CHEMICAL ENGINEERING TRANSACTIONS
VOL. 51, 2016
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Tichun Wang, Hongyang Zhang, Lei Tian

**ISBN** 978-88-95608-43-3; **ISSN** 2283-9216
DOI: 10.3303/CET1651225

# A Temperature Compensation Algorithm Based on Curve Fitting and Spline Interpolation

Shu-lan Xia*[a], Ji-lin Wang[b], Ru-gang Wang[b], Li Zhao[c]

[a]College of Electrical Engineering, Yancheng Institute of Technology, Yancheng 224051, Jiangsu, PR China
[b]College of Information Engineering, Yancheng Institute of Technology , Yancheng 224051, Jiangsu, PR China
[c]College of Information Science and Engineering ,Southeast University, Nanjing 210096, Jiangsu, PR China
xslnj@126.com

The zero and sensitivity of piezo resistive pressure sensors will drift with temperature because of the temperature characteristics of the semiconductor, and it is the main factor causing the measurement error of pressure sensor. For high-precision pressure monitoring system, temperature drift has become an important obstacle to improve performance of the system, especially in the field of applications with large changes of ambient temperature. On the basis of analysing the advantages and disadvantages of a variety of temperature compensation methods, a temperature compensation method combined with polynomial curve fitting and three spline interpolations is proposed, and it can improve the performance of the system.

## 1. Introduction

The characteristic of piezo resistive pressure sensor is high sensitivity, dynamic response, high precision, and long working life; therefore it obtains more and more application in modern industry (Wang et al., 2007). It is a kind of pressure sensor using the piezo resistive effect of semiconductor materials. But because of the core component is piezo resistive diaphragm which is sensitive when temperature changes, so it causes the sensor's zero point and sensitivity changing when temperature drift. There are two kinds of common temperature compensation methods, hardware compensation method and software compensation method (Li et al., 2008; Palmer, 2006). The traditional compensate method according to the sensor's hardware characteristics has many faults, such as debug difficulties, poor universality and low accuracy and so on, it is detrimental to engineering(Ishigaki et al., 2007; Zhang, 2008; Wang et al., 2010). While the software compensation method can solve the above problems well, so it acquires more and more attention(Kowalski, 1987; Pramanik, 2006; Guo, 2010). This paper uses software compensation method mainly, it adopt the appropriate sensor information fusion algorithm to compensate the influence of pressure sensor causing by the change from temperature, and puts forward a kind of temperature compensation method which combines polynomial curve fitting and cubic-spline interpolation, this method is flexible, and also can achieves high precision.

## 2. High precision pressure detection system based on software compensation

The method of software compensation combines the microprocessor and pressure sensor, it can make full use of microprocessor, and through compensation algorithms to correct the errors which caused by temperature (Handy et al., 2002; Li et al., 2009). Regardless using what type of software compensation method, the hardware structure is similar, the differences lies in algorithm (Zhao et al., 2005; Wu, 2007). The high precision pressure detecting system which we designed used the high performance micro-controller LPC2478 as its central processor, the processor based on the ARM architecture, its working frequency is 72MHz, and it owns 512K flash memory and some serial interface. Meanwhile, the system using a AD which owns high sampling accuracy and also a piece of SDRAM. The System block diagram is shown in fig.1.

Please cite this article as: Xia S.L., Wang J.L., Wang R.G., Zhao L., 2016, A temperature compensation algorithm based on curve fitting and spline interpolation, Chemical Engineering Transactions, 51, 1345-1350 DOI:10.3303/CET1651225

