IOSR Journal Of Applied Physics (IOSR-JAP)
e-ISSN: 2278-4861.Volume 13, Issue 2 Ser. II (Mar. – Apr. 2021), PP 06-14
www.Iosrjournals.Org

Modeling & Simulation of Multi Parameter Sensor for Aero Engine

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Abstract: *Depending on the field of application, modeling and a model, has different meanings. Generally, modeling deals with mathematical representation. Mathematical models can take multiple forms like statistical models, dynamic models, differential equation game models etc.*
Simulation is analogous to modeling but different in meanings based on the context and the application in which it is used. Based on application, it can deal with so many forms. Computer simulation or computational modeling attempts to simulate or imitate an abstract model of a particular system or device. Computer simulations integrated with mathematical modeling predict/estimate behavior of complex systems. In modeling & Simulation, the model is first developed and then simulated. After gaining some knowledge about model and system, it (model) is revised and again simulated. This process goes on until a satisfactory stage of understanding is achieved for the system/device. This paper describes the application of Computer simulation or computational modeling which was utilized to carry out modeling of a multi parameter sensor.
Need for modeling and simulation arises due to small dimensions of MEMS, difficulty in determining some physical properties, measurement errors that occur when dealing with micro-level systems, to reduce production cost, to render fast design cycle, to allow better understanding of the device/system operation and optimization etc.

Keywords: *Modeling, Simulation, Thickness, Deformation, Sensing*

Date of Submission: 03-03-2021 Date of Acceptance: 17-03-2021

I. Introduction

The major modules of the aero engine include the Fan, the Compressor, the Combustor & the Turbine. During development phase, these modules need to be tested in the standalone mode to study their performances before they are integrated. To study the characteristics of the integrated engine, lots of parameters viz., temperature (both liquid and dry), pressure (both liquid & dry), flow, vibration, speed and thrust etc., at various locations need to be measured [8]. Once the performance of the engine is established, the measurements can accordingly be reduced to suit to the requirements of the flight trials.

These critical measurements include the liquid temperature & Pressure measurements on the engine pipelines and LRU's (line replaceable units).These measurements are not done in one stretch but during different stages of engine tests as there is shortage of space for mounting the probes/sensors.

In lieu of this, survey was done to procure dual/multi-parameter sensors so that multiple measurements can be carried out in single engine test instead of shifting the same to different phases.

Due to non-availability of such specialized sensors and the enormous costs involved, study was carried out to develop a multi-parameter measurement sensor to sense both liquid/gas temperatures and pressures on pipelines and LRU's and model it before it is manufactured/packaged. The schematic of the sensor is shown in fig (1).

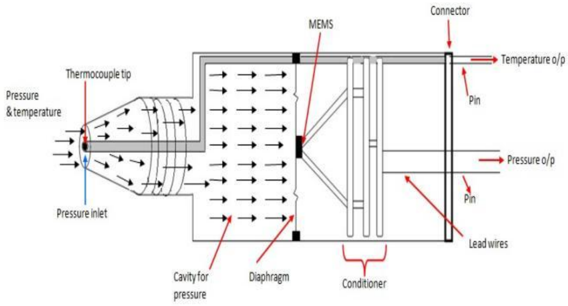

Figure 1. Schematic of multi parameter sensor

The above fig (1) shows the schematic view of the sensor where liquid/gas (whose temperature and pressure is supposed to be measured simultaneously) will be entering from inlet and immediately it will be sensed by Temperature sensor. Same time the pressure of the liquid/gas will be exerting a pressure on the diaphragm of the pressure sensing element. The displacement output of the diaphragm then is converted in electrical and will be available on output terminals after signal conditioning.

In lieu of this, the diaphragm becomes the main primary sensing element whose functioning and mechanical property takes major part in pressure sensing. Similarly the hot junction of the thermocouple is responsible for the time response of its output to be produced. So simulation and modeling of pressure sensing element (diaphragm in this case) and hot junction is the most essential to validate the material and its thickness to be used to capture entire range of pressure and temperature measurements.

As Silicon-100 is a well known material for its capability to be used as a primary sensing element to sense pressure, a diaphragm (Silicon 100) was simulated for different thickness. Directional deformation for different thickness values is shown in fig (2) and (3).

