

To select the desired length of the bolt, a comparison has been made between the different bolt lengths and the stresses. The Chart 3-4 shows the comparison results of various bolt lengths and the stress on the bolt and on the joint. This information shows us the stress increases with increasing the length of bolt. By increasing the length of bolt, its weight also increases. Thus, by considering the weight, enough space for fixing the thermocouple wire to the module and

strength that has also factor of safety 6.4 which is more than enough to withstand the high load in our case.
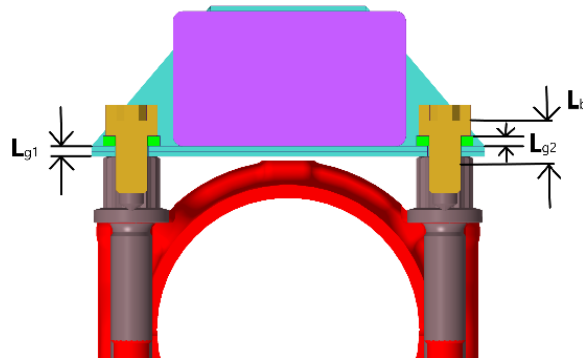
Figure 3-7: Assembly of holder bolts

Figure 3-7 shows the cross-section view of assembly of holder bolts with substitute tube on to the connecting rod. In which the thickness of holder (L_{g1}) is 2mm, thickness of substitute tube (L_{g2}) is 2mm and length of the bolt (L_b) is 9mm. The substitution tube helps in increase of stiffness of joint and reduction of stress on the bolt and support the fatigue damage under the bolt head. It also reduces the bolt stiffness, so that the joint clamp is more stable.
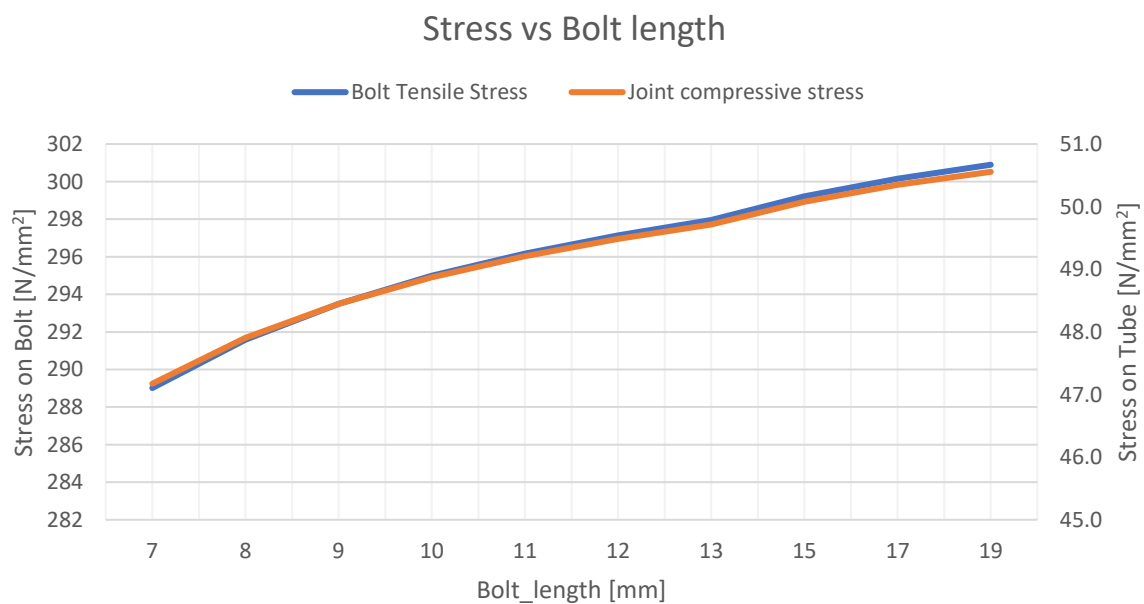
Chart 3-4:Stresses on different bolt lengths

$$k_1 = \frac{S_3 \cdot E_{bolt}}{L_b} = \frac{17{,}9 \cdot 200 \times 10^3}{9} = 3{,}98 \cdot 10^5 [N.mm^{-1}] \qquad (3.5.6)$$

Where, k_1 is the coefficient of the bolt stiffness [N.mm^{-1}].

E_{bolt} is the Young's modulus of Bolt [N.mm^{-2}].

L_b is the length of the bolt [mm].

$$k_{21} = \frac{\left(\frac{\pi(d_2^2 - d_1^2)}{4}\right) \cdot E_{tube}}{L_{g_2}} = \frac{\left(\frac{\pi(11^2 - 6{,}4^2)}{4}\right) \cdot 200 \times 10^3}{2} \qquad (3.5.7)$$
$$= 6{,}28 \cdot 10^6 [N.mm^{-1}]$$

Where, k_{21} is the coefficient of the tube stiffness [N.mm^{-1}].

E_{tube} is the Young's modulus of tube [N.mm^{-2}].

d_2 is the outer diameter of the tube [mm].

d_1 is the inner diameter of the tube [mm].

L_{g2} is the length of the tube [mm].

$$k_{22} = \frac{\left(\frac{\pi(d_2^2 - d_1^2)}{4}\right) \cdot E_{holder}}{L_{g_2}} = \frac{\left(\frac{\pi(11^2 - 6{,}4^2)}{4}\right) \cdot 193 \times 10^3}{2} \qquad (3.5.8)$$
$$= 6{,}06 \cdot 10^6 [N.mm^{-1}]$$

Where, k_{22} is the co-efficient of the holder [N.mm^{-1}].

E_{holder} is the Young's modulus of the holder [N.mm^{-2}].

L_{g1} is the thickness of the holder [mm].

$$k_2 = \frac{k_{21} \cdot k_{22}}{k_{21} + k_{22}} = \frac{6{,}28 \cdot 10^6 \cdot 6{,}06 \cdot 10^6}{6{,}28 \cdot 10^6 + 6{,}06 \cdot 10^6} = 3{,}09 \cdot 10^6 [N.mm^{-1}] \qquad (3.5.9)$$

Where, k_2 is the co-efficient of the joint [N.mm^{-1}].

$$k_m = \frac{k_1}{k_1 + k_2} = \frac{3,98 \cdot 10^5}{3,98 \cdot 10^5 + 3,09 \cdot 10^6} = 0,1141 \qquad (3.5.10)$$

Where, k_m is the Joint stiffness factor.

3.5.4   Calculation of Preload and Stress of Bolt

$$Q_0' = \left(q_z + \frac{k_2}{k_1 + k_2}\right) \cdot F_h = \left(1,3 + \frac{3,09 \cdot 10^6}{3,98 \cdot 10^5 + 3,09 \cdot 10^6}\right) \cdot 2206 \qquad (3.5.11)$$
$$= 4822 \ [N]$$

I define preload $Q_0 = 5000$ [N].

$$Q_{1m} = Q_0 + \frac{1}{2} \cdot \frac{k_1}{k_1 + k_2} \cdot F_h = 5000 + \frac{1}{2} \cdot \frac{3,98 \cdot 10^5}{3,98 \cdot 10^5 + 3,09 \cdot 10^6} \qquad (3.5.12)$$
$$= 5126 \ [N]$$

$$Q_{1a} = \frac{1}{2} \cdot \frac{k_1}{k_1 + k_2} \cdot F_h = \frac{1}{2} \cdot \frac{3,98 \cdot 10^5}{3,98 \cdot 10^5 \cdot 3,09 \cdot 10^6} = 126 \ [N] \qquad (3.5.8)$$

Where, Q_0' is the mounting preload [N].

Q_{1m} is the Central operation force [N].

Q_{1a} is the amplitude force [N].

$$F_{1h} = F_h \times k_m = 2206 \times 0.1141 = 252 \ [N] \qquad (3.5.14)$$

$$F_{2h} = F_h \times (1 - k_m) = 2206 \times (1 - 0.1141) = 1954 \ [N] \qquad (3.5.15)$$

$$Q_{1max} = Q_0 + F_{1h} = 5000 + 252 = 5252 \ [N] \tag{3.5.16}$$

$$Q_Z = Q_0 - F_{2h} = 5000 - 1954 = 3046 \ [N] \tag{3.5.17}$$

Where, F1h is the Change of Force in bolt due to applied force [N]

F2h is the Change of Force in joint due to applied force [N]

Q1max is the Total tensile force in bolt [N]

QZ is the Clamping force in joint [N]

The bolted joint diagram is used to visualise the load deflection characteristics of the bolt and the material which it clamps. It also helps in visualising how bolted joint withstand the external load and its get elongation for that load. The Figure 3-8 shows the bolted joint diagram. In the diagram line 1 represents the stiffness of bolt and line 2 represents the stiffness of Joint material.
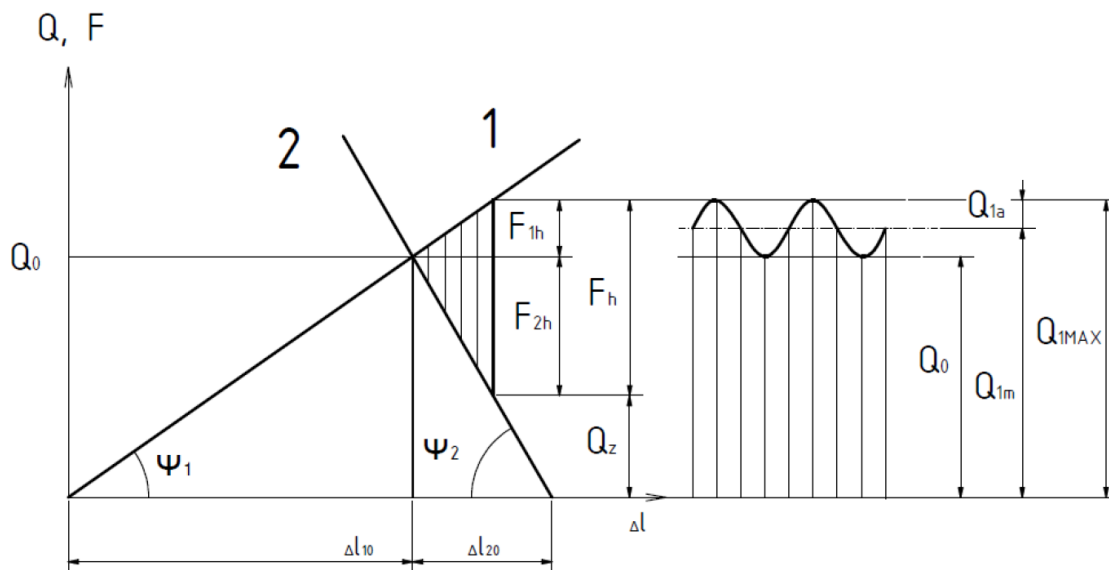
Figure 3-8: Bolt Joint Diagram

$$\sigma_{Q_0} = \frac{Q_0}{S_a} = \frac{5000}{17,9} = 279 \ [N.mm^{-2}] \tag{3.5.18}$$

$$\sigma_m = \frac{Q_{1m}}{S_a} = \frac{5126}{17,9} = 286,5 \ [N.mm^{-2}] \tag{3.5.19}$$

$$\sigma_a = \frac{Q_{1a}}{S_a} = \frac{126}{17,9} = 7 \ [N.mm^{-2}] \tag{3.5.20}$$

$$\sigma_{Joint} = \frac{Q_Z}{A_J} = \frac{3046}{63} = 48,4 \ [N.mm^{-2}] \tag{3.5.21}$$

$$\sigma_{Bolt} = \frac{Q_{1max}}{S_a} = \frac{5252}{17,9} = 293 \ [N.mm^{-2}] \tag{3.5.22}$$

$$\Delta L_{10} = \frac{Q_{1max}}{k_{10}} = \frac{5252}{397635} = 0,013 \ [mm] \tag{3.5.23}$$

$$\Delta L_{20} = \frac{Q_{1max}}{k_{10}} = \frac{3046}{3087178} = 0,001 \ [mm] \tag{3.5.24}$$

