The Method Study of A kind of Data Driven Pressure Sensor's Real Time Fault Diagnosis

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Abstract. The electrode distance variance and capacitance style pressure sensor is talked about .The change rate of the pressure is treated as judging basis of whether the fault is existed. Make the bridge output signal as the sensor's output signal and one of the detection signal,also make the operational amplifier output signal as another detection signal. The expressions of each element in drift failure when in changeless input signal are obtained.and the change laws of them are analyzed.On the basis of these works it is verified that different elements' failure can be distinguished and solved. After such works the fault location and the fault evaluation are realized.The simulation tells that the value of the fault diagnosis's results are relatively close to the true value of the fault.

Introduction

Fault diagnosis judges the system status and the abnormal condition of the system,and provide the basis of system's recovering by the diagnosis result[1].It's very helpful to modern large-scale and complicated systems.In recent years,there are many researches on controlling system's fault diagnosis both at home and abroad.The main study subject is the pressure sensor,among which the liquid level sensor makes up a large portion[2].The research methods involve fault decision scheme method[3]、fuzzy modified model reference adaptive controller[4]、lifting wavelet and probabilistic neural net-work[5]、 neural network predictor[6] and so on.

The paper acquires the output signal's change laws of the sensor's measuring circuit when the circuit is in single element failure by researching the relationship between the input signal and the output signal.By making the measuring circuit's bridge output signal's signal、the operational amplifier's output signal's signal as the detection information,it is proved different elements' fault can be distinguished.Thus the fault location and the fault evaluation are achieved.By the test of the simulation,it is concluded that the fault can be detected when a single element is in at least1% value drift.It is also concluded that error of the value diagnosis is less than 10%.

The pressure sensor's operational principle and the measuring circuit

The pressure sensor in the paper is electrode distance variance and single-capacitance style pressure sensor.Its fixed electrode above is fixed by the insulator and variable electrode is below.When the variable electrode is under pressure,its diaphragm will get deflection .The distance between the fixed electrode and the variable electrode gets changed and the relative electrical signal appears which can show the value of the pressure[7].

The measuring circuit is shown in Fig. 1,the diaphragm of the sensor consists of the round working electrode and the annular reference electrode.The two electrodes make up the sensitive capacitance C_2.The pressure causes the change of the diaphragm via the conduit and makes the value of C_2 changed.The value of C_2 without the pressure is C_{20}.The internal impedance of the operational amplifier is so large that we can regard it open circuit.So C_1,C_2 and other two auxiliary capacitances make up the bridge's four bridge arms.The bridge's potential difference on the cross is the bridge output U_a,which is the output of the measuring circuit linked to the Single Chip Microcomputer(SCM).The U_o is the operational amplifier output as another detection signal.

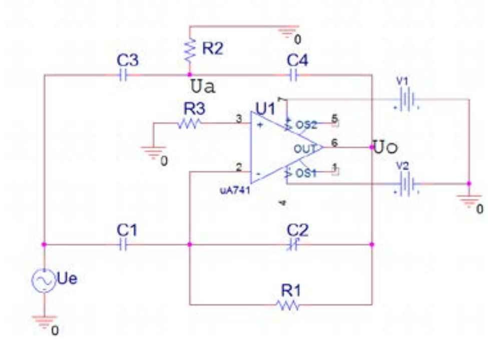


Fig .1. The measuring circuit of the sensor.

When $U_e(t)=\sin 100\pi t$ and the original value of U_a is zero ,Eq.1 is acquired :

$$U_a(t)=Me^{\frac{-1}{R_2(C_3+C_4)}t}+Ne^{\frac{-1}{C_2R_1}t}+\frac{A}{K}\cos wt+\frac{B}{K}\sin wt \tag{1}$$

In Eq.1

$A=w^3C_2^2C_3R_1^2R_2-w^3C_1C_2C_4R_1^2R_2-w^2C_1C_3C_4R_1R_2^2-w^3C_1C_4^2R_1R_2^2+wC_3R_2$. $B=w^4C_2^2C_3^2R_1^2R_2^2+w^4C_2^2C_3C_4R_1^2R_2^2-w^4C_1C_2C_3C_4R_1^2R_2^2-w^4C_1C_2C_4^2R_1^2R_2^2+w^2C_3^2R_2^2+w^2C_3C_4R_2^2+w^2C_1C_4R_1R_2$.