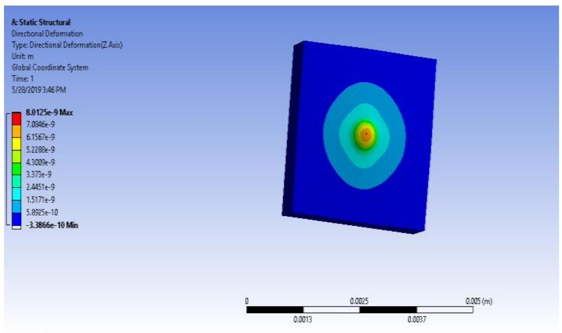

Figure 2. Directional deformation with 0.1 mm thickness

Fig (2) shows the directional deformation with 0.1 mm thickness of Silicon 100 when pressure is changed. The range of directional deformation with pressure difference is shown in first two rows of table (2).

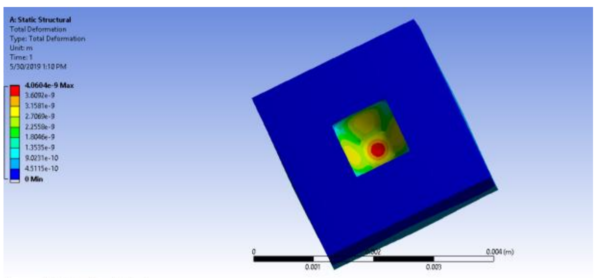

Figure 3. Directional deformation with 0.2 mm thickness

Fig (3) shows the directional deformation with 0.2 mm thickness of Silicon 100 when pressure is changed. The range of directional deformation with pressure difference is shown in third and fourth rows of table (2).

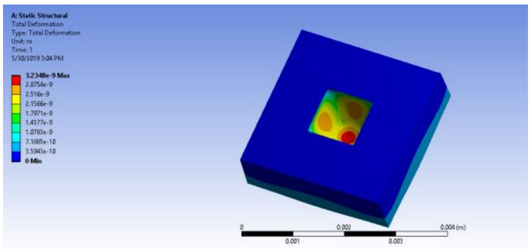

Figure 4. Directional deformation with 0.3 mm thickness

Similarly fig (3) shows the directional deformation with 0.3 mm thickness of Silicon 100 when pressure is changed. The range of directional deformation with pressure difference is shown in fifth and sixth rows of table (2).

II. Modeling And Simulation

The fundamental notion of the core of Modeling and Simulation is that models are approximations of the real world [12]. The first step in Modeling and Simulation is ‘creating a model approximating an event or a system’. Then the model can be modified in which simulation allows for the repeated observation of the model [12]. After one or many simulations of the model, analysis takes place to draw conclusions, verify and validate the research and make recommendations based on various simulations of the model. Thus, modeling and simulation is a problem based discipline that allows for repeated testing of a hypothesis. The International Council of Systems Engineering (INCOSE) suggests that a system is a construct or collection of different elements that together produces results not obtainable by the elements alone [12].

This study infused computer modeling and simulation tools used in this work provides a basis to choose primary sensing element for a developmental pressure sensor with respect to its physical and mechanical strength against expected sheer forces.

The simulation and modeling was carried out in two parts, first is for simulation and modeling of Pressure sensing part and second is for realization of Temperature sensing part.

2.1 Simulation and Modeling for Pressure Sensing Part [9]

A diaphragm (Silicon 100) was simulated using software package with following details.
The density of SILICON-100 which was chosen for modeling and simulation was considered as 2330 kg m^-3.
The other Isotropic Elasticity details of Silicon100 are given in table 1.
The details mentioned in table 1 were used as constants for Silicon 100 and whole analysis of pressure change and its effect was carried out based on those constants.

Table 1. Isotropic Elasticity of SILICON100

Temperature in ºC	Young's Modulus In Pa	Poisson's Ratio	Bulk Modulus In Pa	Shear Modulus In Pa
20	1.3e+011	0.22	7.7381e+010	5.3279e+010

The table 1 shows the Isotropic Elasticity details of Silicon100 which were used throughout the analysis as constants.

The details of simulation and modeling are given below in graphical view to understand the linearity of deformation with pressure change for a fixed thickness of material (Si 100).