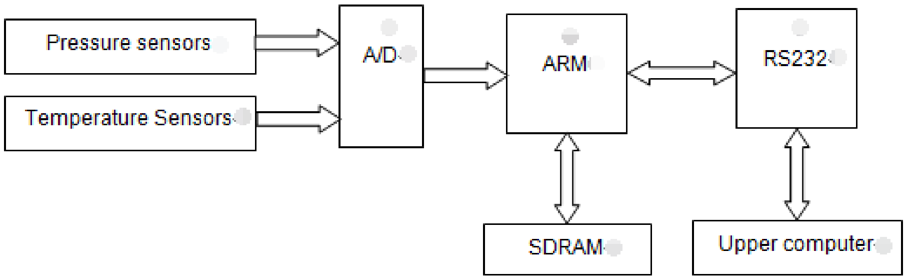


*Figure 1: The System block diagram*

## 3. Algorithm analysis and the implementation

At present, the software compensation method has interpolation method, curve/surface fitting method, querying table method and the method using BP neural network (Wu et al., 2012). In the interpolation method (Li et al., 2015), first it requires that the data is correct, and also requires knowing the relationship between dates. The curve fitting method tries to find a smooth curve, it can fit data's well, but not necessary to pass any data. Querying table method is a method which must filling a series of parameters into a parameter list, after obtaining the measurements, process dates according to the relative parameters in the table. Querying table method requires large storage space, so it does not suit for microprocessor. Neural network method is a method that through establishing the artificial neural network model, and also through the sample to train the network parameters, but the largest shortcoming is the instability of network, and the long training time (Ren et al., 2014). This paper puts forward a method combined with curve fitting and cubic spline interpolation compensation algorithm; this algorithm can increase the compensation performance significantly. The following content wants to explain the theory of polynomial fitting and cubic-spline interpolation firstly.

### 3.1 Polynomial curve fitting

In the curve fitting method, polynomial fitting is the most appropriate method, because this method with easy calculation, and well-fitting effect (Tang et al., 2014). According to the given data (xi, yi), i=1, 2, …, m, polynomial fitting is the method which make a polynomial :

$$y = \sum_{k=0}^{n} a_k x^k \tag{1}$$

Let the squares error is minimum, i.e.

$$E = \sum_{i=1}^{m} \left( y_i - \sum_{k=0}^{n} a_k x_i^k \right)^2 = \min \tag{2}$$

Therefore let:

$$\frac{\partial E}{\partial a_k} = 0 \text{ (k=1,2,…,m)} \tag{3}$$

Then:

$$\sum_{k=0}^{n} (\sum_{i=0}^{m} x_i^{j+k}) a_k = \sum_{i=0}^{m} x_i^j y_i \qquad \text{j=1, 2, … , n} \tag{4}$$

Formula 1 can be unfolded as linear equations about coefficient ai, if this equation has a unique solution; the unique solution is the coefficient of the fitting polynomial.

### 3.2 3-spline Interpolation

Spline interpolation is a kind of improved subsection interpolation, it structures spline function in every adjacent area, meanwhile in order to guarantee the continuity at this node, it requires 2-order smoothness at the point, and namely it owns continuous 2-order derivatives.

The function of 3-spline interpolation is defined as follows (Wang et al., 2007).

Assuming that the given interval [a, b] has n+1 nodes, and a=x0<x1<…<xn=b. If the function s(x) is a polynomial which order is no more than three in any interval [xk,xk+1],and s(x) owns continuous 2-order derivatives in the interval [a, b],So can define s(x) is cubic spline function of nodes x0,x1, …,xn.
According to the above definition , s" is a linear function in every adjacent area [xk,xk+1].If making the s"(xk)=mk(k=1,2,…,n), s"(x) can be expressed as the next formula in area [xk,xk+1].

$$s^{n}(x)=m_k\frac{x_{k+1}-x}{h_k}+m_{k+1}\frac{x-x_k}{h_k} \tag{5}$$

In order to derivation conveniently, let hk=xk+1-xk. Then integral to formula (5) two times, so

$$s(x)=m_k\frac{(x_{k+1}-x)^3}{6h_k}+m_{k+1}\frac{(x-x_k)^3}{6h_k}+A_k(x-x_k)+B_k \tag{6}$$

Take the value of xk, xk+1into the above formula, and then get the expression of Ak and Bk:

$$A_k=\frac{y_{k+1}-y_k}{h_k}-\frac{h_k}{6}(m_{k+1}-m_k) \tag{7}$$

$$B_k=y_k-m_k\frac{h_k^2}{6} \tag{8}$$

From formula (6) (7) (8) can find out that if the value of mk (k=1, 2, … , n) is known , the value of s(x) can find out conveniently.
The solution of mk is using the continuity characteristics of the nodes defined above, i.e. s´+(xk)=s´_(xk),And add the two boundary constraint conditions of endpoints, refer to the reference of Numerical Analysis(Yanfeng Zhang et al., 2007) ,can get the equations which can solve by chase-after method , it can reduce the computation greatly.

