Proceedings of the
International Conference on Mechanical Engineering 2007
(ICME2007) 29- 31 December 2007, Dhaka, Bangladesh

ICME07-TH-16

A Model Based Analysis of Temperature Behavior of a Manufacturing Cell

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ABSTRACT

This paper deals with analysis of temperature behavior of an industrial manufacturing cell.. For analyzing the temperature behavior of the room, several experimental measurements are done using sensors at different conditions. A model of the room is developed based on the measurement data. A second order response surface model (RSM) is used to express the time dependent temperature field. We have performed a comparative study with measured data for the three cases of design of experiment (DOE): full factorial design, Central Composite Design (CCD) and D-optimal design. In the model analysis, the causes of small deviation of the results are stated. At last some suggestions for the further development of the model are suggested.

Keywords: Response surface model, Design of experiment, polynomial function.

1. INTRODUCTION

The monitoring and controlling of automated assembly processes can be based on some measurement of reference level of the construction unit or tools. The adjustment of construction units in a manufacturing cell is also based on some absolute dimensions. But there are some factors that make disturbances for the dimensions and lead to errors for the assembly process. Temperature variation can be also one of the most important factors. Due to temperature variation, objects in its form and size are changed by thermal expansion or contraction. For this reason, the co-ordinates of reference point vary. Air temperature fluctuations can again lead to measuring errors.

In this paper, different possible temperature distributions in a manufacturing cell or room are to be described on the basis of measured and investigated data. In the description, different conditions like as room air heating, sun exposure, window opening etc. are considered. Regarding object temperatures, both local and temporal variation is to be taken in consideration. It is also required that whether a connection between room air and object temperature distribution exists and which way the temperature equalizing occurs. Normally, at the ground level room air temperature is lower then the upper level air due to natural convective heat transfer. The temperature distribution in other two directions (along the axis of length and width of the room) is also considered with the vertical variation.

2. MOTIVATION

Precise temperature measurement is an important part of modern technology. Nowadays, temperature measurement and control is carrying out through a variety of methods and tools, based on different physical principles. High temperature variation in a manufacturing cell causes also problem in process automation due to change in relative position caused by thermal expansion of various objects. To monitor the thermal condition it is a good practice to have a look on the temperature field of the working zone. An average temperature is overall idea of thermal condition. But in most cases the local temperature distribution is important for control purpose.

Many tasks in manufacturing, assembling and alignment are normally defined by the problem of measuring the relative position of two components, re-positioning them and re-measuring. This cycle is repeated until the components are correctly located with respects to one another and/or with respect to some reference coordinate system. Leica's laser tracker make it suitable for measuring the relative position of two parts or components during the manufacturing process accurate to some 30-50 microns with the development of an Absolute Distance Meter (ADM) [1]. If the temperature variation is high then the relative position of the parts may change due to thermal deformation of the parts. In that case, a dimensional compensation should be required to consider the thermal affects for determination of relative position properly.

Normally, there are differences in temperatures inside a room, such as at the top and bottom, near the windows and doors, near walls and in the middle and at the southern and northern sides due to some physical causes. If the room consists of some machinery and parts, then also there occurs heat transfer between them due to temperature difference which causes a continuous fluctuation in room temperature depending on locations.

This work is motivated to get the thermal distribution of an assembly room depending on various factors like as sunshine, cold weather, heat source etc. A mathematical data based model is developed depending on some limited number of measuring points with the principle of response surface method.

3. THEORETICAL BACKGROUND

3.1 Theory for Modeling Temperature field

The temperature model can be developed in various methods. Computational Fluid Dynamics (CFD) allows computation of indoor air temperature distribution and air velocity gradient [2]. Some researchers also done this with Volume element method (VEM) based on the discretization of the energy equation and on the scale analysis of the momentum conservation equation [3]. Some also applied acoustic method for getting the temperature distribution in a room [4], [5]. In this paper the response surface method (RSM) is used to create a data based model to get the temperature field of an assembly room.

The temperature field of a room based on some limited number of measurement points can be obtained using second order response surface techniques [6]. This is also able to handle non-uniform placement of measuring points. A second order response surface model is used to express the temperature field which is time dependent. Least squares regression can be used to find out the coefficients of the model.