$K=(w^2C_2^2R_1^2+1)[1+w^2R_2^2(C_3+C_4)^2]$, $N=\frac{-wC_1C_4R_1R_2}{(w^2C_2^2R_1^2+1)(R_1C_2-R_2C_3-R_2C_4)}$, $M=-N-\frac{A}{K}$.

Also when $U_e(t)=\sin 100\pi t$,the expression of U_o is in Eq. 2

$$U_o(t)=\frac{wC_1R_1}{w^2C_2^2R_1^2+1}e^{\frac{-1}{C_2R_1}t}-\frac{wC_1R_1}{w^2C_2^2R_1^2+1}\cos wt-\frac{w^2C_1C_2R_1^2}{w^2C_2^2R_1^2+1}\sin wt. \tag{2}$$

The parameters of the measuring circuit's elements are in Table 1. C_{20} =1nF.When the system Is in work,the value of C_2 changes from 1nF to 1.067nF,which correspondences the pressure from 0 to 40kPa.In fact,a very small change(less than 1%) in C_2 can cause 5KPa(level more than 50cm) change in pressure.The other elements have the similar characteristics.So when the element is in drift faults,the pressure or the liquid level shown by the system will change fiercely which is larger than the permit change rate .This characteristic can help us know the existence of the fault.

Put the parameters of the elements into Eq. 1 and Eq. 2 and calculate the normal range of the amplitude and the phase of U_a and U_o .Only when these four detection signals are all in the normal range,the circuit may be normal.

Table 1 The parameters of the pressure sensor capacitance's material and the circuit's element

Parameters	Value	Parameters	Value
C_{20}	1nF	C_1	1nF
C_3、C_4	1nF	R_1	2MΩ
R_2	10MΩ	U_e	$\sin 100\pi t$

The fault diagnosis method of the pressure sensor

The fault diagnosis need to judge whether the fault is existed at first.If existed,judge the location of the fault and its value.The paper researches on the single-element drift fault.The requirements above can be achieved by detecting the amplitude and the phase of U_a and U_o .

Judge the existence of the fault.

Take the advantage of the characteristic that the pressure and the liquid level never changes fiercely.The liquid level change formula is

$$Q_1 - Q_2 = S\frac{dh}{dt}. \tag{3}$$

Q_1、 Q_2 are the inflow and outflow of the tank,*S* is the cross-sectional area of the tank and *h* is the liquid level.Then can get Eq. 4

$$(\frac{dh}{dt})_{\max} = \frac{\Delta Q_{\max}}{S}. \tag{4}$$

$(\frac{dh}{dt})_{\max}$ is the liquid level's biggest change rate permitted in normal.When the change rate of the liquid level is beyond it,it is certain that fault is existed.

The flow is calculated in Eq.5:

$$Q = \sqrt{P/\rho gML}. \tag{5}$$

In Eq. 5,*P* is the differential pressure, ρ is the liquid density,*g* is the gravity,*M* is the pipeline's friction and *L* is the pipeline's length.Make differential pressure *P*=100KPa.The pipeline's length *L*=0.4m. The pipeline's friction M=$10.3n^2/d^{5.33}$.The roughness *n*=0.012.The pipeline of the liquid is 1/4 inch style.So *d*=0.635cm. It is calculated $\Delta Q_{\max} \approx 1.8287\times10^{-4} m^3/s$.The cross-sectional area of the tank *S*=15.5179cm^2,see[3].So it can be calculated $(dh/dt)_{\max} = 11.78cm/s$.Given this result ,we can calculate the pressure change rate in normal is less than 1.154KPa/s even further. So it's proved that the element's drift rate of at least 1% can be detected.

The location of the fault diagnosis.

If it is certain the fault exists,the fault location can be determined by whether and how many signs are beyond their normal range..By Eq.1 and Eq.2, we can respectively get C_2, C_1, C_3, C_4, R_1, R_2, six elements in its single drift fault but other five elements normal,the function expressions whose variable is respectively the amplitude and the phase of U_a and U_o.

When the fault is in the reference capacitance C_1, the amplitude and the phase of U_a as well as the amplitude of U_o get changed but the phase of U_o doesn't change.The simulation in Fig. 2 shows the change curve by time of U_o when C_1 changes from 0.4nF to 1.9nF. It is proved that when C_1 rises, the amplitude of U_o rises but the phase constants(The curves coincidence at the fixed zero).So if the amplitude and the phase of U_a as well as the amplitude of U_o are beyond the normal range but phase of U_o is still in the normal range,surely the fault is in C_1.