**3.3 Temperature compensation model and algorithm**

Pressure sensor is generally calibrated under standard temperature and standard pressure pj (j=1, 2, …, m) (Li et al., 2015), the number of marked point is n×m. Through the appropriate algorithm can obtain the relation among (ti, pj, uij) which comes from actual measurement processing, it is p=f (t,u).Here the parameter u is the output voltage of pressure sensor.
If the measurements Δpmax=max(Δp1, … , Δpj, …,Δpm) ,j=1,2, …,m ,according to p=f(t,u),while the true value is pj,so the measurement error is Δpj=∣p´j-pj∣, j=1,2, …,m. In the whole measurements, the maximum error of pressure sensor is Δpmax, so the composition error which relatives to the scale span pFS is ξ=(Δpmax/pFS)×100％.
According to this temperature compensation model, and combining with curve fitting and cubic-spline interpolation, the procedure of the temperature compensation algorithm is as follows:
Step 1 , fixed temperature t1 as a constant, doing a polynomial fitting with(u12,p1), (u22,p2) , …, (um2,pm),then can get the relation curve between p and u under temperature t1,p=f1(u).The order of the polynomial is decided by measured data ,and usually using quadratic polynomial fitting ,it can also use linear fitting if the preference of the sensor is well, quadratic polynomial fitting can be realized through Matlab .
Step 2 similarly, fixed temperature t2 as a constant, then can get the relation curve between p and u under temperature t2, p= f2 (u). The rest can be done in the same manner, until fixed temperature tn as a constant, then can get the relation curve between p and u under temperature tn, p=fn (u).
Step 3 take the actual measurement voltage u into p=f1 (u), p=f2 (u), ⋯ , p=fn(u), find out the pressure value under the standard temperature.
Step 4 process the above pressure value and standard temperature using cubic spline interpolation, then obtain the relation curve between pressure p and temperature t, it is p=g(t), The program of cubic spline interpolation realizes on the ARM platform using C programming language.
Step 5 Taking the real-time temperature into formula p=g (t), then will get the pressure value without temperature affects through the information fusion technology.

## 4. Experimental process and result analysis

Table 1 gives the output voltage value of sensor when the marked point pressure is 0, 5, 10, 20, 30, 40, 60 and the temperature is 0 ℃, 10 ℃, 20 ℃, 40 ℃and 60 ℃.

According to the algorithm steps above , processing the experimental data , i.e. fix the temperature ,and then process p, u using 2-order fitting, On this basis, using cubic-spline interpolation to process the temperature and the pressure, fusion the information of the pressure and the temperature, so can get the correct pressure results. In the actual working temperature T = 27 ℃, the calibration pressure P=20.000 MPa, the system detects the voltage values u=62.335mv,take these results into the above curve equation, get the pressure value at different interpolation points .Then use cubic-spline interpolation to process the value of pressure and temperature, the cubic-spline interpolation curve is shown in fig.2.

*Table 1: Experimental data*

| Press-ure P/MPa | t=0℃ | t=10℃ | t=20℃ | t=40℃ | t=60℃ |
|---|---|---|---|---|---|
| | U/mv | U/mv | U/mv | U/mv | U/mv |
| 0 | 6.969 | 6.110 | 5.759 | 4.478 | 2.468 |
| 5 | 23.215 | 22.363 | 21.879 | 20.811 | 19.147 |
| 10 | 39.081 | 38.243 | 37.879 | 36.861 | 35.507 |
| 15 | 54.874 | 54.040 | 53.815 | 53.041 | 51.745 |
| 20 | 70.732 | 69.884 | 69.682 | 68.972 | 68.046 |
| 25 | 86.514 | 85.672 | 85.496 | 84.836 | 83.966 |
| 30 | 102.253 | 101.551 | 101.242 | 100.632 | 100.112 |
| 35 | 118.046 | 117.214 | 116.930 | 116.233 | 115.772 |
| 40 | 133.899 | 133.075 | 132.561 | 131.904 | 131.163 |
| 45 | 149.298 | 148.624 | 148.123 | 147.745 | 147.046 |
| 50 | 165.041 | 164.383 | 163.642 | 163.301 | 162.861 |
| 55 | 180.857 | 180.019 | 179.095 | 178.96 | 178.440 |
| 60 | 196.212 | 195.383 | 194.504 | 194.404 | 193.924 |