Where, σ_{Q0} is the tensile stress from Preload [N.mm^{-2}].

σ_m is the tensile stress from central operating force [N.mm^{-2}]

σ_a is the tensile stress from amplitude force [N.mm^{-2}]

σ_{bolt} is the maximum stress in the bolt [N.mm^{-2}]

σ_{Joint} is the maximum compressive stress in the Joint [N.mm^{-2}]

A_J is the area of the joint [mm^2]

ΔL_{10} is the Bolt extension due to applied force [mm]

ΔL_{20} is the Joint compression due to applied force [mm]

$$\tan \gamma = \frac{i \cdot P}{\pi \cdot d_2} = \frac{1 \cdot 1}{\pi \cdot 5,35} = 0,0595 \ \rightarrow \gamma = 3,4 \ [deg] \tag{3.5.25}$$

Where, γ is the thread pitch angle [deg]

P is the thread pitch [mm]

i is the number of threads [-]

$$\tan \beta_n = \tan \beta \cdot \cos \gamma = \tan 30 \cdot \cos 3,4 = 0,5763 \rightarrow \beta_n$$
$$= 29,96 \, [deg]$$
(3.5.26)

$$\tan \varphi' = \frac{f}{\cos \beta_n} = \frac{0,15}{\cos 29,96} = 0,173 \rightarrow \varphi' = 9,82$$
(3.5.27)

$$\tan(\gamma + \varphi') = \tan(3,4 + 9,82) = 0,235$$
(3.5.28)

Where, β_n is the Flank angle profile [deg]

B is the thread angle [deg]

f is the friction of co-efficient [-]

3.5.5   Determination of fatigue strength characteristics and safety calculation

$$M_k = Q_0 \frac{d_2}{2} \tan(\gamma + \varphi') = 5000 \cdot \frac{5,35}{2} \tan(3,4 + 9,862)$$
$$= 3152 \, [N.mm]$$
(3.5.29)

$$W_k = \frac{\pi \cdot d_3^3}{16} = \frac{\pi \cdot 4,733^3}{16} = 20,8 \, [mm^3]$$
(3.5.30)

$$\tau = \frac{M_k}{W_k} = \frac{3152}{20,8} = 151,5 \, [N.mm^{-2}]$$
(3.5.31)

$$\tau_k = 0,57 \cdot \sigma_{kt} = 0,57 \cdot 1100 = 627 \, [N.mm^{-2}]$$
(3.5.32)

$$k_\tau = \frac{\tau_k}{\tau} = \frac{627}{151} = 4,14$$
(3.5.33)

$$\sigma_{red\_max} = \sqrt{\sigma_{Bolt}^2 + \alpha^2 . \tau^2} = \sqrt{293^2 + \sqrt{3}^2 . 151^2} = 394 \ [N.mm^{-2}] \quad (3.5.34)$$

$$k_{red\_max} = \frac{\sigma_{Pl}}{\sigma_{red-max}} = \frac{935}{393} = 2{,}38 \quad (3.5.35)$$

$$\sigma_{c(-1)} = 0{,}61 . \sigma_{pt} = 0{,}61 . 1200 = 732 \ [N.mm^{-2}] \quad (3.5.36)$$

$$\sigma_{c(-1)}^x = \frac{\sigma_{c(-1)}}{\varphi} = \frac{732}{5} = 146{,}4 \ [N.mm^{-2}] \quad (3.5.37)$$

$$\psi_\sigma = 0{,}02 + 2 . \sigma_{pt} . 10^{-4} = 0{,}26 \quad (3.5.38)$$

$$\psi_\sigma^x = \frac{\psi_\sigma}{\phi} = 0{,}052 \quad (3.5.39)$$

$$k_\sigma = \frac{\sigma_{c(-1)}^x - \psi_\sigma^x . \sigma_{Q_0}}{\sigma_a + \psi_\sigma^x(\sigma_m - \sigma_{Q_0})} = \frac{146{,}4 - 0{,}052 . 279}{19 + 0{,}052 . (298 - 279)} = 6.6 \quad (3.5.40)$$

$$k = k_\sigma . \sqrt{1 - \left(\frac{1}{k_\tau}\right)^2} = 6{,}6 . \sqrt{1 - \left(\frac{1}{4{,}14}\right)^2} = 6{,}4 \quad (3.5.41)$$

Where, M_k is the torsion of the bolt when reaching the preload [N.mm]

W_k is the torsion section modulus [mm^3]

τ is the torsional stress [N.mm^{-2}]

k_τ is Torsion safety factor [-]

τ_k is the maximum permitted torsion [N.mm^{-2}]

σ_{red_max} is maximum reduced stress [N.mm$_{-2}$]

k_{red_max} is the maximum static stress safety factor [-]

$\sigma_{c\ (-1)}$ is fatigue limit for the pulsating stress [N.mm^{-2}]

σ_{pt} is the tensile strength [N.mm^{-2}]

σ_{PL} is the Proof load of Tube [N.mm^{-2}]

ϕ is the overall reduction in fatigue strength co-efficient [-]

ψ_σ^x is the influence factor of the σ_m [-]

k_σ is dynamic safety co-efficient [-]

k is the resulting safety factor [-]

3.6   Flexible Thermocouple wire routing

The thermocouple wires from 7 locations of the piston are made into single twisted wire to make the installation easy. The single twisted wire is attached to final position Figure 3-10 in underside near bottom of piston skirt and then a semi loop is made in space to allow the wire to move along the movement of the connecting rod. Then the wire is attached along the connecting rod towards its down side and finally attached to the telemetry transmitter module on one side Figure 3-11. The Figure 3-9 shows the wire route of thermocouple wires with 2 parts of hanging wire.
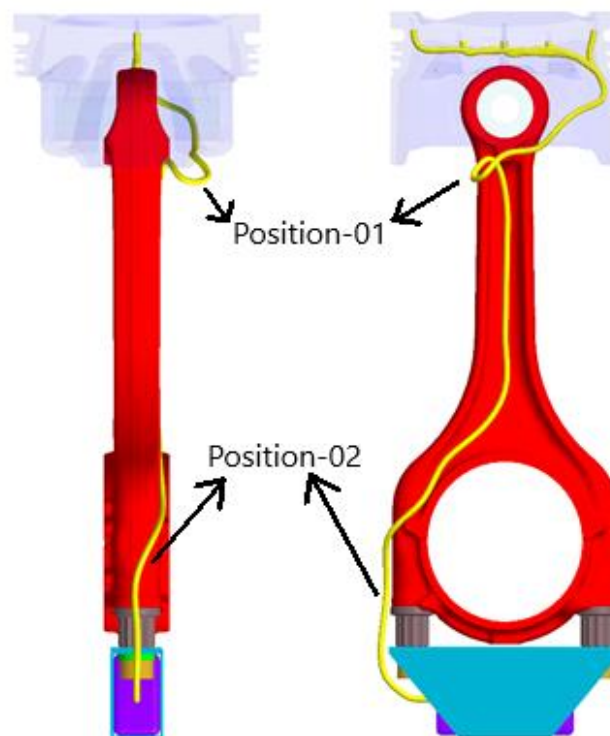
Figure 3-9.Thermocouple wire route

Since, the piston moves at high speed, the inertia force acts on the hanging part of wire at position 01 and at position 02 and are subjected to stress. The oscillation of connecting rod with respect to crank angle is shown in Chart 3-5. It shows that the maximum de flection angle of the connecting rod on both direction from central axis is found 18.27°.
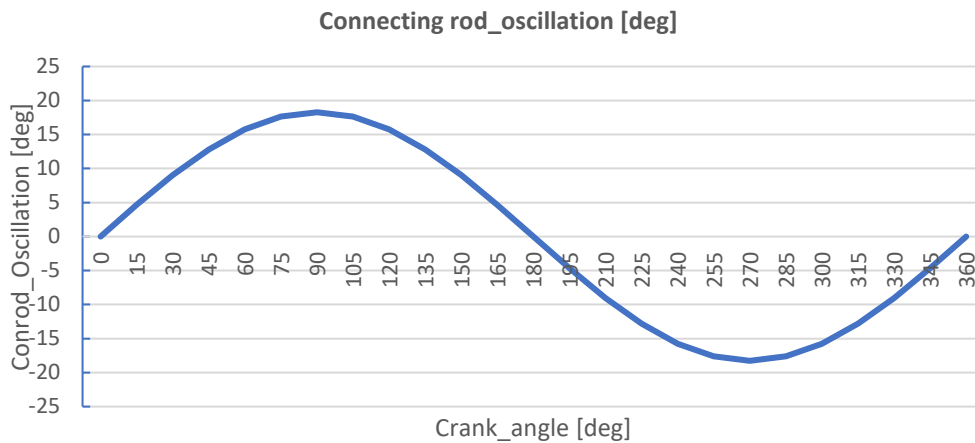
Chart 3-5:Oscillation of Connecting rod