During the indoor air temperature measurements, our target is to obtain the information comprising the entire temperature field of room. However, In our case, information of temperature is available for only a few points due to lack of quantity in measuring equipment. In order to capture local fluctuation and non-linear variation, a large number of measurement points are required. When there is only a limited number of measuring points are available, then thermocouples/ sensors must be placed in such a way that it covers the most important characteristics of the field. An easier way for interpolation is the use of response surface methodology (RSM) to approximate the entire field by a single function.

To get the temperature field of the room, a second order polynomial function in three special dimensions can be considered as follows [7]:

$$T(x,y,z) = \beta_0 + \beta_1 x + \beta_2 y + \beta_3 z + \beta_{11} x^2 + \beta_{22} y^2 + \beta_{33} z^2 + \beta_{12} xy + \beta_{13} xz + \beta_{23} yz \quad (1)$$

where, *x, y, z* are coordinates of the room, *T* is the room air temperature and *β*'s are polynomial coefficient. Both *T* and *β* are changes with time.

It is almost impossible to get the real values of temperature of each location by experimental method due to lack of available resources. The response surface method can be used to get at least a better understanding of overall temperature response of the room air. The matrix transformation of the Eq. (1) for each *n* measurement points becomes as:

$$Y = Xb \quad (2)$$

where

$$X = \begin{bmatrix} 1 & . & . & . & 1 \\ x_1 & . & . & . & x_n \\ y_1 & . & . & . & y_n \\ z_1 & . & . & . & z_n \\ x_1^2 & . & . & . & x_n^2 \\ y_1^2 & . & . & . & y_n^2 \\ z_1^2 & . & . & . & z_n^2 \\ x_1 y_1 & . & . & . & x_n y_n \\ x_1 z_1 & . & . & . & x_n z_n \\ y_1 z_1 & . & . & . & y_n z_n \end{bmatrix}' ; \; b = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \beta_3 \\ \beta_{11} \\ \beta_{22} \\ \beta_{33} \\ \beta_{12} \\ \beta_{13} \\ \beta_{23} \end{bmatrix} ; \; Y = \begin{bmatrix} T_1 \\ .. \\ .. \\ T_n \end{bmatrix}$$

The coefficient vector *b* can be determined by least square regression using elementary matrix operations:

$$b = \left(X'X\right)^{-1} X'Y \quad (3)$$

After getting the coefficient vector from Eq. (3), it is possible to get the entire room air temperature field in three-dimensional space by Eq. (1).

We have chosen second-order model as it can work well as an approximation to the true response surface [6]. Also there is considerably practical experience indicating that second-order models work well in solving real world problems. The second order equation given in (1) includes the following effects of dimensions:

Table 1: Effects of three parameters for second order temperature model

Main effects	Second order effects	Interactions
x	x^2	xy
y	y^2	xz
z	z^2	yz

3.2 Design of Experiment

Design of experiment (DOE) is an important aspect of RSM. The main objective of DOE is the selection of position where response should be evaluated. The optimal design of experiment depends on the mathematical model of the process or system. Normally, this mathematical model can be any form of polynomial for which there is a specifically designed experiment which is the best for the model.

In case of temperature behavior analysis of room, the thermal effects of humidity, dust particle, etc. are neglected. Also the thermal conductivity and heat transfer co-efficient assume to be constant throughout the room.

The possible locations of each independent variable in the N-dimensional space are called as 'levels'. The space of the room can be designed for experiment depending on the following methods (for more details of the DOE see [7]):

(i) Full factorial design
(ii) Central composite design
(iii) D-optimal Design.

At least ten measuring points are required to get the value of coefficients for a three dimensional second order polynomial that is given in Eq. (1). However, number of measuring points is generally taken more to include the local effects for temperature variation. In general, points are arranged in regular grid to estimate the domain of interest with three parameters. These points are generally set in structured grid to ensure uniform weighting of the measurement points. Extra points also can be added in the places, which can include the most important factors that have significant influence on the temperature field. The arrangement of measuring points based on different experimental design view is discussed in the following sections.