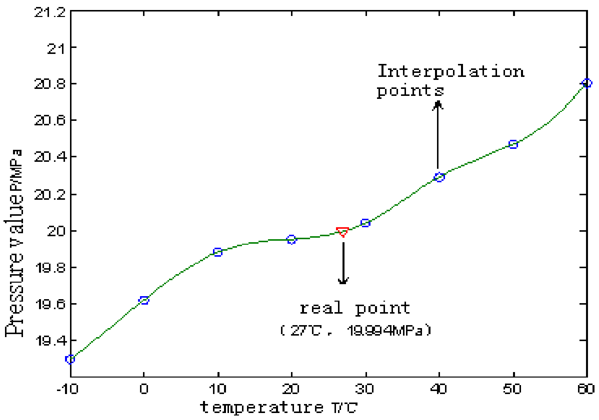


*Figure 2: Spline interpolation examples*

According to the aforementioned algorithm steps, the experimental data are processed. First, keeping the temperature constant, after curve fitting:

t=10℃:$p=0.0001u^2+0.7412u-4.2437$

t=30℃:$p=0.7314u-1.7433$

t=50℃:$p=0.7891u-1.6154$

t=70℃:$p=0.8432u-1.6014$

Take the actual temperature T = 27℃ into the function above, can compute the pressure value is P=19.994Mpa.The actual input pressure value 20MPa at this time, the measurement error relative to scale span is $(\Delta p/pFS) \times 100\% = (0.006\ Mpa\ /60\ Mpa) \times 100\% = 0.01\%$.

From the value can find out that the measurement error of system is small at this point, and it can eliminate interference caused by temperature well.
The high pressure sensor used in this experimental is honeywell 13mm series which owns well linear characteristics (the scale span of it is 60MPa).This algorithm can develop the characteristic effectively. According to the calculation, the scale span integrated error compensated by temperature in the laboratory is (0.021 / 60)×100％=0.035％.The results show that after using the combining method of curve fitting and cubic-spline interpolation, the performance of the system improve significantly. Meanwhile, we can through increasing the marked point pressure and temperature to improve the performance further.
After curve fitting keeping the temperature constant, it has a good linear characteristic. We tested at the temperature points: 8.2℃、4.6℃、22.3℃和 36.5℃. The pressure through temperature compensation is shown in Table.2

*Table 2: The pressure through temperature compensation*

| P/MPa | 8.2℃ | 4.6℃ | 22.3℃ | 36.5℃ |
|---|---|---|---|---|
| | U/mv | U/mv | U/mv | U/mv |
| 0 | 9.99 | 9.994 | 0.02 | 9.992 |
| 5 | 5.006 | 4.994 | 5.002 | 4.994 |
| 20 | 9.993 | 9.993 | 20.02 | 9.996 |
| 25 | 25.009 | 25.02 | 24.983 | 25.005 |
| 30 | 30.006 | 29.994 | 29.004 | 30.006 |
| 35 | 34.992 | 34.994 | 35.008 | 35.02 |
| 40 | 40.005 | 39.994 | 39.993 | 39.996 |

Table 3 gives the overall fusion effect of the algorithm performance test when the marked point pressure is 10, 20, 30, 40, 50 and the temperature is 17.6 ℃, 23.3 ℃and 32.5 ℃(Test method is same as above).

*Table 3: The test result*

| P/MPa | 17.6℃ | 23.3℃ | 32.5℃ |
|---|---|---|---|
| 10 | 10.012 | 10.992 | 10.001 |
| 20 | 20.004 | 19.986 | 19.998 |
| 30 | 30.005 | 30.002 | 29.993 |
| 40 | 40.008 | 39.992 | 40.021 |
| 50 | 49.997 | 49.994 | 50.004 |

## 5. Conclusion

This paper puts forward a novel temperature compensation method which combines Quadratic curve fitting and cubic-spline interpolation, it can realize high precision temperature compensation when the marked points is less, so that it can reduce the sensor's calibration time and workload effectively. For obtaining higher precision requirement of the pressure sensor, in full condition of cost, hardware's compute power and running speed, through the marked point method can improve the system performance; this method has certain theoretical significance and engineering application value on solving the temperature compensation of high precision pressure sensor.

### Acknowledgements

This work is supported by the Yancheng Institute of Technology Talents Project of China and the National Natural Science Foundation of China under Grant No. 60975017.

### References

Guo B., 2010, Information fusion for tactile sensor array signals, Journal of Chongqing University, 33(6), 55-59.
Handy M.J., Haase M., Timmermann D., 2002, Low energy adaptive clustering hierarchy with deterministic cluster -head selection, Mobile and Wireless Communications Network.

