

The Effects of Interstitial Media on Thermal Condition Monitoring

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Abstract

The effects of interstitial media on thermal condition monitoring are studied in this paper. Conclusions are drawn from an experimental setup where thermal energy is introduced to the system and results are deduced using the *t*-hypothesis statistical approach. The statistical result can be used in practical monitoring and controlling processes.

1. Introduction

Precise machine condition monitoring systems often monitor temperature to determine the health of a machine. However, due to physical or practical limitations, the temperature of interest cannot be measured directly and must be inferred from temperature measured in another location. An example of this problem is illustrated in Figure 1& 2, where the temperature of a rotating component (rotor) of the mechanical seal face rig was of interest.

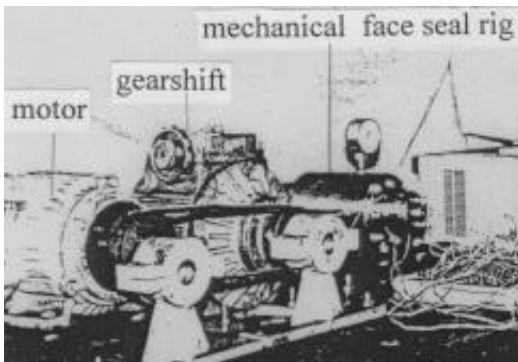


Fig. 1 Test setup for the system

In order to measure the temperature of the rotating member, the thermal information of a stationary ring (stator) which contacted the rotor, was used to reflect the condition of the rotor. However, the mechanics of contact greatly affect the heat flux and temperature distribution and must be investigated to provide accurate health

monitoring. This problem is discussed in detail in this paper.

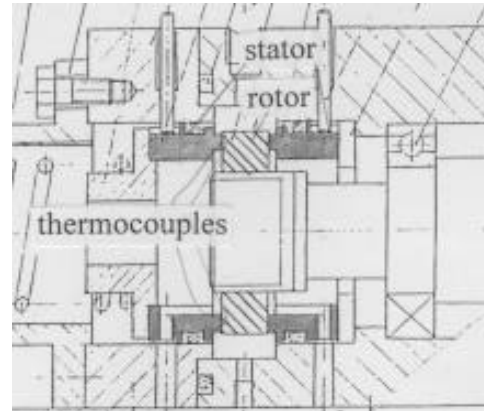


Fig. 2 Schematic of mechanical seal face

2. Effects of Interstitial Media on Thermal Condition Monitoring

The stator and the rotor of the mechanical face seal assembly were modeled in order to study the effects of the interstitial media on the nonlinearity of the temperature rise distribution through the contact face. An experimental setup was developed to verify the results. The rotor shown in Figure 2 was heated to different heat excitation power levels to simulate failure operation modes in the machine. The tests were conducted at 26.8°C and the heat excitation power ranged from 8W to 12W. The rings were made of steel and had a surface roughness of 0.8 μm . Three different interstitial media were examined, including air, No. 32 mechanical oil, and water. The thermal conductivities were 46.5w/m.k for the steel ring, 0.023w/m.k for air, 0.14w/m.k for the mechanical oil, and 0.58w/m.k for water.

For each medium, the temperature rise of the stator and the rotor were monitored, and the degree of nonlinearity in the temperature rise was determined using the *t*-hypothesis test. The hypothesis tested was as follows. The ratio of the

temperature rise of the stator, K_A , and the rotor, K_B , at a fixed time interval, was first estimated by the parameters μ_1 and μ_2 respectively. These parameters were determined from the temperature measurements of the rotor and the stator. Two conditions were then examined, the first being to accept a null hypothesis, H_0 , where $\mu_1 = \mu_2$, and the second to accept an alternative hypothesis, H_1 , where $\mu_1 \neq \mu_2$. The hypothesis test was conducted at a significance level, α .

2.1 t-Hypothesis Test

Hypothesis testing is a procedure where a sample of data is used to choose between two descriptions of the sample population represented by the null hypothesis, H_0 , and the alternative hypothesis, H_1 . The data are examined to see if they are consistent with the null hypothesis, or if they are inconsistent with the null and conform more closely to the alternative hypothesis.

The *t-hypothesis* test was used to test the mean of the normal distribution using samples that are normal. This method is used to determine the nonlinearity of the temperature rise since the normal distribution is a common phenomenon of the physical system. Assuming two independent samples, μ_1 and μ_2 , with normal distributions $N(\mu_1, \sigma_1^2)$ and $N(\mu_2, \sigma_2^2)$, the means of samples are \bar{K}_A and \bar{K}_B , respectively. Similarly, the mean-squares of the sample are s_1^2 and s_2^2 respectively. When σ_1 and σ_2 are unknown, we assume that $\sigma_1 = \sigma_2$ at a significance level α , and that the null hypothesis is $\mu_1 = \mu_2$ and the alternative hypothesis is $\mu_1 \neq \mu_2$. the region of the rejection is:

$$|\bar{K}_A - \bar{K}_B| \geq t_{\frac{\alpha}{2}}(n_1 + n_2 - 2) S_w \sqrt{\frac{1}{n_1} + \frac{1}{n_2}} \quad (1)$$

where

$$S_w^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2} \quad (2)$$

Assuming the upper limit of the probability of $P\{\text{accept } H_0 \mid H_0 \text{ not true}\}$ is 0.2, that is $\beta = 0.2$,

when $\frac{|\mu_1 - \mu_2|}{\sigma} \geq 0.5$, the sample size of 24 is

decided based on the table. So letting $n_1 = n_2 = 24$, we know that

$$\bar{K}_A = \frac{1}{24} \sum_{i=1}^{24} K_{Ai} \quad (3)$$

$$\bar{K}_B = \frac{1}{24} \sum_{i=1}^{24} K_{Bi} \quad (4)$$

$$s_1^2 = \frac{1}{n_1 - 1} \sum_{i=1}^{24} (K_{Ai} - \bar{K}_A)^2 \quad (5)$$

$$s_2^2 = \frac{1}{n_2 - 1} \sum_{i=1}^{24} (K_{Bi} - \bar{K}_B)^2 \quad (6)$$

$$S_w^2 = \frac{s_1^2 + s_2^2}{2} \quad (7)$$

and the region of the rejection is

$$|\bar{K}_A - \bar{K}_B| \geq t_{\frac{\alpha}{2}(2n-2)} S_w \sqrt{\frac{2}{n}} \quad (8)$$