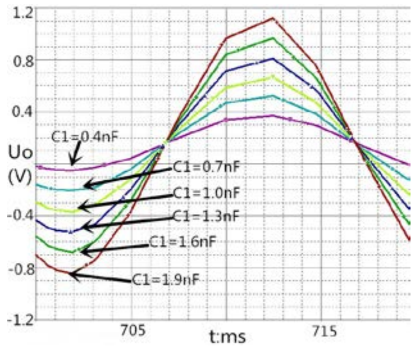
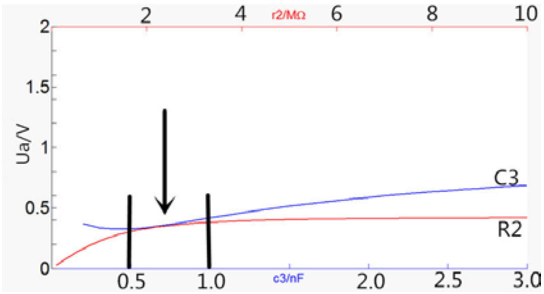


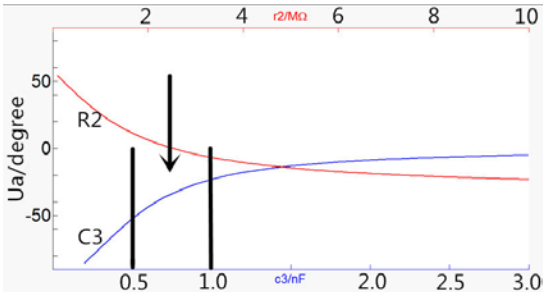
Fig.2 The change of U_o in different C_1 values

When C_2 or R_1 has the drift fault, the amplitude and the phase of both U_a and U_o will be beyond the normal range. The variation trend of U_o's amplitude and phase caused by C_2 and R_1 are different.This characteristic leads to the different range of both U_a and U_o,and the fault location of C_2 or R_1 can be distinguished.

When C_3、 C_4 or R_2 has the drift fault,only the amplitude and the phase of U_a get changed but the amplitude and the phase of U_o are still in normal range.As Fig 3 shows, only when C_3 is between 0.5nF to 1nF,the amplitude of U_a may be near to R_2's change .But at the same time, their phase of U_a are very different.This can help to distinguish whether the fault location is in C_3 or R_2.The distinguish between C_4 and R_2 is similar.



(a) The curve of the amplitude



(b) The curve of the phase

Fig.3 The curve of amplitude and phase of C_3 and R_2 with operational amplifier output

To the distinguish of fault between C_3 and C_4.Because these two elements are in the above of the circuit as apart to make up the bridge.So it's possible that one C_3 value and another C_4 value may cause the same amplitude and the phase of U_a. So it's needful to make an extra judgment.Define the current in C_3 and C_4 as I_{C3} and I_{C4},like Eq.6 and Eq. 7:

$$I_{C3} = C_3 \frac{d(U_e - U_a)}{dt} . \tag{6}$$

$$I_{C4} = C_4 \frac{d(U_a - U_o)}{dt} . \tag{7}$$

Acquire the signal of C_3 and C_4,then combine with U_a to complete the extra judge to know whether the fault is in C_3 or C_4.

The evaluation of the fault.

After the fault location is sure,it's realizable to evaluate its value.On the basis of Eq.1 and Eq.2, make the fault element as the unknown number and the other elements as the values in Table 1.Substitute the value of U_a and U_o and simultaneous 2~4 equations.The solution is the value of the fault.The change rate of C_2 is below 6.7% when C_2 is normal.During the fault diagnosis,the upper computer displays no pressure value.So we can't know the real-time exact value of C_2 and just make $C_2 \approx C_{20}$=1nF. In Eq.8 to Eq.13, the unit of capacitance is F and resistance is Ω and the voltage amplitude is V.