3.6.1 Determination of stress of wire at position 01
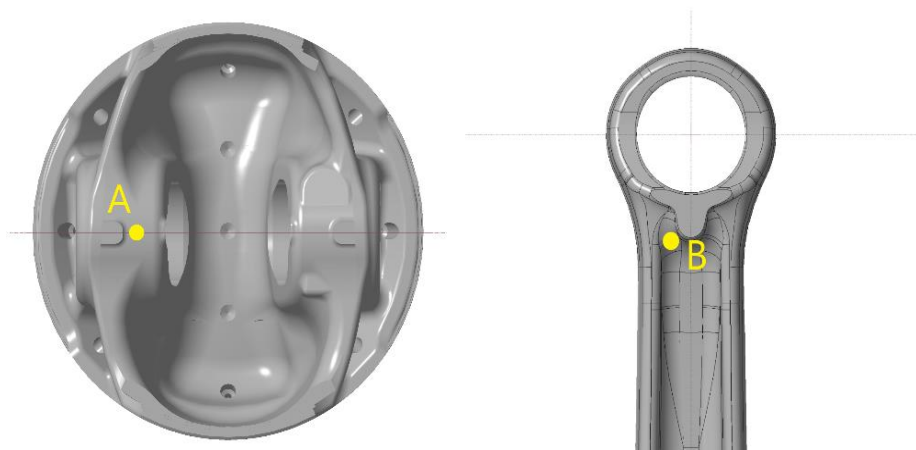
Figure 3-10: Position of attachment of wire at piston and at connecting rod

The Figure 3-10 shows the final attachment point of thermocouple wire at the piston (Point A) underside and at the connecting rod (Point B) near to the small eye. The point A is located at distance of 17mm from the thrust plane of the piston in the picture and on the piston pin plane. The point B is at 18mm from the centre axis of the small eye of the connecting rod. Thus, the length of wire which hang between these points A and B is 15mm by allowing free motion of connecting rod without any damage to the wire. To find the maximum acceleration of wire at this position 01, Horizontal component and Vertical component of acceleration at this position

is resolved to total acceleration of the wire at that position. The angular acceleration of horizontal component Chart 3-6 vertical component Chart 3-7. and the total acceleration Chart 3-8 at position 01 are shown in the following charts are determined from dynamic simulation in PTC Creo.
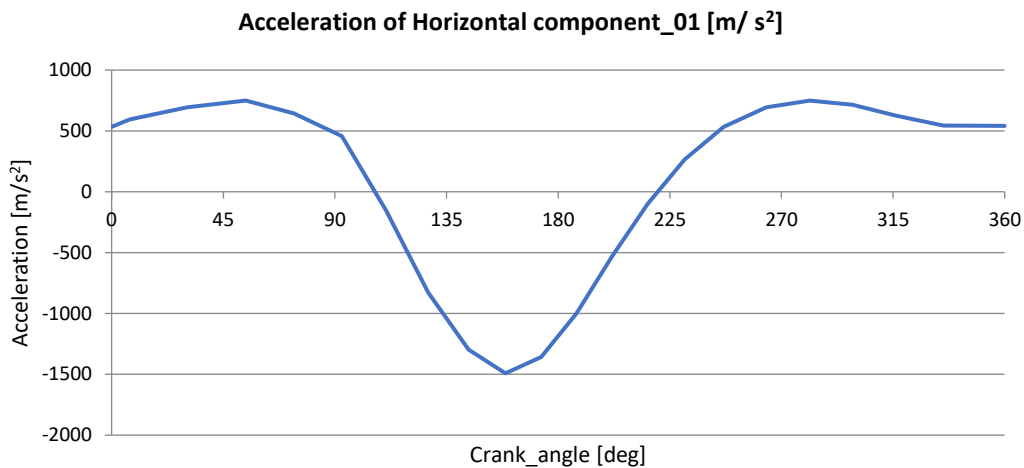
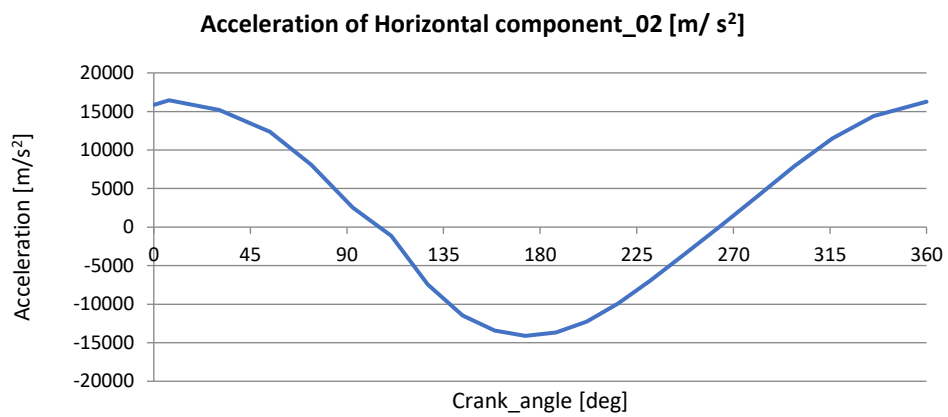*Chart 3-6:Acceleration of Horizontal component of wire at position 01*
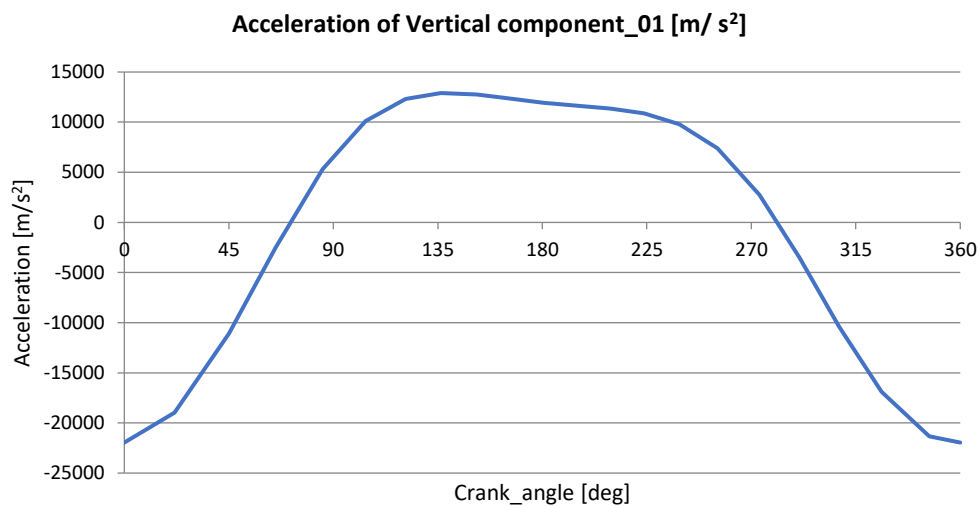
Chart 3-7:Acceleration of Vertical component of wire at position 01

From the Chart 3-8 the maximum acceleration acting on the wire at position 01 at full load (6000rpm) is found as 21961 [m.s^{-2}].

Total Acceleration_01 [m/ s²]
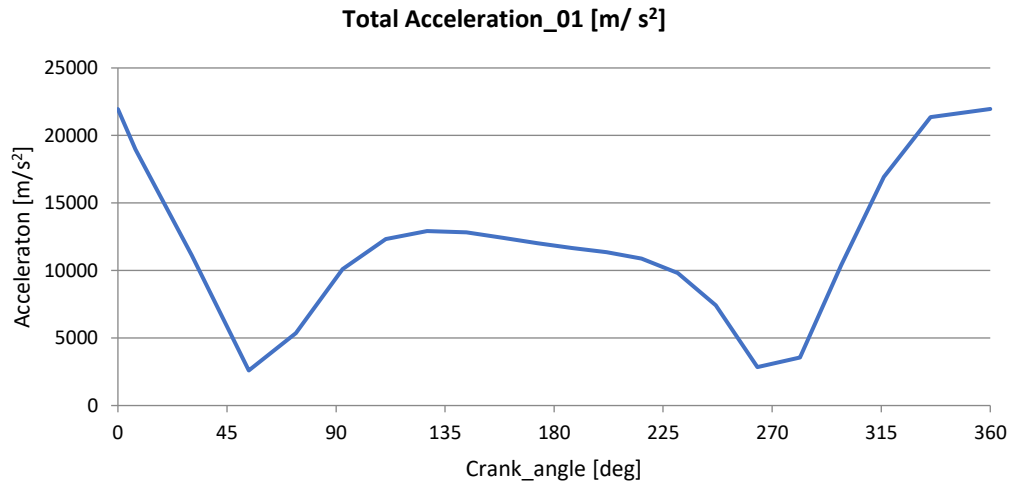
Chart 3-8:Total Acceleration of wire at position 01

$$d_{wire} = 0{,}003 \, [m] \tag{4.1}$$

$$A_{wire} = \frac{\pi}{4} d_{wire}^2 = \frac{\pi}{4}.3^2 = 7.10^{-6} \, [m^2] \tag{4.2}$$

$$\rho_{wire} = 8385 \, [kg.m^{-3}] \tag{4.3}$$

$$V_{wire\_01} = A_{wire} \times L_{wire\_01} = 7.10^{-6} \times 0.015 = 1{,}06.10^{-7} [m^3] \tag{4.4}$$

$$m_{wire\_01} = V_{wire\_01} \times \rho_{wire} = 1{,}05.10^{-7} \times 8385 = 8{,}89.10^{-4} \, [kg] \tag{4.5}$$

$$\propto_{wire\_01} = 21961 \, [m.s^{-2}] \tag{4.6}$$

$$F_{wire\_01} = m_{wire\_01} \times \propto_{wire\_01} = 8{,}89.10^{-4} \times 21961 = 20 \, [N] \tag{4.7}$$

$$\sigma_{wire\_01} = \frac{F_{wire\_01}}{A_{wire}} = \frac{20}{7.10^{-6}} = 2{,}8 \, [MPa] \tag{4.8}$$

Where, d_{wire} = Diameter of the wire

A_{wire} = Area of the wire

ρ_{wire} = total density of the wire

V_{wire_01} = Volume of the hanging wire at position 01

m_{wire_01} = mass of the hanging wire at position 01

α_{wire_01} = Maximum acceleration of wire at position 01

F_{wire_01} = Inertia force acting on the wire at position 01

σ_{wire_01} = Stress on the wire at position 01.