3.3 System Description

Temperature measurement system consists of sensors, wiring, measured data recording system and a PC. The figure shows the simplified view of the measuring system:

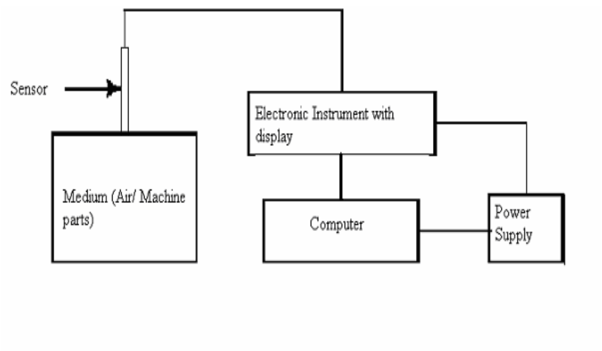

Fig 1: General experimental set-up for measuring temperature

Electronic date recording system: The THERM 5500-2 is measurement data recording system (see Fig 2), which operates with a variety of function in all areas of application of laboratory with its modularity and its applicability. The microprocessor technology of the equipment makes a high accuracy with free programming of measuring points. It has the quality for measuring tasks with high requirements in terms of the measuring accuracy. The output voltage of the system evaluates the measured temperature. The output voltage has a relation with temperature, which is determined by the base value and k-factor.

Fig 2: THERM 5500-2 date recording system

Sensors: For measuring the temperature at different location of the room, resistance thermometers (RTDs) have been used. It is a sensor of choice when sensitivity and application flexibility are the most common criteria. It gives accurate temperature for low temperature measurement with best linearity. The type of the sensors is Pt100, Class B with temperature coefficient of 0.385 $\Omega/ {}^0K$.

Measuring System Compensation: The calibration of the sensor along with the Therm5500 measuring system is done to compensate the lead wire resistance. The compensation is performed with two standard values: ice-water temperature (0^0C) and boiling water temperature (100^0C). Necessary equipments are: one ice-water tab, water heater and one thermometer. In the calibration process, the compensation of k-factor (k) and Base value (B) is required for the THERM-5500 measuring system. Sensor output is in the form of voltage (u) giving the measured temperature in ^0C. The Base value B and k-factor is shown in the figure 3.

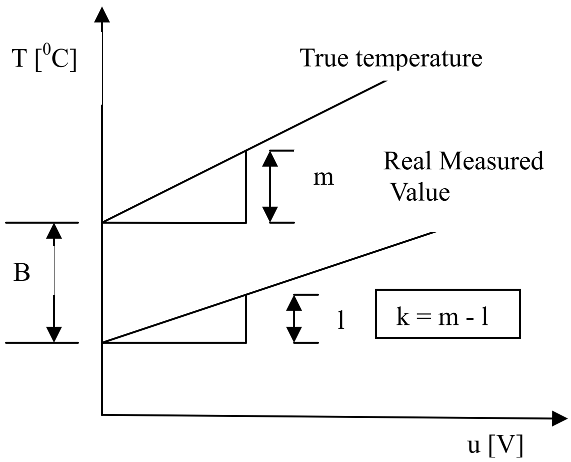

Fig 3: Relation between the sensor output voltage and measured temperature

4. MODEL ANALYSIS

A second order model of the room temperature given in Eq. (1) is visualized under several experimental designs. These are discussed in this section.

4.1 With 3-level Factorial Design

For this design 27 points in a regular grid is considered as measurement points in the region of interest with dimension of 18m x 15m x 6m shown in Fig. 4. This region is selected as in this area the measuring equipment, electronic system and the sensor cables can be handled with no major problem.

Using the 10 sensors, the temperature measurement for 27 points at the same time is impossible. So measurement is taken at 3 steps within 1.5 minutes assuming that within this time there are no major changes of temperature in the room. Three stands each one containing 3 sensors for each step give 9 (ie.3 x 3) points measurement at the same time.

The Table 2 shows the measured and modeled temperature values of some points at the same time. The table also shows the minimum and maximum error that obtained from the model in the region of interest.