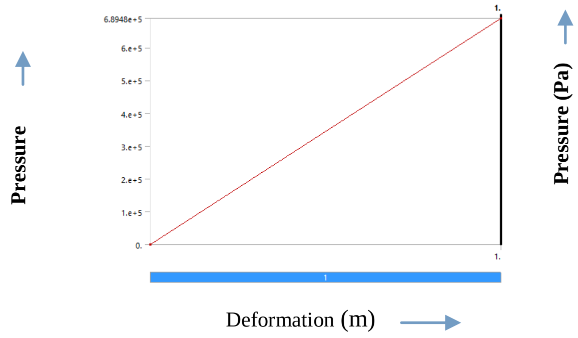

Figure 5. Plot for Load v/s deformation for 0.1 mm

Fig (5) shows that directional deformation with 0.1 mm thickness of Silicon 100 is highly linear when pressure is changed from minimum to around 368 psi.

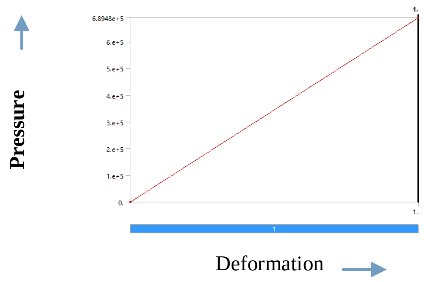

Figure 6. Plot for Load v/s deformation for 0.2 mm

Fig (6) shows that directional deformation with 0.2 mm thickness of Silicon 100 is also highly linear when pressure is changed from minimum to around 347 psi.

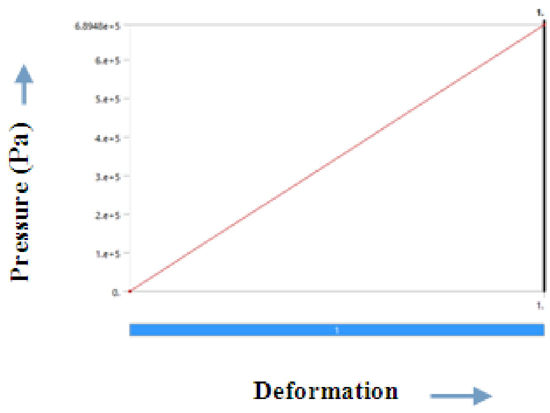

Figure 7. Plot for Load v/s deformation for 0.3 mm

Fig (7) shows that directional deformation with 0.3 mm thickness of Silicon 100 is also highly linear when pressure is changed from minimum to around 345 psi.
It is observed from the above fig. 5, 6 and 7 that the diaphragm has linear deformation for all the three thickness values. Now, here we need to see that which value of thickness is more suitable as per pressure sensor's required range.
Table (2) shows the pressure range and corresponding deformation for all the three thickness values. So, appropriate thickness value can be chosen from table (2) as per suitable pressure rage required.

Following points are observed from table 2 that-

- 0.1 mm thickness is suitable to handle pressure from 0.0356662 psi to 368.077 psi.
- 0.2 mm thickness is suitable to handle pressure from 0.0329 psi to 347.162 psi.

- Similarly, 0.3 mm thickness is suitable to handle pressure from 0.059 psi to 344.827 psi.

Table 2. Evaluation of Pressure range and deformation [11]

Thick-ness (mm)	Property		Results	Pressure (Pa)	Directional Deformation (m)
0.1	Vol	8.5599e-009 m^3	Min	245.91	-3.3866e-010
	Mass	1.9945e-005 kg	Max	2.5378e+006	8.0125e-009
0.2	Vol	8.5985e-009 m^3	Min	226.89	-2.8838e-010
	Mass	2.0034e-005 kg	Max	2.3936e+006	4.06e-009
0.3	Vol	8.641e-009 m^3	Min	405.34	-2.0901e-009
	Mass	2.0133e-005 kg	Max	2.3775e+006	2.0799e-009

It is observed from the table 2 that the diaphragm made up of Silicon 100 with above three values of thickness would support the particular range of applied pressure along with its directional deformation. It was found from the simulation that the pressure measurement range is decreasing with increase in thickness of diagram, it was simulated till 0.3 mm because required pressure range is falling in above three ranges only. If thickness is increased further in simulation the results would be corresponding to lesser pressure than requirement. Hence simulation was performed till 0.3 mm of thickness.