3.6.2 Determination of Stress of wire at position 02

The Figure 3-11 shows the final attachment points of wire on connecting rod (Point C) near to the big eye and on the telemetry module (Point D). The point C is located at 25mm from the centre axis of the big eye of the connecting rod. The point D is on one side of telemetry module for fixing the wires. The length of hanging part of wire on space between the points C and D is 85mm. To find the maximum acceleration of wire at this position 02, Horizontal component and Vertical component of acceleration at this position is resolved to total acceleration of the wire at that position. The Chart 3-9, Chart 3-10 shows the horizontal and vertical component of the wire at position 02. The total acceleration of wire at position 02 is shown in Chart 3-11 are determined from dynamic simulation in PTC Creo.
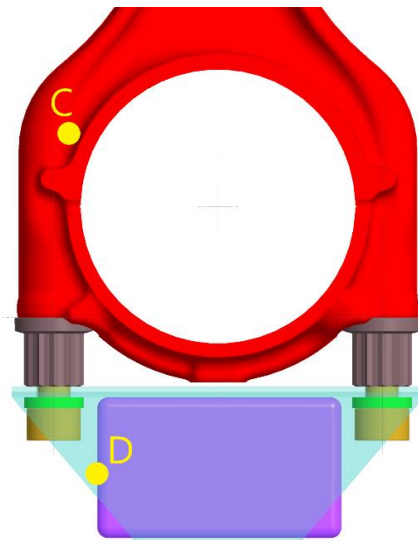
Figure 3-11: Position of attachment of wire at connecting rod and to module

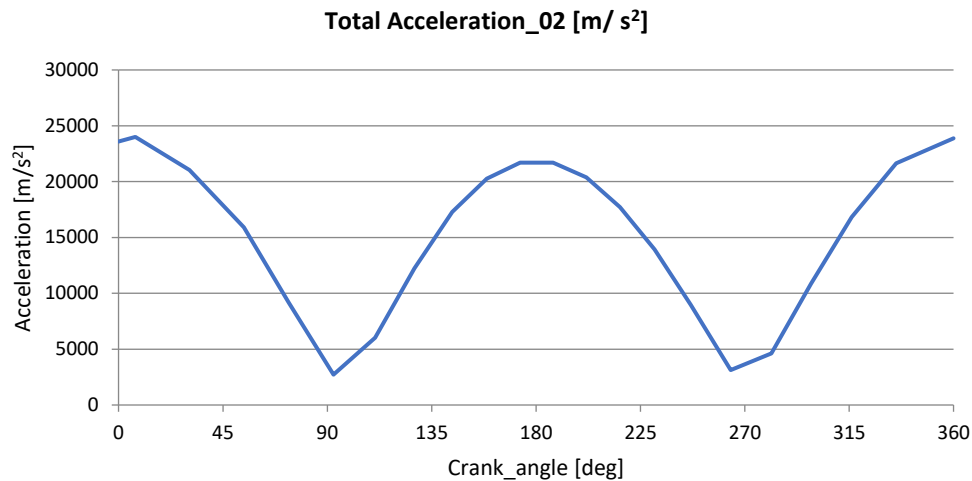*Chart 3-9:Acceleration of Horizontal component of wire at position 02*
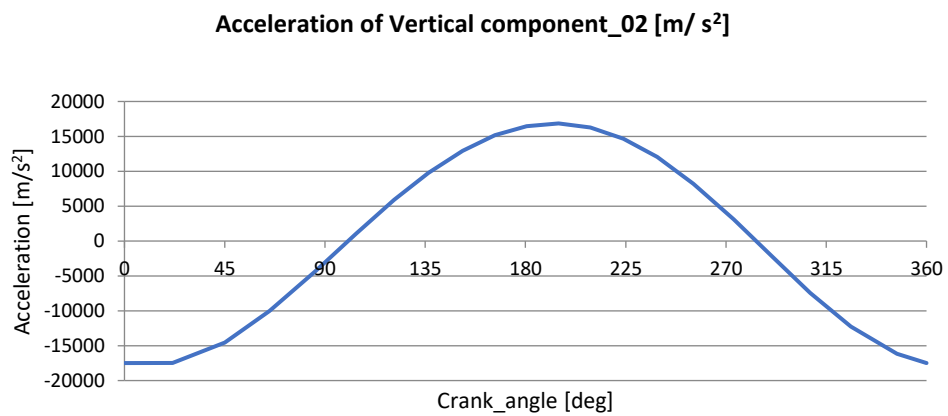
Chart 3-10:Acceleration of Vertical component of wire at position 02

Total Acceleration_02 [m/ s²]

Chart 3-11:Total Acceleration of wire at position 02

From the Chart 3-11, the maximum acceleration acting on the wire at position 01 at full load (6000rpm) is found as 23883 [m.s^{-2}].

$$d_{wire} = 0{,}003 \ [m] \tag{4.9}$$

$$A_{wire} = \frac{\pi}{4} d_{wire}^2 = \frac{\pi}{4}.3^2 = 7{,}07 \ . \ 10^{-6} \ [m^2] \tag{4.10}$$

$$\rho_{wire} = 8385 \ [kg.m^{-3}] \tag{4.11}$$

$$V_{wire\_02} = A_{wire} \times L_{wire\_02} = 7{,}07 \ . \ 10^{-6} \times 0.085 = 6{,}01 \ . \ 10^{-7} [m^3] \tag{4.12}$$

$$m_{wire\_02} = V_{wire\_02} \times \rho_{wire} = 6{,}01 \ . \ 10^{-7} \times 8385 = 5{,}04 \ . \ 10^{-3} \ [kg] \tag{4.13}$$

$$\propto_{wire\_02} = 23883 \ [m.s^{-2}] \tag{4.14}$$

$$F_{wire\_02} = m_{wire\_02} \times \propto_{wire\_02} = 5{,}04 \ . \ 10^{-3} \times 23883 = 120 \ [N] \tag{4.15}$$

$$\sigma_{wire\_02} = \frac{F_{wire\_02}}{A_{wire}} = \frac{120}{7{,}07 \cdot 10^{-6}} = 17 \ [MPa] \tag{4.16}$$

Where, V_{wire_02} = Volume of the hanging wire at position 02

m_{wire_02} = mass of the hanging wire at position 02

α_{wire_02} = Maximum acceleration of wire at position 02

F_{wire_02} = Inertia force acting on the wire at position 02

σ_{wire_02} = Stress on the wire at position 02.

Since, tensile strength of iron wire is 540 [MPa] and constantan wire is 450 [MPa], the maximum stress acting on the wire are 2,8 [MPa] and 17 [MPa] at both positions 01 and position 02. The acting stress is very less comparable to the tensile properties of the wires. Thus, the wire can withstand without any damage at high speed when subjected to bending due to oscillation of the connecting rod.

3.7   Adhesives

To attach the thermocouple wires into the piston a comparison has been made as shown in Table 3 with different glues and its properties and availability in local market. Finally, to fix wires into the piston and to attach it on the connecting rod adhesives like Arctic Mx-2 and Loctite 9492 is used. The installation procedure is in such a way that the initially the welded thermocouple wires are inserted into each hole in the piston and Arctic Mx-2 glue is applied for the inner small sized hole and Loctite 9492 is applied to outer bigger diameter hole. Belzona 1111 is used to attach the wire along the connecting rod. Figure 3-12 shows the scheme of the wire installation inside each hole.
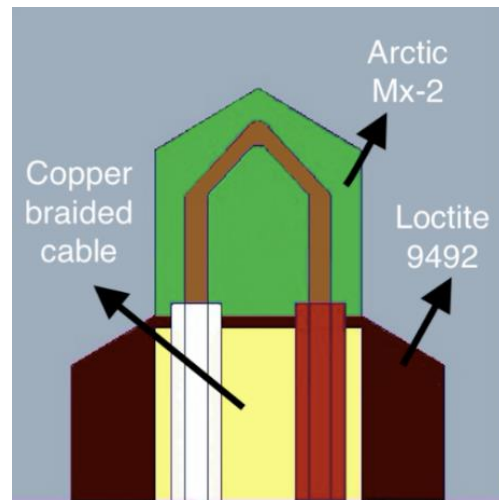
Figure 3-12: Thermocouple installation

Table 3:Comparison of Adhesives

	LOCTITE EA 9492	Belzona 1111	Arctic Alumina	Arctic silver − 5	**Arctic MX-2**	Supreme 12AOHT-LO
Electrical Resistance	✓	✓	✓	✓	✓	✓
Thermal Conductivity	✗	✗	✓	✓	✓	✗
Operating Temp [°C]	Up to 190	Up to 200	-40 to >160	-40 to >180	Up to 300	Up to 260
Viscosity	**Low**	High	Low	Low	Low	Low
Hardness [@ 25°C]	✓	✓	-	-	-	✓
Chemical & oil resistance	✓	✓	-	-	✓	✓
Cure schedule @25°C [hr]	24	22	Few hours	Few hours	-	✗
Working life, @25°C [min]	15	15	3-4	3-4	-	15
Cost [Czk]	**1200 (400g)**	1800 (400g)	240	190	**120 (8g)**	✗
Availability	✓	✓	✓	✓	✓	✗

3.8 Outline of Measurement Setup
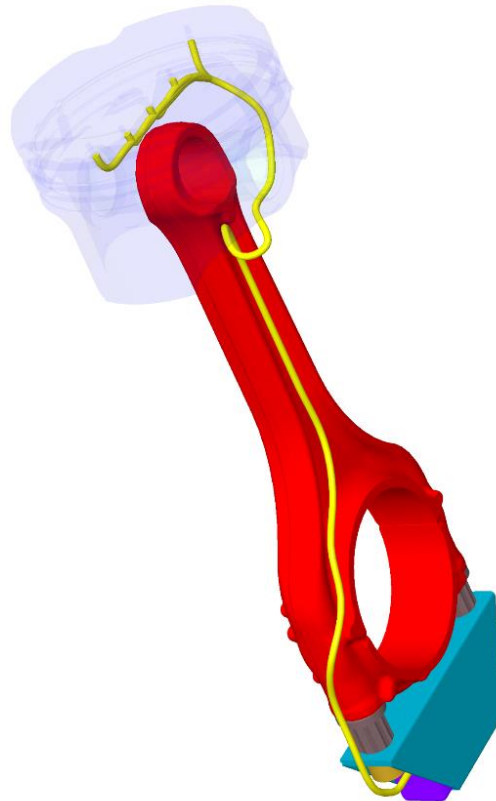
Figure 3-13: Overall assembly

The Figure 3-13 shows the 3D view of overall assembly of the measurement system. In which, the piston (little blue) is made little transparent to view the attachment of the thermocouple wire (yellow) in the holes in underside of the piston. The probe tip of the thermocouple wires is fixed to each holes of the piston with glue Arctic Mx-2. The wires from different holes of the piston are twisted into a single wire and wrapped with a copper braided cable to reduce the stress on the wire at high speed oscillation of the connecting rod and for easy installation. Then the singe wire (yellow) is attached till to the final point (Point A) as mentioned in Figure 3-10 near to the bottom piston skirt in the underside. The telemetry transmitter module (violet) is fixed to the stainless-steel holder (dark cyan) with glue Loctite EA 9492. The holder (dark cyan) is attached to the connecting rod bolt (dark grey) with M6 bolt (orange). An extra tube

(green) or also can called washer is used in between the M6 bolt (orange) and holder (dark cyan) to reduce the stress on the bolt head. The thermocouple wires (yellow) is from the underside of the piston is attached to the connecting rod (red) at the point (point B) as shown in Figure 3-10 with the help of glue Loctite EA 9492. Then the wire from (Point B) is routed in such a way in Figure 3-13 to the point near to the big eye of the connecting rod (Point C) as mentioned in Figure 3-11. Finally, the wire from the (Point C) is fixed to the (Point D) one side of the telemetry transmitter module (dark cyan) in respective channels.