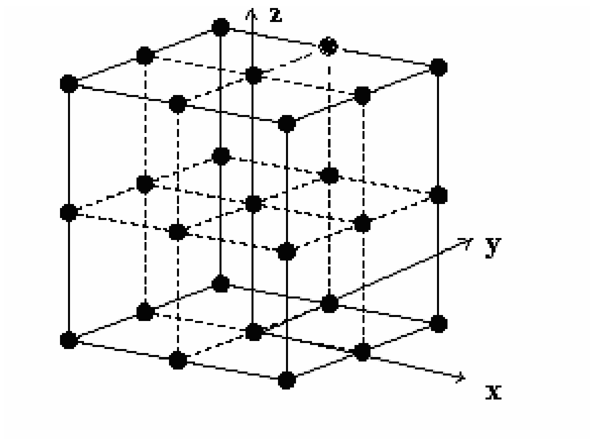

Fig 4. 3-level full factorial design arrangement

Table 2: Comparison between 3-level factorial modeled and measured temperature

Location (x, y, z)	Mea-sured T(^{0}C)	Mod-eled T (^{0}C)	Diffe-rence	Absolute Error (%)
(2.4,-2.8,2)	18.5	18.44	0.06	0.30
(2.4,0,1)	18.6	18.20	0.40	2.15
(2.4,0,0.2)	16.6	16.65	-0.05	0.30
(2.4, 0, 2)	18.0	18.30	-0.30	1.67
(0,0,1)	18.5	18.31	0.19	1.02
(0,0,0.2)	17.1	16.92	0.18	1.05
(0,0,2)	18.1	18.24	-0.14	0.80
(-2.4,0,1)	18.8	18.18	0.62	3.29
(-2.4,0,2)	18.2	17.95	0.25	1.37

4.2 With Central Composite Design (CCD)

For visualization of temperature, 15 points are considered as measurement location taking the same dimension of room as in full factorial design as shown in Fig 5. Though the arrangement of measurement points is more complex with compare to full factorial design, it gives better result then the other methods. From table 3, it can be seen that most of the modelled temperature have less than 1% error with compare to measured temperature at different locations.

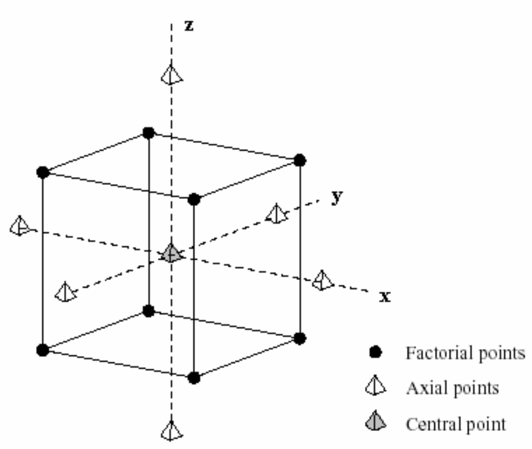

Fig 5: Central Composite design arrangement

CCD consists of three types of measurement points which are called as: Factorial points, axial points and Central points. Some experimental results showed that CCD can be a better arrangement for cylindrical shape room because of its geometric structure which is more suitable to arrange the measuring points for this method.

Table 3: Comparison between CCD modeled and measured temperature

Location (x, y, z)	Measured T (^{0}C)	Modeled T (^{0}C)	Differ-ence	Absol-ute Error (%)
(1.2,1.15, 0)	19.2	18.78	0.42	2.18
(0, 0, 0)	18.5	18.45	0.05	0.27
(0, -3.55, 0)	18.8	18.64	0.16	0.85
(3.1, 0, 0)	19	19.04	-0.04	0.21
(0, 3.55, 0)	18.8	19.02	-0.22	1.17
(-3.1, 0, 0)	18.5	18.51	-0.01	0.05
(0, 0, 1.35)	18.5	18.7	-0.20	1.08
(0, 0, -1.35)	18	17.82	0.18	1.00

4.3 Ten Points Measurement/D-Optimal Method

To get the temperature field of the room, the second order polynomial equation needs at least ten-point measurement for its solution. As ten is the minimum number of measurement points, the selection of position of the points is very important to get the entire temperature field. Sometimes it may also happened that singularity problem create for matrix solution and give an inaccurate result. For this D-optimal design can be used by which the position of 10 points can be found. This can be obtained by using Matlab Statistics toolbox. The better position also can be found by fixing 7 or 8 corner of the region and then changing the other two position by trial and error method where shows the minimum error.