2.2 Realization of Temperature Sensing Part

3D thermocouple junction is modelled,meshed and analysed using "Transient thermal analysis" system of Ansys Workbench Ver18.2.Analysis is done by modelling the thermocouple junction as sphere of 0.2mm diameter and two thermocouple wires of length 0.4 mm from the surface of bead.

3D meshed model of the sensor is shown in Figure 8. Model is meshed with Tetrahedron elements.

A. Material properties

It is assumed that junction bead has the average values of material properties of that of Chromel and Alumel. Following are the properties considered for the analysis

Thermal conductivity =24.35 W/mK
Specific heat= 523J/kgK
Density =8555 Kg/m3

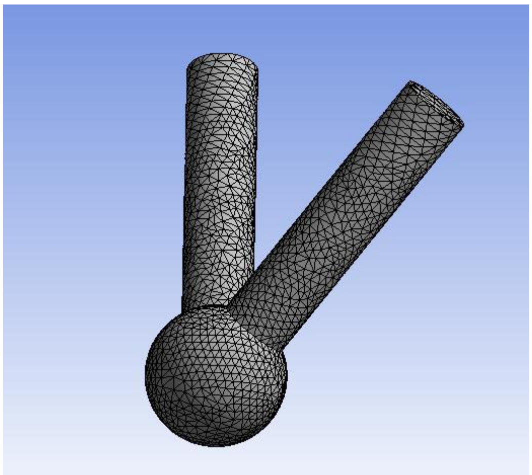

Figure 8 Junction bead

B. Mesh Attributes:

- 19997Tet elements, 12723nodes.
- Aspect ratio < 5 and Skewness< 1 for 99.99% elements

C. Thermal boundary conditions:

Initially the thermocouple junction bead is at room temperature and is then placed in the oil bath which is at a temperature of 100 ºC. Heat transfer coefficient of oil taken to be 200W/mK is applied on the surface of the sphere and the wires. Time response is shown in Figure 9.

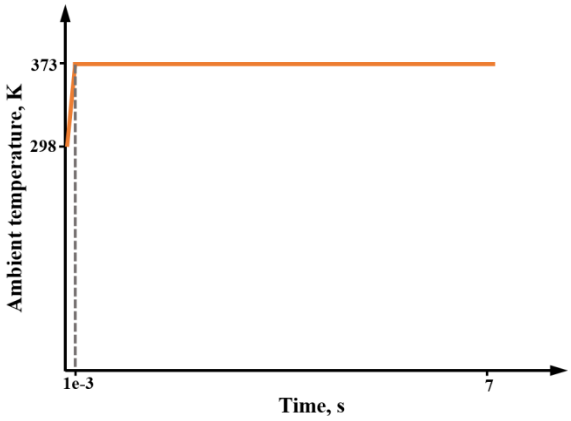

Figure 9 Time response

Initially ambient temperature of bead is 298K and it is ramped to constant value of 373K in 1millisecond. Cycle time of 7 seconds is taken to study the thermal response with 700 time steps (from 1miilisecond to 7 seconds).

D. Results of 3D FE thermal analysis:

3D transient FE Thermal analysis is carried out and the 3D nodal temperature distribution at the instant of 1 second, 3.5seconds and at the end of 7 seconds is presented in the Figure 10.