When the fault is in C_1,substitute $w = 100\pi$、$C_2 \approx C_{20}$=1nF、$C_3 = C_4 = 1$nF、$R_1 = 2M\Omega$、$R_2 = 10M\Omega$,simultaneous three equations and solve the equation set :

$$|U_o|^2 = \frac{(-6.283185307 \times 10^8 C_1)^2 + (3.94784176 \times 10^8 C_1)^2}{1.945422898} . \tag{8-1}$$

$$|U_a|^2 = (\frac{-1.364276174 \times 10^{10} C_1 + 4.381843721}{56.45865634})^2 + (\frac{-5.818806403 \times 10^9 C_1 + 27.53193609}{56.45865634})^2 . \tag{8-2}$$

$$a\tan(\angle U_a) = \frac{-1.364276174 \times 10^{10} C_1 + 4.381843721}{-5.818806403 \times 10^9 C_1 + 27.53193609} . \tag{8-3}$$

When the fault is in C_2,substitute $w = 100\pi$、$R_1 = 2M\Omega$、$R_2 = 10M\Omega$、$C_1 = C_3 = C_4 =$ 1nF, simultaneous four equations and solve the equation set :

$$|U_o|^2 = \frac{0.6283^2 + (3.9478 \times 10^8 C_2)^2}{(3.9478 \times 10^{17} C_2^2 + 1)^2} . \tag{9-1}$$

$$a\tan(\angle U_o) = \frac{0.6283}{3.9478 \times 10^8 C_2} . \tag{9-2}$$

$$|U_a|^2=(\frac{1.24025\times10^{18}C_2^2-1.24025\times10^{8}C_2-9.26091}{1.59802\times10^{19}C_2^2+40.47841})^2+(\frac{7.79272\times10^{18}C_2^2-7.79272\times10^{9}C_2+21.7131}{1.59802\times10^{19}C_2^2+40.47841})^2 \cdot \quad (9\text{-}3)$$

$$a\tan(\angle U_a)=\frac{1.24025\times10^{18}C_2^2-1.24025\times10^{8}C_2-9.26091}{7.79272\times10^{18}C_2^2-7.79272\times10^{9}C_2+21.7131} \cdot \quad (9\text{-}4)$$

When the fault is in R_1,substitute $w=100\pi$、$C_2 \approx C_{20}$=1nF、$R_2=10M\Omega$、$C_1=C_3=C_4=$ 1nF, simultaneous four equations and solve the equation set :

$$|U_o|^2=\frac{(-3.14159\times10^{-7}R_1)^2+(9.8696\times10^{-14}R_1^2)^2}{(9.8696\times10^{-14}R_1^2+1)^2} \quad (10\text{-}1)$$

$$a\tan(\angle U_o)=\frac{3.14159\times10^{-7}}{9.8696\times10^{-14}R_1} \quad (10\text{-}2)$$

$$|U_a|^2=(\frac{-6.20125\times10^{-6}R_1+3.14159}{3.99506\times10^{-12}R_1^2+40.47841})^2+(\frac{9.8696\times10^{-7}R_1+19.7392}{3.99506\times10^{-12}R_1^2+40.47841})^2 \quad (10\text{-}3)$$

$$a\tan(\angle U_a)=\frac{-6.20125\times10^{-6}R_1+3.14159}{9.8696\times10^{-7}R_1^2+19.7392} \quad (10\text{-}4)$$

Solve Eq. 9 and Eq.10. It’s proved when Eq. 9 has real solution, Eq.10 has no real solution.And vice versa.

When the fault is in C_3,substitute $w=100\pi$、$C_1=C_4=$1nF、$R_1=2M\Omega$、$C_2\approx C_{20}$=1nF、$R_2=10M\Omega$,simultaneous two equations and solve the equation set :

$$|U_a|^2=(\frac{-1.81941\times10^{9}C_3-7.44151}{1.3766\times10^{19}C_3^2+2.75319\times10^{10}C_3+15.16075})^2+(\frac{1.37659\times10^{19}C_3^2+9.8696\times10^{9}C_3-1.92244}{1.3766\times10^{19}C_3^2+2.75319\times10^{10}C_3+15.16075})^2 \quad (11\text{-}1)$$

$$a\tan(\angle U_a)=\frac{-1.81941\times10^{9}C_3-7.44151}{1.3766\times10^{19}C_3^2+9.8696\times10^{9}C_3-1.92244} \quad (11\text{-}2)$$

When the fault is in C_4,substitute $w=100\pi$、$C_1=C_3=$1nF、$R_1=2M\Omega$、$C_2\approx C_{20}$=1nF、$R_2=10M\Omega$,simultaneous two equations and solve the equation set :

$$|U_a|^2=(\frac{-6.20125\times10^{18}C_4^2-7.44151\times10^{9}C_4+4.38184}{1.3766\times10^{19}C_4^2+2.75319\times10^{10}C_4+15.16075})^2+(\frac{-3.89636\times10^{18}C_4^2+1.18435\times10^{10}C_4+13.76597}{1.376597\times10^{19}C_4^2+2.75319\times10^{10}C_4+15.16075})^2 \quad (12\text{-}1)$$

$$a\tan(\angle U_a)=\frac{-6.20125\times10^{18}C_4^2-7.44151\times10^{9}C_4+4.38184}{-3.89636\times10^{18}C_4^2+1.18435\times10^{10}C_4+13.76597} \quad (12\text{-}2)$$