4   Software Development

4.1   Hardware

ADWITECH is a company providing custom made electronic devices for specific applications. WTCM (Wireless Thermocouple Measurement) is one of their product which is used in our project for the measurement of temperature.

WTCM is a low-power wireless module working in 2.4Ghz ISM band designed especially for temperature measurement in demanding conditions. J type thermocouple is used. It temperature measure range from 0 to 480 ° C. The module can handle an environment includes standard 4 stroke engine oil and an ambient temperature may rise to 85°C.

For the calculation of temperature and cold end compensation, 100 calibrators are used to ensure a minimum error. Between the points with a spacing of 5 ° C is made linear interpolation.

The battery voltage is measured in the measuring circuit, and it should be voltage range between 2.8-3.3V. If the voltage drops below the critical voltage value, the module goes off and stops sending activity and it start reporting after recharging. The Figure 4-1 shows the schematic of the telemetry transmitter module.
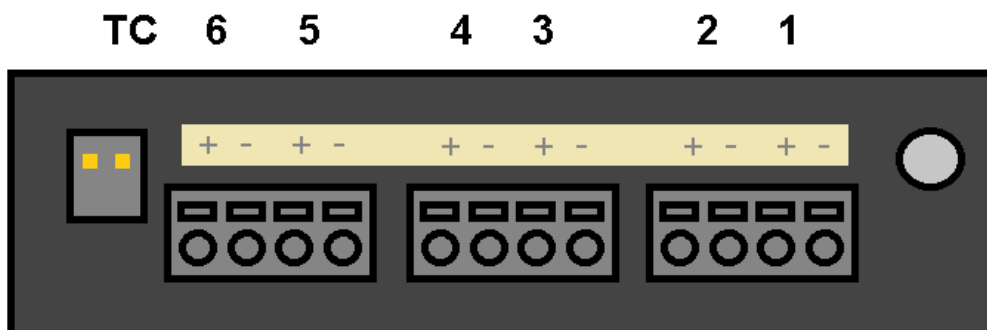
Figure 4-1: Telemetry Module [22]

4.1.1   Transmitter Module

The transmitter module has 6 channels on one side of it and a charge port at that side. Each channel has 2 ports for positive and negative thermocouple wires. So, the white wire which is positive is connected to the positive end and red wire of thermocouple is connected to negative end of the module. The Figure 4-2 shows the telemetry transmitter module with thermocouple wires fixed. The module starts send measurement data immediately once it's get activated.
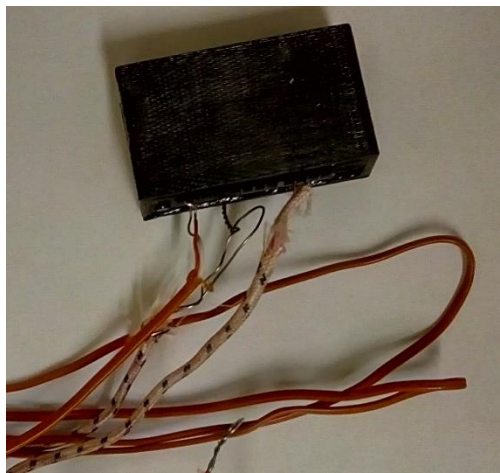
Figure 4-2: Telemetry transmitter Module

4.1.2   Telemetry receiver unit

The receiver unit is placed outside of the engine crank case. This receiver is connected to the central computer through USB port. Once it received the measurement data from transmitter module, it sends the data to the computer through the USB cable as hexadecimal strings. As the string format is not in user readable format, it must be further processed. The Figure 4-3 shows the telemetry receiver unit.

Figure 4-3: Telemetry Receiver unit

4.1.3   Charger unit

The transmitter module is capable to give measurement data up to 8 hours. Then it stops working if the battery voltage drops down below 2,89 [V]. Then it must be plugged in with the charger cable. The charging last for 3 to 4 hours to fully charge the module. The fully charged battery would be 3.3 [V]. The figure shows the charger unit for transmitter module. The one end of the charger is connected to the transmitter module and other end is connected to the USB port of computer. And the charger should not have left charging unless it is connected to the USB port of computer. The Figure 4-4 shows the telemetry charger unit.

Figure 4-4: Telemetry Charging unit

4.1.4 Communication Protocol and setting

Setting the PC-GTW connection, the GTW unit can be used in device mode called "GTW" or as standard serial COMx port. The details of the communication frame settings are shown in the Table 4. The messages that are sent from the computer are x byte, but the received messages are always 32 bytes.

Module activity message:

The module reports periodically even if it is sleeping and when it measures based on the wakeup/sleeping messages. The output message from the module looks like,

HEX: "D0 D0 D4 AA AA 82 00 0c E9 01 18 00 00 49 20 61 6D 20 54 48 45 52 4D 20 36 00 00 00 00 00 94 5C"

STRING: "ÐÐÔŞŞ, .. é .... I am THERM 6 .....".

In which, 0x82 - module type thermo measurement 6 channels. 0x0C E9 - two-byte battery value. 0x0CE9 → 3305 (dec) this value represents voltage in the circuit in mV, i.e. the circuit is powered by 3,305V. 0x01 18 - The two-byte value of the internal module temperature 0x0118 → 280 (dec) represents the value the number of degrees tenth, i.e. 280, corresponds to a temperature of 28.0 ° C. other bytes contain only text information. 0x94 5c is a two-byte sum of the CRC sum, basically it is not necessary to use it because of another CRC sum is used for wireless communication. This sum serves only for failure communication between the controller and the serial line converter. If the module is asleep, the message is sent every minute, if it is active, it is sent every 7th measurement.

WAKEUP/SLEEP request command:

The message is intended for sleeping and awakening the module. The user sends this message which activates the response algorithm on the GTW. If the user sends this command more than one time consecutively, they are stored in a row. The wakeup/sleep command looks like this,

PC → GTW: 00 00 00 AA 00 01 60 D0 D0 D4

GTW → PC: 00 00 00 AA 00 01 60 D0 D0 D4 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 95 54.

Start of Measurement Message:

Once the module wakes up, it will be triggered and will send a measurement start message. And then it automatically sends measured data. The Measured data looks like this,

HEX: D0 D0 D4 AA 11 01 00 53 54 41 52 54 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 53 CF.
STRING: ĐĐÔŞ...START.................SĎ.

Measured data Message:

The measured data sends by the module will contains the name of the module, 6 channels temperature values, an internal temperature value of module and the voltage value of the module battery.

HEX: D0 D0 D4 00 84 0E 5C 01 41 0E 5C 0E 5C 0E 5C 0E 5C 01 00 0C E8 00 00 00 00 00 00 00 00 00 30 31.

In this message, 0xD0D0D4 represent the Module address. 0x0E 5C is the value of the first channel. 0x01 41 is the value of the second channel and so on up to for sixth channel. 0x01 00 is the internal temperature value of the module. 0x0C E8 represents the two-byte value of battery voltage.

Measurement end message:

A message that announces the end of a measurement based on user request. The message will look like,

HEX: D0 D0 D4 AA 11 FF 00 45 4E 44 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 BE D3.

STRING: ĐĐÔŞ.˙.END....................ľÓ.

Reset message:

This message sends a GTW and has no other than a notification function.

HEX: 00 00 00 FF FF 00 52 45 53 45 54 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 3A 4D

STRING: ...˙˙.RESET...................:M.

4.2   Software

In this thesis work one of the main tasks is to integrate the telemetry data into data acquisition system. So, LabVIEW software which was used for the integration of data which are received from the telemetry system, since LabVIEW is the main software used in the laboratory.
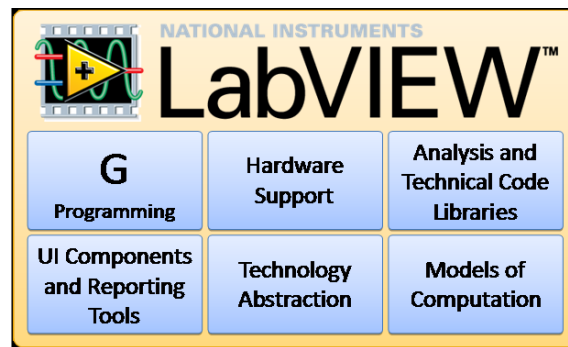
Figure 4-5:LabVIEW

4.2.1   LabVIEW

LabVIEW stands for Laboratory Virtual Instrument Engineering Workbench. National Instrument company developed this software using "G" programming language, which has an advantage that the programmers need not to know any syntax, rather than they only connect the boxes which represents some functions together by the virtual wires as shown in Figure 4-6. They also can choose easily the preconfigured controls and create user interface through which the other users can use the program and comfortable control.