The following table 4 shows the difference between measured temperature and modeled temperature of the room with error percentage.

Table 4: Comparison between D –optimal and measured temperature

Location (x, y, z)	Mea-sured T (^{0}C)	Mode-led T (^{0}C)	Differ-ence	Abs-olute error (%)
(2, 1, 2)	19.4	19.4	0.00	0.00
(-2.5, -3, 2)	19.3	19.3	0.00	0.00
(-2.5,-3,0.2)	18.8	18.8	0.00	0.00
(-2.5,3, 0.2)	18.5	18.5	0.00	0.00
(2.5, 3, 2)	19.1	19	0.10	0.52
(2.5, 3, 0.2)	19	19	0.00	0.00
(2.5,-3, 0.2)	18.6	18.8	-0.20	1.07
(2.5, -3, 2)	18.8	19.4	-0.60	3.19
(0, 0, 0.2)	19.4	18.95	0.45	2.32
(1, 1, 1)	19.4	19.4	0.00	0.00

Fig. 6 and Fig. 7 show the temperature vs. Time plot at two different points for measured and modelled temperature. It is quit clear that, the modelled and measured temperature has common trend in temperature variation with time scale. But we see that there is an offset between the measured and modeled temperature. This is may be a part of sensor's inaccuracy for temperature measurement and also the inherent error in assuming second order model for temperature distribution for the room.

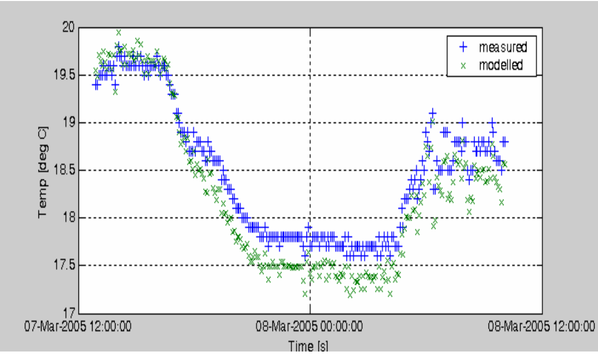

Fig 6: Comparison between modelled and measured temperatures at (x,y,z) = (0,0,0.2)

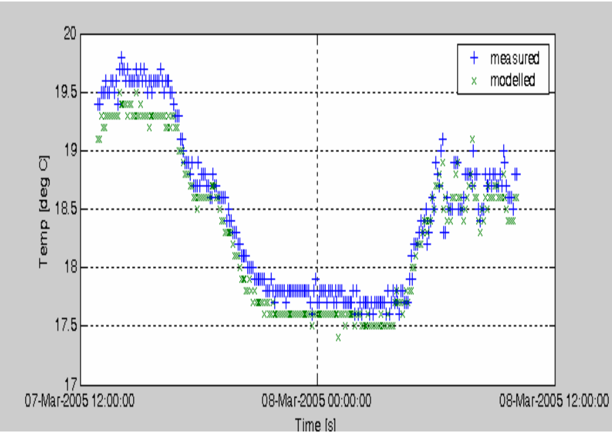

Fig 7 Comparison between modelled and measured temperatures at (x,y,z) = (2.5, 3, 2)

The measuring system error which may arise from some causes of: Sensor calibration, heat conduction in sensor lead, sensor self heating, electrical noise, radiation error, read-out error, etc. For minimizing the error, we have performed the linear compensation of the measuring system time to time.

5. CONCLUSIONS

The aim of this work has been to analyze the temperature of a manufacturing cell with some measurements. A second order polynomial is taken to approximate the temperature field. The room temperature is measured in varying number of points based on some experimental design using the concept of response surface methodology. The model's results are found to give a reasonable overall impression of the entire field considering the limited number of measurement points.

The most particular weakness of the second order response surface is the combined lack of possibility to show the highly non-linear behavior and detailed local information. For instance, the local influence for door opening is a sudden local influence. This kind of influence can't be express by limited number of measurement, which needs a detailed measurement. In this case, whole field visualization techniques combined with smoke visualization may be a good solution.

However, the second order model gives a satisfactory result to investigate the whole temperature field of the manufacturing cell. It can give the temperature at any point for any time based on the measured data with some tolerable error.

6. REFERENCES

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