When the fault is in R_2,substitute $w=100\pi$、$C_1=C_3=C_4=$1nF、$C_2\approx C_{20}$=1nF、$R_1=2M\Omega$, simultaneous two equations and solve the equation set :

$$|U_a|^2=(\frac{-1.24025\times10^{-13}R_2^2+3.14159\times10^{-7}R_2}{5.50639\times10^{-13}R_2^2+1.39478})^2+(\frac{1.97392\times10^{-13}R_2^2+1.97392\times10^{-7}R_2}{5.50639\times10^{-13}R_2^2+1.39478})^2 \quad (13\text{-}1)$$

$$a\tan(\angle U_a)=\frac{-1.24025\times10^{-13}R_2+3.14159\times10^{-7}}{1.97392\times10^{-13}R_2+1.97392\times10^{-7}} \quad (13\text{-}2)$$

Solve Eq. 11、Eq.12 and Eq.13. It’s proved when Eq. 13(R_2) has real solution, Eq.11(C_3) and Eq.12(C_4) have no real solution. When Eq.11 or Eq.12 has real solution,Eq.13 has no real solution

For the distinguishment of C_3 and C_4,we need to simultaneous Eq.11 and Eq.6 and simultaneous Eq.12 and Eq.7.Then all elements’ single drift fault can be distinguished、located、evaluated.

The result of the fault diagnosis and the analysis

Chapter 3 proves that six elements’ fault location and evaluation can be achieved. Now make six elements in the circuit as a group of certain values.Make the fault diagnosis in the method of the paper. The diagnosis value compared with the true value is shown in Table 2.

Table 2 proves when a single element of six is in drift fault,the fault location can be achieved.In fault evaluation,the evaluation error is almost less than 5% when the drift value goes larger than normal.And the evaluation error can be a little larger ,but still under 10%, when the drift value goes less than normal. Among all elements,the evaluation error of C_3 and C_4 are larger than other elements.Because evaluate the fault of C_3 and C_4 can only use the sign of bridge output U_a.These conclusions are helpful to giving fault characteristic reference and system recovering.

Table 2 The comparison of the fault diagnosis and the true fault value

Element	True fault value	Diagnosis value	Relative error	Element	True fault value	Diagnosis value	Relative error	Element	True fault value	Diagnosis value	Relative error
C_1 [nF]	0.2	0.209	4.50%	R_1 [$M\Omega$]	0.2	0.216	8.00%	C_4 [nF]	0.2	0.232	16.0%
	0.5	0.511	2.20%		1	1.059	5.90%		0.5	0.517	3.40%
	1.5	1.519	1.27%		1.6	1.643	2.69%		1.5	1.549	3.27%
	2	2.052	2.60%		4	4.083	2.08%		2	2.018	0.90%
	3	3.067	2.23%		8	8.098	1.23%		3	3.226	7.53%
C_2 [nF]	0.2	0.220	10.0%	C_3 [nF]	0.2	0.193	-3.50%	R_2 [$M\Omega$]	0.001	0.0011	10.0%
	0.5	0.549	9.80%		0.5	0.488	-2.40%		0.1	0.1034	3.40%
	1.4	1.423	1.64%		1.5	1.446	-3.60%		1	1.064	6.40%
	2	2.021	1.05%		2	1.927	-3.65%		4	4.035	0.88%
	3	3.033	1.10%		3	2.851	-4.97%		8	7.855	-1.81%

Summary

The pressure sensor’s structures、operational principle and relevant parameters are briefly introduced.Analyses the influence for the detected signal under the elements’ s single drift fault quantitatively.The fault can be detected according to the change rate of the pressure.The fault location and fault evaluation can be achieved by detected signal and the extra signal.Substitute the relevant signal value into the corresponding equation set to evaluate the fault value.The diagnosis value is close to the true value by simulation.The error characteristic of fault evaluation is also acquired by the simulation test. In the aspect of reduce the error of fault evaluation and the data processing of the equation set, it still need some further research.

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