It supports many hardware devices like different sensor, motors, calculators, etc. It has different drivers to support the hardware devices, which are freely available to download from their website and use. LabVIEW file is called as VI (Virtual Instrument). Basically, LabVIEW software is a great tool for DAQ system. Still it can also support instrumental devices with the help of drivers which are available from NI website.
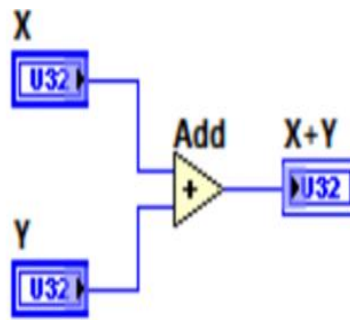
Figure 4-6:Principle of Graphical Program

4.2.2 Algorithm of Programming

Algorithm is the basic step in the development of a computer program. This gives the step by step instructions to write the program. The Figure 4-7 shows the step by step procedure for programming the LabVIEW software. It says that firstly the instrument is to be initialised. Then the time check is made to check the activation of the telemetry transmitter module. If the set time is elapsed without activation of the module, an activation command is send to the module from the computer. Once the module gets activated, it starts to send signal to receiver. The received signal is analysed for data. If no data is received, the process is repeated until the receives of data. Once the data is received, is subjected to data check as it contains many unwanted bytes from previous iteration. So, the next step is to eliminate the unwanted data. Once the desired data is obtained from filter process, then the desired data is subjected to process of converting to numerical values of the temperature measurement in degree Celsius, since the received data is in the form of hexadecimal string. Then the temperature values are stored in array for the consecutive iterations and the values are displayed to the user. In parallel the measurement values are stored in the computer to a desired folder. This process continues till the stop condition of the program is executed by the user. In between if any error occurs the program stop running and to start from the beginning after the error is rectified.
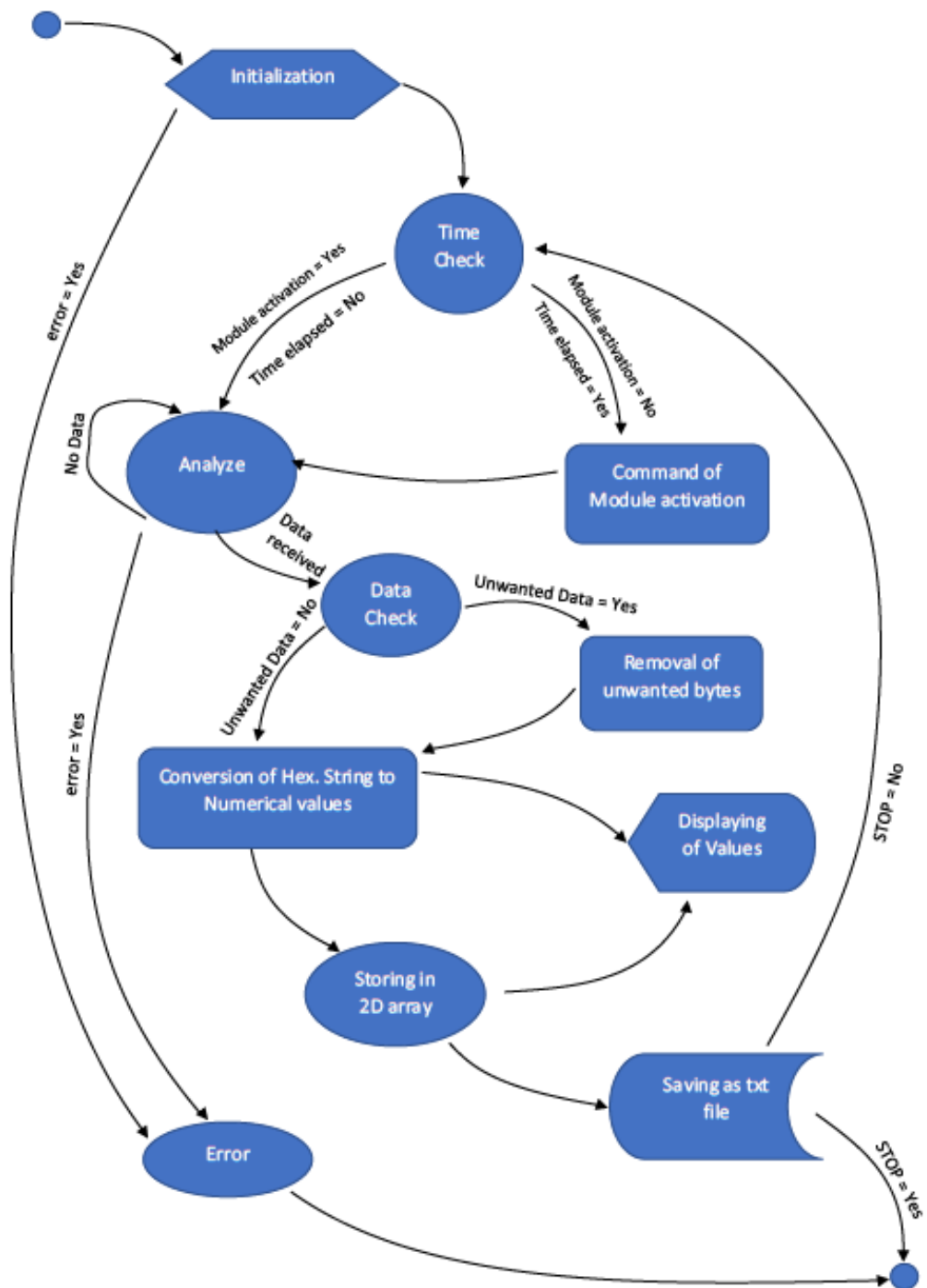
Figure 4-7: Algorithm of Programming

4.2.3   Block Diagram

LabVIEW in this case used for Serial communication of telemetry module by opening VISA resource and configures COM port. It then performs serial port write, serial port configures, serial port read and serial port close. The following Figure 4-8 shows the main VI in block diagram of the LabVIEW software. The function and connections are made according to procedure described in algorithm.
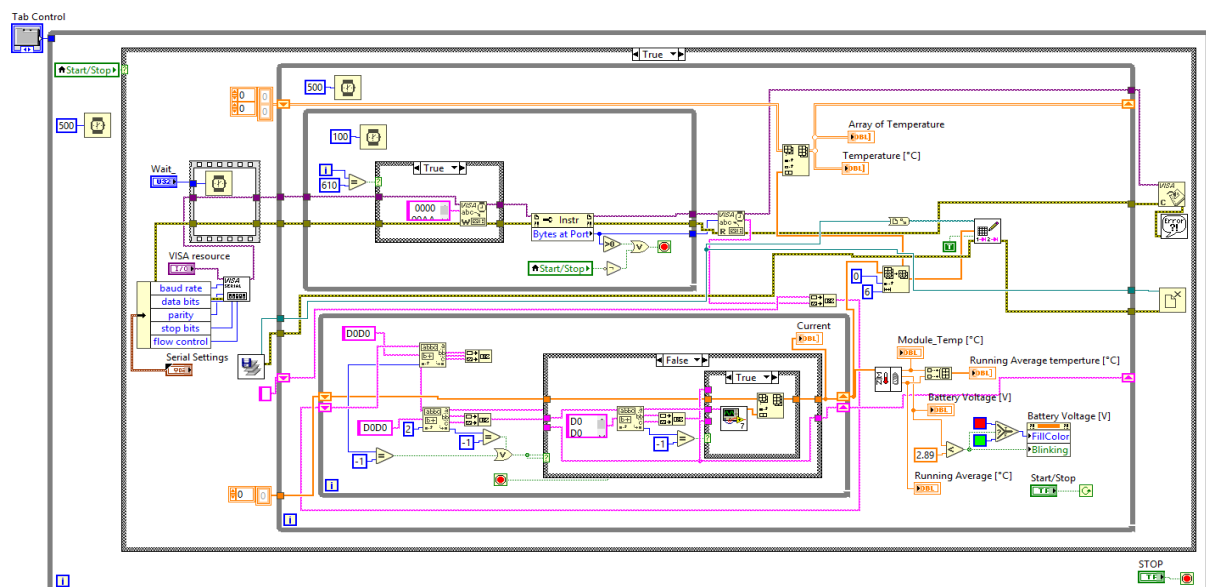
Figure 4-8: LabVIEW - Main VI

The step by step procedure of programming is described below.

Step 1: Start of Measurement:

To run the LabVIEW program, the button named "Start/Stop Measurement" should be ON. In LabVIEW language this is a case structure function with True or False as shown in Figure 4-9 values wired to selector terminal which determines which case to be executed. In our Case Start/Stop Measurement "Ture" executes the program.
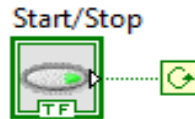
Figure 4-9: Start/Stop Boolean Function

Step 2: VISA Initialisation:

In LabVIEW program, VISA is used which is a standard I/O for instrumentation programming. VISA provides interface independence. It's one of the advantages is that regardless of the interface type, it uses many of the same operations to communicate with instruments. It makes easy to switch interfaces and it also gives the users who wants program instruments for different interfaces.

Table 4:Frame setting of Telemetry Module

Baud rate	3000000
Data bits	8
Stop bits	1
Parity	None
Flow Control	none

The above shown Table 4 give the details of communication frame setting of telemetry module. The messages that are sent from the computer are x byte, the received messages are 32 bytes.
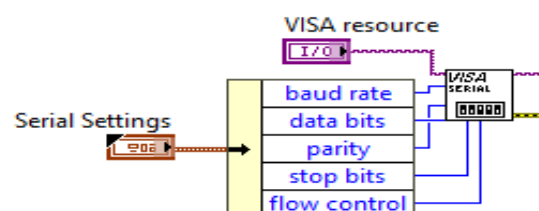
Figure 4-10: VISA Initialisation

Step 3: Activation of module:

After the serial settings are done, the telemetry module must be activated to start the measurement of data. Serial write function was used to write the command "0000 00AA 0001 60D0 D0D4" for the activation of the telemetry module. This command is programmed in such a way to execute only once, with condition if there are no bytes are received from the module for consecutive 61 seconds. Once the activation command is send from the computer to the module, the module sends back the activation confirmation command "00 00 00 aa 00 01 60 D0 D0 D4 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 95 54" to the computer. Then the receiver starts receiving the bytes from the transmitter module. This process is a loop, every iteration the time is checked to confirm the activity of the module. The below Figure 4-11 shows the module wakeup block in the LabVIEW program.
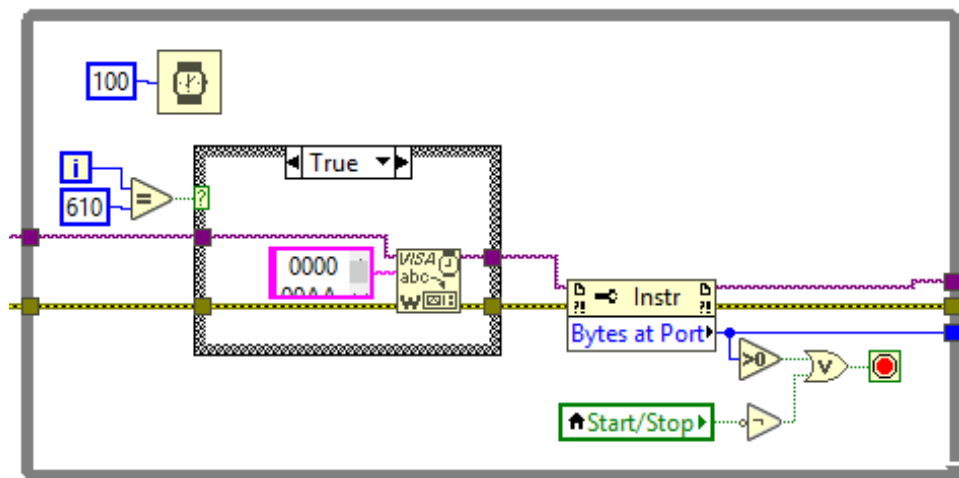
Figure 4-11: Module activation

Step 4: Reading measured Data:

Once the module is wakeup, it starts to function and collect measured data from the thermocouple wires. Then the module sends the acquired data to the telemetry receiver in the form of hexadecimal string as bytes. The VISA serial read function reads the bytes from the

module and sends it to the further modulation of the string data. The below Figure 4-12 shows the VISA serial read function in LabVIEW.