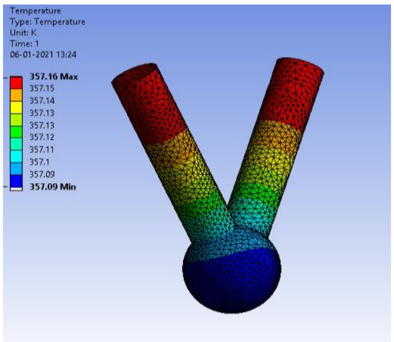

Figure 10 A Temperature distribution at the instant of 1 second

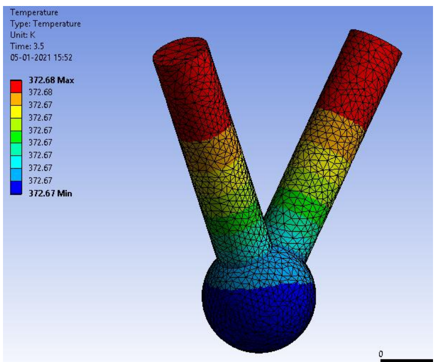

Figure 10 B Temperature distribution at the instant of 3.5 second

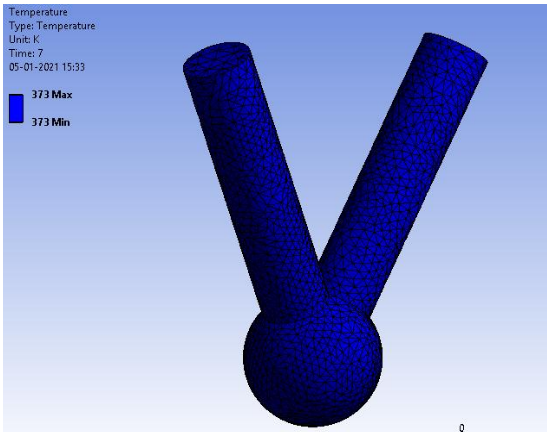

Figure 10 C Temperature distribution at the instant of 7 second

Figure 10 Nodal Temperature distributions of the thermocouple wires and the junction bead at different instants

From the Figure 10, it can be seen that the body reaches uniform metal temperature of 357K, 372K and of 373 K at the instant 1 second, 3.5 seconds and by the end of 7 seconds respectively. It is observed that there is a negligible temperature gradient within the body at a given instant during the transient analysis.

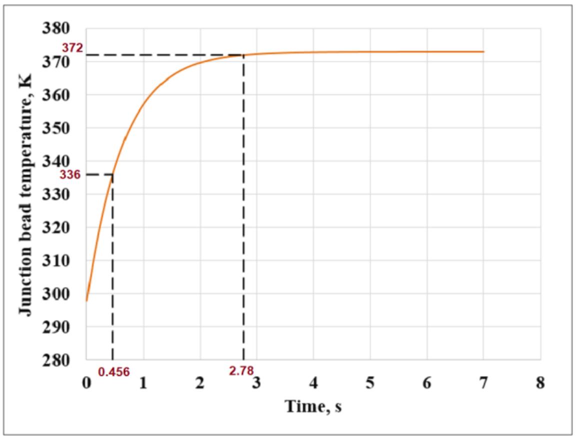

Figure 11 Transient thermal response of an outer node of the junction bead

The transient thermal response of an outer node of the junction bead is shown in Figure 11. It is observed from the Figure 11 that it takes around 0.456 seconds for the bead to reach 63 ºC (336K) and it takes 2.7824 seconds to reach 99 ºC (372K). There is an error in the estimated thermal response of 14% and -7% for reaching 63 ºC and 99 ºC respectively, compared to the actual response.

As temperature measurement of an aero engine is carried out in harsh environment, the first and foremost requirement is ruggedness of temperature sensor, then compatibility with the medium to be measured, the range and finally accuracy of measurement [8]. Based on the application and temperature ranges, a thermocouple was selected to be integrated with the sensor. The sensor was inspected, analyzed and selected with ref to ITS-90 temperature calibration recommendations [4]. A K-type thermocouple with 0.1 mm thickness was selected based on requirements, ITS-90 recommendations and environmental conditions. The ITS-90 (which is basically recognized as International Temperature Scale) is an internationally known and accepted guide to thermocouple and resistance thermometry. This guide is used as a temperature standard worldwide which is divided into three main parts. And an Epilogue: Theory & Standards, Sensors, Equipment & Practice and further practical points. It has been written to provide a simple yet authoritative guide to thermocouple and resistance thermometry. Its purpose is to define procedures by which specified, high quality yet practical thermometry systems could be calibrated such that the values of temperature obtained from them would be concise and consistent instrument-to-instrument and sensor-to-sensor – while simultaneously approximating to the appropriate thermodynamic values within the limits of the technology available. The thermocouple calibration is given in table (4).