Kowalski, 1987, Miniature Pressure Sensors and Their Temperature Compensation, Sensors and Actuators, 11(4), p 367-376.
Li D.D., Liang T., Li S.N., Yao Z., Xiong J.J., 2015, Design of SOI High Temperature Pressure Sensor Based on MEMS Process, Chinese Journal of Sensors and Actuators,28(9),1315-1320, DOI:10.3969/j.issn.1004-1699.2015.09.009.
Li G., Li Z.S., Li Q., Li J.H., 2009, The Study of Multi Sensor Fusion Technology Based on the Neural Network, Microcomputer Information, 25(16), 145-147.
Li Q., Li L., Liu Z., Ma J., Tian L., Feng T., 2008, Intelligent Pressure Sensor System With Temperature Compensation, Chinese Journal of Scientific Instrument, (29)9,1934-1938, DOI: 10.3321/j.issn:0254-3087.2008.09.028.
Li X., Jiang Z.H., Lu Y.Z., Pan W., Yu Y.S., 2015, Temperature monitoring and analysis system of beehive based on micro-sensor array,Transducer and Microsystem Technologies, 34 (11),63-65+68 DOI:10.13873/J.1000-9787(2015)11-0063-03.
Palmer J., 2006, Precise Pressure Sensor Temperature Compensation Algorithms, Master thesis, New York: State university of New York.
Pramanik, 2006, Temperature Compensation of Piezoresistive Micro-machined Porous Silicon Pressure Sensor by ANN, Microelectronics Reliability, 46 (2-4), 343-351.
Ren Z., Cai T., Tan Q.L., Li C., Zheng T.L., Xiong, J.J., 2014, High-Temperature Performance of Wireless Passive Pressure Sensor Based on Alumina Ceramic, Chinese Journal of Sensors and Actuators, 27(9),1169-1173, DOI:10.3969/j. issn.1004－1699.2014.09.003.
Tang S.W., Li B.B., Wang X., 2014, Design of multiple parameters automatic test system for multi-channel pressure sensor, Transducer and Microsystem Technologies ,33(12),64-66+72,DOI:10.13873/J.1000-9787(2014)12-0064-03.
Tsukasa I., 2007, An information fusion-based multi objective security system with a multiple-input/single-output sensor, IEEE Sensors Journal, 7(5), 734-742.
Tsukasaan I., 2007, Information fusion-based multi objective security system with a multiple-input/single-output sensor, IEEE Sensors Journal, 7(5), 734-742.
Wang B.J., Liu X.J., Liu B.Q., 2008, The technology and application of pressure calibration ,Metrology & Measurement Technology,28(3),64-65,DOI: 10.3969/j.issn.1674-5795.2008.03.023.
Wang P.T., Zhai D.T., Cheng X.F., 2007, Design of Temperature Compensation System of Pressure Sensors, Information Technology and Informatization, 14 (3), 112-113+115, DOI: 10.3969/j.issn.1672-9528.2007.03.044.
Wang X.Z., Zhang T., He L., 2010, Application of fuzzy adaptive back-propagation neural network in thermal conductivity gas analyzer, Neurocomputing, 73, 579-583.
Wu D., Xie G.J., Jin Z., Jing T., Yuan Y.H., Song Z.Y., 2012, Design Optimization for the Sensitivity of SOI Pressure Sensor, Chinese Journal of Sensors and Actuators,25(8),1064-1068, DOI:10. 3969/j. issn. 1004－1699. 2012. 08. 009
Wu Z., 2007, Design of Pressure Measurement System based on Multi- sensor Technology, Microcomputer Information,23(34),138-139+157,DOI: 10.3969/j.issn.1008-0570.2007.34.056.
Zhang Y.F., Yan J.M., 2007, Compensation Method of Pressure Sensor Base on Minimum Two Multiplication Principle, Computer Measurement & Control, 15 (12), 1870-1874, DOI:10.3969/j.issn.1671-4598.2007.12.075.
Zhang Y.L., 2008, Research on multi-sensor data fusion based on improved BP algorithm, Journal of Southeast University (Natural Science Edition),38(SUPPL. 1), 258-261.
Zhao H., Wang X.F., 2005, Application of LM algorithm in data fusion disposal of sensor ,Transducer and Microsystem Technologies, 24(5), 77-79+85, DOI: 10.13873/j.1000-97872005.05.028.