Figure 4-12: VISA Read measured data

Step 5: Elimination of unwanted data:

The module sends four measured values at a time to get robust of device. The received data sometimes have 32 bytes or sometimes unwanted extra data (bytes) or broken data from previous iteration of measurement. So, the unwanted bytes must be removed in such a way that the function called Match pattern is used. This function search for the string "D0D0", eliminate it and send the remaining data to the next process of the program. This function is used twice as shown in Figure 4-13 to eliminate the unwanted data on front and back end side of required data. In some iteration, bytes received doesn't have any extra unwanted bytes from previous iteration, so in that case the Match pattern function sends the data without any filtration of data to next process of conversion.
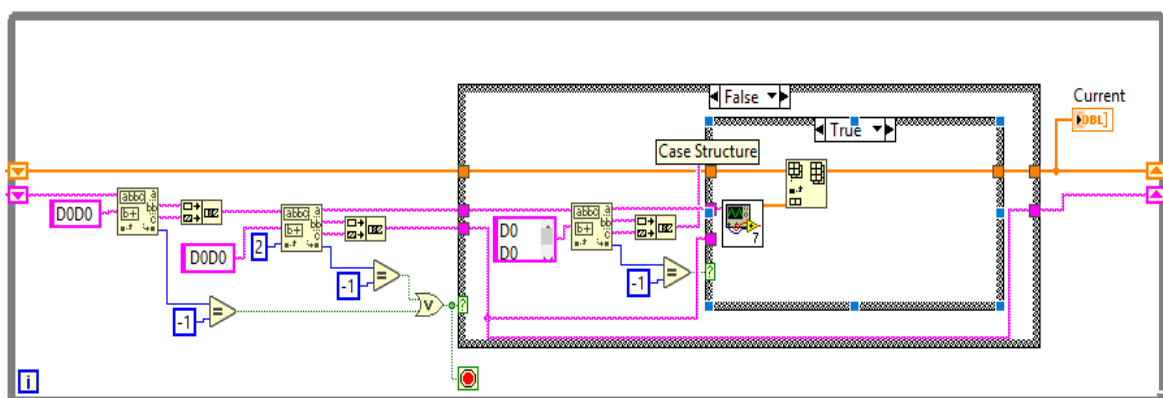
Figure 4-13:Elimination of unwanted data

Step 8: Processing the measured data:

After eliminating the unwanted data from the received bytes, the required string data is send for the processing of converting the string to real numerical values of temperatures. For this work a separate sub VI (1) is created. This sub VI (1) uses various functions like Match pattern, Type cast, decimate 1D array, Index array, join numbers, build array to convert the 32 bytes hexadecimal string to real numerical values of temperatures and sends the output data as 1D array to the main VI. The main VI calls this sub VI (1) every iteration of the loop. The following Figure 4-14 shows the sub VI of Data processing. The output data of this sub VI contains temperature values of 6 channels in degree Celsius, an internal temperature value in degree Celsius and battery voltage value in Volt.
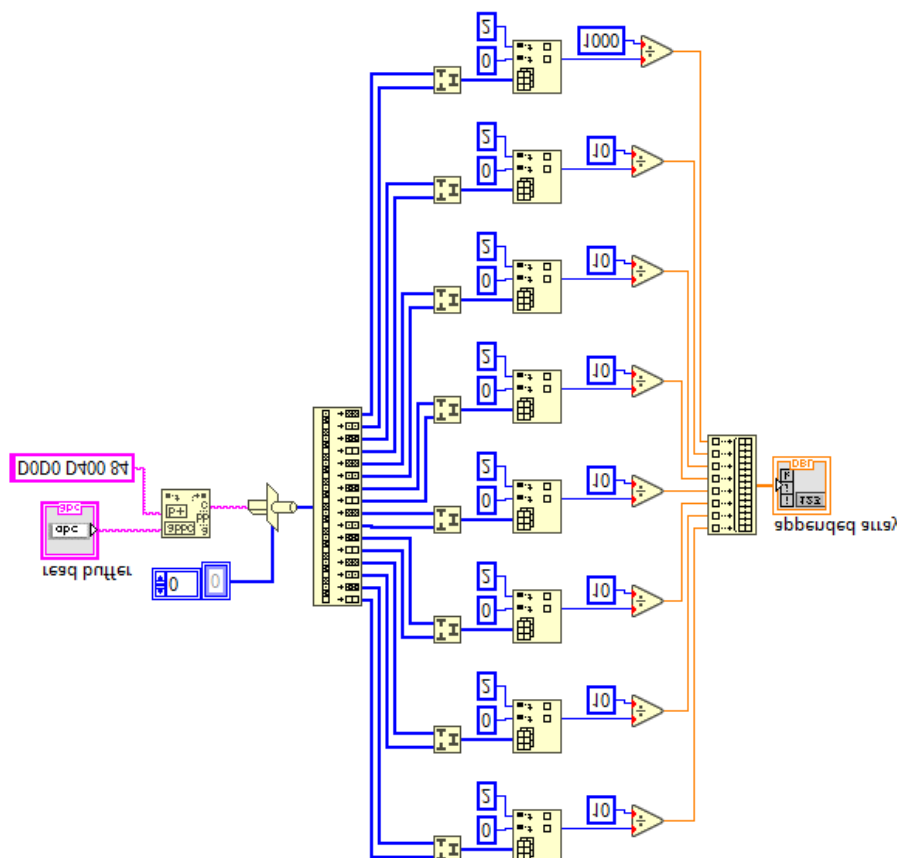
Figure 4-14: Sub VI (1) - Processing data

Step 7: Storing data in array:

Another sub VI (2) was created to further process the 1D array from the previous sub VI (1). In this sub VI (2), the previously processed 1D array data are separated as 6 channel temperature values and running average value of them. And internal temperature of module and Battery voltage are separated from the 1D array. The running average value averages the 6 channels for every measurement. The battery voltage values use property node function to change the display colour of battery voltage to red alert if the voltage drops below 2.89[V], if not it displays in green colour. This helps the user to know that the module is out of power and it need to be Plug in and charged. The below figure shows the sub VI (2). The Figure 4-15 shows the sub VI (2) for display of values.
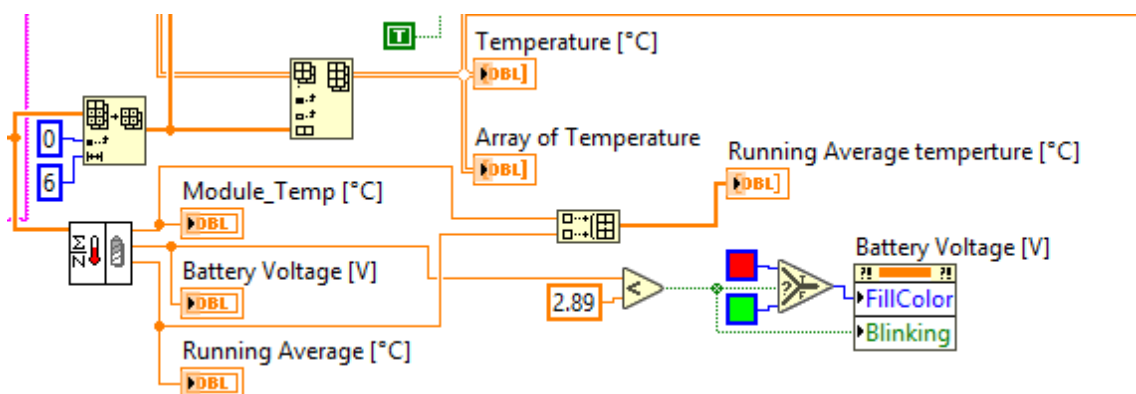
Figure 4-15: Sub VI (2) - Display values

Step 8: Saving File:

The final thing of the program is to save the measured values as .txt file. The text file contains the header which has date and time of measurements and the channel's name. The values are stored as row by row. The text file is stored in location where the main VI is saved in computer. For this a function called Application Directory is used, which create a path for the text file to be stored. Then Open/Create/Replace File function are used to create an empty txt file, Write to Text File function is used to write the header to the text file, and Write to Spreadsheet file.vi

function is used to write the 1D array data of measured values of temperature as string format in the text file, and finally Close File function is for closing the text file. The below Figure 4-16 shows the sub VI (3) for saving the file.
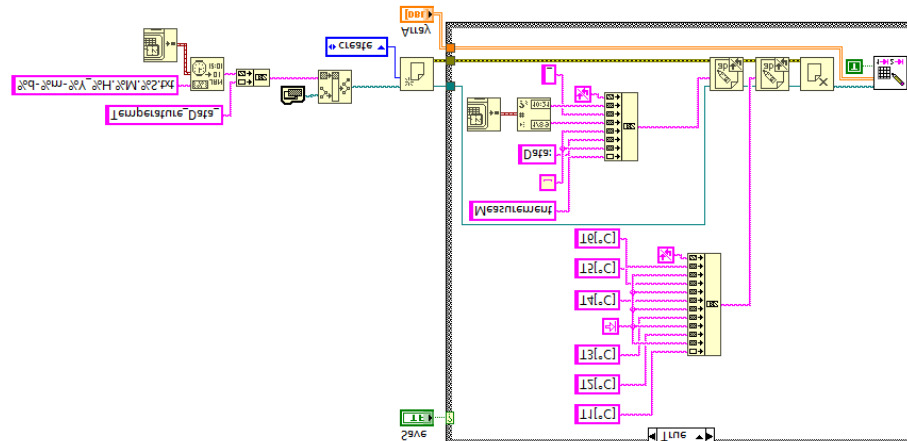
Figure 4-16: Sub VI (3) - Saving file