III. Integration

With ref to para 2.1 of this paper, silicon diaphragm of thickness 0.1 mm was selected as a primary sensing element for pressure which can bear pressure from 245.91 Pa to 2.5378e+006 Pa (or from 0.0356662 psi to 368.077 psi).

Similarly with ref to para 2.2, a K-type thermocouple with 1 mm thickness was selected as a temperature sensor for a range from room temperature to above 900 ºC. The pressure and temperature sensors were integrated in a single assembly and sensor was tested for the performance of both (Temperature sensing and pressure sensing parts).

IV. Results

After the modeling and simulation both the sensing parts were tested in an isolated manner and results are shown in table (3 and 4)

4.1 Testing of Pressure Sensing Part [1] [2] [6] [10]

The pressure sensing part (Silicon 100 with 0.1mm thickness) was analyzed at three temperatures i.e. at 26 ºC, 100 ºC and at 300ºC for its corresponding accuracy with application of pressure values. The results are shown in table 3.

Table 3 shows that the pressure sensor has got offset error which is more than the specified tolerance but other values are well within the specified tolerance of ±0.5% of FS (Full Scale) till 20 bar or 300 psi.

Table 3. Testing of Pressure Sensing Part

Pressure (bar)	**Indicated output (mV) at different temperature of medium**			**Max Deviation (% of FS)**	**Tolerance** (% of FS)
	at 26 ºC	**at 100** ºC	**at 300** ºC		
0	3.155	3.157	3.158	**0.63***	±0.5
10	99.33	99.33	99.331	-0.13	
20	199.298	199.3	199.302	-0.14	

Table 3 shows that the pressure sensor was tested at different values of medium temperature. The medium used for testing was sebecate oil which was applied to the pressure sensor at room temperature (26 ºC), at 100 ºC and Silicon oil was used as a medium to be applied at 300 ºC. Other than offset, the sensor is maintaining its accuracy at all the three above said temperatures and well within the required error band of tolerance.

4.2 Testing of Temperature Sensing Part [1] [2] [5] [7]

The temperature sensing part (K type thermocouple with 1mm thickness) was evaluated till 950 deg C for its accuracy and results are shown in table 4.

Table 4. Evaluation of Accuracy [3]

Reference rdg (Deg C)	DUT rdg (Deg C)	Tolerance
26.50	26.5	Class1
110.05	109.08	
198.03	199.03	
298.80	297.74	
399.70	397.89	
499.70	497.87	
599.50	598.85	
701.71	700.17	
800.76	800.08	
951.84	952.01	

In above table (table-4), reference reading represents the actual temperature, DUT reading represents the temperature read by DUT (Device Under Test) which is K-type thermocouple in this case. Tolerance requirement is within class-1. Class-1 tolerance of thermocouple is expressed using following formula-

Class-1 Tolerance (ºC) = 0.004* Reference rdg (ºC)

From the table 4 it is also observed that all the readings are falling within calss-1 tolerance. It shows that the thermocouple chosen is appropriate as per the requirement of temperature range and its corresponding required accuracy of Class 1.

V. Results & Discussions

The load verses pressure characteristics are highly linear in all the three dies as shown in plots in fig. 5, 6 and 7. The pressure handling capability is found maximum with 0.1 mm thickness which is 368 psi. The directional deformation is also found maximum with 0.1 mm thickness. It shows that the silicon die with thickness of 0.1 mm is best suited to make a sensor of 300 psi g range because it is highly suitable to take load of pressure from 0.0356662 psi to 368.077 psi. Similarly a K-type thermocouple with thickness of 1 mm is best suited for cornering and routing internally as well as for achieving required ruggedness also.

VI. Conclusion And Future Scope

The modeling/simulation carried out in this, gives the actual behavior of the design before it is subjected to use in application. It also brings out the scope areas where this research would be referenced to model sensors in the application with respect to futuristic applicability.

As a result of this analysis the silicon diaphragm with thickness of 0.1 mm and a K-type thermocouple with thickness of 1 mm were selected for manufacturing of multi parameter sensor for aero engine application.

It has been seen that the pressure sensing diaphragm introduces offset error which is beyond tolerance. It gives the future scope for improvement, this offset error can be corrected using electronics tuning because relation of directional deformation and applied pressure is highly linear.

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