Errors:

During running of the program there are few possibilities for occurrence of error. The error occurs if factors like desired VISA source is not selected by the user or if some disconnection of the receiver USB happened. This error is handled by a function called Simple Error Handler. This function detects the error and displays a prompt dialog box as representing the error status, error code and the error source. The Figure 4-17 show the error caused by not selecting the VISA source before the program starts. In the prompt dialog box, the error code-1073807346 means there is no VISA resource is detected for the running of the program. If this error occurs the user must be check the proper connection of receiver to the computer and make sure it is selected in the front panel.
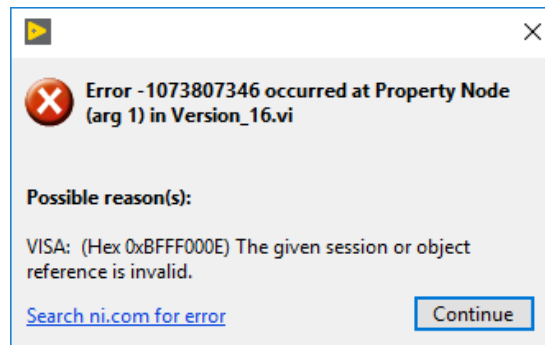
Figure 4-17:Resource Error

4.2.4 Front Panel

The front panel of LabVIEW is the window where, different controls (such as numeric inputs, switch, knobs, etc.) can be viewed. It also called as LabVIEW HMI (Human Machine Interface). Also, the controls can be accessed by right-clicking in the empty area of the front panel. The front panel of the software has 2 Boolean buttons (main central STOP and Start/Stop Measurement) and a tab control which has 3 pages (Settings, Measurement, Charts). The main Stop button is the control to stop all the sub VI in the main computer. The Figure 4-18 shows the main central Stop button. This Boolean button act as central control and it is used to control all the VI that runs in the computer at a time. This button has local variable to every VI in the main software to control each VI. The Start/Stop Measurement button is a button to start and stop our measurement. If it is ON state it is viewed as bright yellow light and if it is in OFF state it is viewed as dark yellow light.

Figure 4-18: LabVIEW Central stop button

Tab: Settings

The first page of the tab control is named as 'Settings' tab. This tab contains the VISA resources name selector control and wait time control, Serial settings cluster control and Save button. The VISA resources name selector control allows the user to select the Module resource which is connected to the computer through USB port. The wait control is the numeric control of wait time of the program to execute in millisecond. The default value of the wait time is set to 500ms which could give robust results. The serial settings cluster control is the cluster of control which has control for baud rate, data bits, parity, stop bits and flow control. These controls are chosen according to the Table 4. The setting is made default and the user need not to set it for every time of program run. The user can just select the VISA source and can hit the run button of the program. The Figure 4-19 shows the settings page of tab control in front panel.

Figure 4-19: Front Panel - Setting tab

Tab: Measurement

The second page of the tab control is called measurement tab. This tab contains the numeric 1D array indicator which displays the values of current temperature of 6 channels of every iteration of measurement. The numeric 2D array indicator stores and displays the repeated consecutive iteration of temperature values of 6 channels. A numeric indicator displays the

running average value of the 6 channels. An another numeric indicator displays the internal temperature of the module and tank indicator shows the voltage level for battery. This tank indicator displays the voltage level of module in green colour until it 2.89[V], below which it changes to red colour and blink as an indication that the battery of the module is less and it helps the user to know about that the module is out of power and it need to be charged. The Figure 4-20 shows the Measurement page of the tab control.
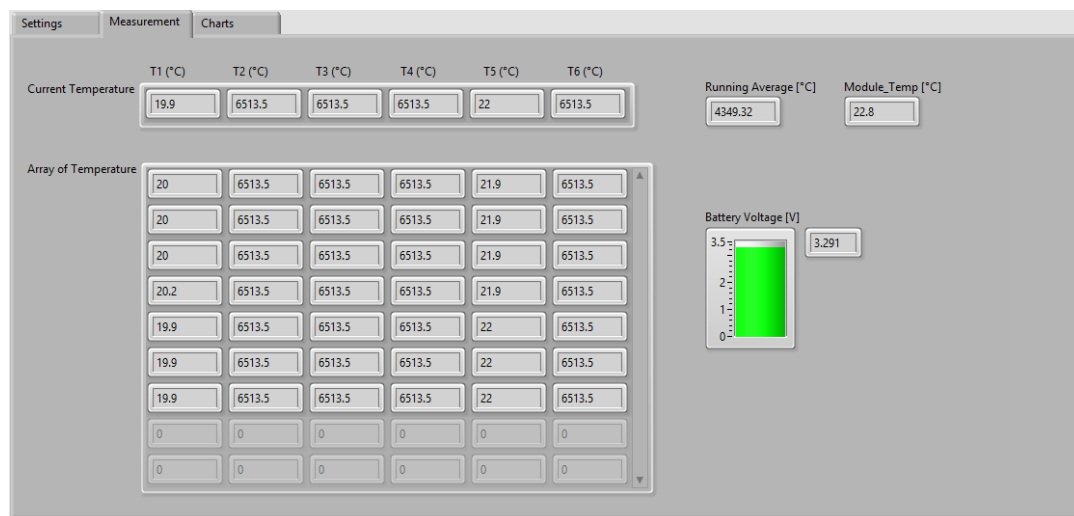
Figure 4-20: Front Panel - Measurement tab

Tab: Charts

The third page of the tab control is Charts tab. This tab contains 2 waveform charts indicators. The waveform chart is the graphical representations of 6 channel's temperature values and the average temperature values and the module internal temperature values. The below Figure 4-21 shows the Charts page of the tab control of the front panel.
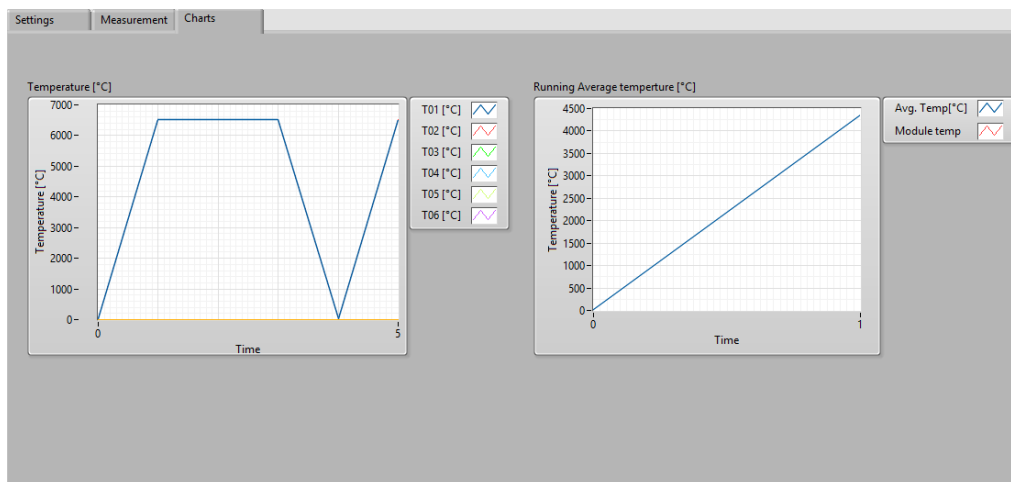
Figure 4-21: Front Panel - Chart tab

4.2.5 File Saving

Once the measurement is done and the program is stopped by hitting stop button, the measured values of the temperature are stored in the computer to the default folder of LabVIEW files as .txt files. The .txt file has header of current measurement date and time with channel names and its units. The Figure 4-22 shows the .txt file of measured values of temperature for 2 channels.

Figure 4-22: Saved File (.txt)

5 Summary and Conclusion

This diploma thesis is part of larger project that dealt with the design of single cylinder spark ignition engine that will be used in the laboratory. The main objective of this diploma thesis was to a design and development of an appropriate solution for Piston temperature measurement for the engine.

During this study, the preliminary design of the engine piston, connecting rod were modified in the Creo Parametric 4.0 software with respect to a change in the geometry of the various proposed solutions. Jig part was designed to help the modification process of piston easy. Then, the thermocouple wires were prepared, and a trial installation were made to find the proper solution for installation into the piston. Then, Module holder and thermocouple wire route from piston to module was designed, stress calculations for holder bolts and force calculations for thermocouple wire were made in excel file. The latter part of the study was focused regarding the development and improvement of robust Data Acquisition system software. LabVIEW software was used for programming to communicate the telemetry system to the central computer in the laboratory.

Future Suggestions:

- The module holder was manufactured with laser cut process, but it needs to be bend according to the specified dimensions.

- Since the engine and piston are not yet manufactured, further process of this thesis work couldn't be proceeded. Once the engine gets ready, the thermocouple has to be installed with the proper suggested glues and to be check if the glues are perfectly working.

- The telemetry module has been already bought and the software program is running well now. But it has to be installed in the central computer of the laboratory and improve it according to the needs.

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List of Figures

List of Tables

List of Charts

List of Attachments in CD

Attachment 1:   Thesis.pdf

Attachment 2:   Excel file of calculation of bolt and wire

Attachment 3:   Production Drawings

    3.1. Piston with thermocouple holes.pdf
    3.2. Module Holder.pdf
    3.3. Jig for Piston.pdf
    3.4. Module Holder with holes.dxf
    3.5. Module holder without holes.dxf

Attachment 4:   LabVIEW Software VI – Version 14

    4.1. Main VI   - Temperature Measurements
    4.2. Sub VI (1) - Processing data
    4.3. Sub VI (2) - Display values
    4.4. Sub VI (3) - Saving File
    4.5. WTCM hardware manual

Attachment 5:   CAD Files of PTC Creo 4.0

    5.1. Piston.prt
    5.2. Connecting rod.prt
    5.3. Crank shaft.prt
    5.4. Connecting rod bolt.prt
    5.5. Holder.prt
    5.6. Module.prt
    5.7. Holder bolt M6.prt
    5.8. Thermocouple wire.prt
    5.9. Overall assembly.asm