When the significance level, α , is 0.05, the region of rejection is given by

$$|\bar{K}_A - \bar{K}_B| \geq t_{0.025(2n-2)} S_w \sqrt{\frac{2}{n}} \quad (9)$$

2.2 Experimental Setup

Heat power was applied to the machine at two different levels, 8 Watts and 12 Watts. The interstitial media was changed and the temperatures of the two sides of the contacting rings were measured at 1 minute time intervals. The experimental data are shown in Tables 1 – 3 for air, No. 32 mechanical oil, and water, respectively. Among those tables, the first column represents the index of sampling points, the second column is the temperature rise of the stator when the heat power was 8 Watts, the third column is the temperature rise of the stator when the heat power is 12 Watts, the and the fourth column is the ratio of temperature rise,

$K_A = \frac{T_{A12}}{T_{A8}}$, in which we were particularly interested. The fifth column contains the temperature rise of the rotor when the heat power was 8 Watts, the sixth column was the temperature rise of the rotor when the heat power

was 12 Watts, and the seventh column is the ratio of temperature rise $K_B = \frac{T_{B12}}{T_{B8}}$.

T_A			T_B			
	8W	12W		8W	12W	
i	T_{A8}	T_{A12}	K_A	T_{B8}	T_{B12}	K_B
1	4.47	4.55	1.0179	6.11	6.49	1.0622
2	5.17	5.30	1.0251	7.72	8.65	1.1205
3	6.20	6.73	1.0855	9.28	10.46	1.1272
4	7.60	7.88	1.0368	11.03	12.05	1.0925
5	8.80	9.08	1.0318	12.49	13.99	1.1201
6	10.37	10.70	1.0318	13.98	14.86	1.0629
7	11.81	12.21	1.0339	14.68	16.27	1.1083
8	13.24	13.63	1.0295	16.12	17.97	1.1148
9	14.51	14.67	1.0110	17.27	19.55	1.1320
10	15.28	16.14	1.0563	18.79	20.94	1.1144
11	16.54	17.68	1.0689	19.99	22.60	1.1306
12	17.74	19.06	1.0744	21.12	23.95	1.1340
13	19.22	20.78	1.0812	22.56	25.23	1.1184
14	20.40	22.10	1.0833	23.65	26.70	1.1290
15	21.67	23.10	1.0660	24.86	28.08	1.1295
16	22.98	24.02	1.0453	26.10	29.37	1.1253
17	24.06	25.39	1.0553	27.18	30.77	1.1321
18	25.27	26.99	1.0681	28.27	31.97	1.1309
19	26.49	28.72	1.0842	29.37	33.10	1.1270
20	27.56	30.14	1.0936	30.35	34.42	1.1341
21	28.66	31.58	1.1019	31.37	35.51	1.1320
22	29.82	32.31	1.0835	32.39	37.72	1.1646
23	30.90	34.51	1.1168	33.46	38.79	1.1593
24	31.86	35.95	1.1171	34.34	39.60	1.1532

Table 1 The temperature rise where the interstitial media was air

T_A			T_B			
	8W	12w		8w	12w	
i	T_{A8}	T_{A12}	K_A	T_{B8}	T_{B12}	K_B
1	1.79	2.96	1.6536	3.06	4.37	1.4281
2	2.77	3.47	1.2527	3.70	5.30	1.4324
3	3.41	4.71	1.3812	5.07	7.22	1.4241
4	3.89	6.26	1.6093	5.82	8.77	1.5069
5	5.98	8.41	1.4064	7.92	10.91	1.3775
6	6.04	10.22	1.6921	11.12	12.62	1.1349
7	9.36	11.81	1.2618	11.28	14.10	1.2500
8	10.33	13.77	1.3330	12.06	15.32	1.2703
9	13.61	14.74	1.0830	14.87	16.91	1.1372
10	13.10	16.16	1.2336	14.23	18.21	1.2797
11	14.14	18.02	1.2744	15.09	19.90	1.3188
12	14.89	19.57	1.3143	16.32	21.30	1.3051
13	16.03	20.72	1.2926	17.31	22.57	1.3039

14	16.65	22.25	1.3363	18.72	24.05	1.2847
15	18.68	24.02	1.2859	20.46	25.52	1.2473
16	20.26	24.99	1.2335	20.86	26.69	1.2795
17	20.45	26.60	1.3007	22.86	28.12	1.2301
18	22.21	27.81	1.2521	23.83	29.41	1.2342
19	22.97	29.06	1.2651	24.93	30.74	1.2331
20	24.20	30.53	1.2616	26.23	32.23	1.2287
21	25.12	31.76	1.2643	27.13	33.58	1.2377
22	26.18	33.05	1.2624	28.30	34.59	1.2223
23	27.36	34.53	1.2621	28.81	36.40	1.2635
24	28.26	35.62	1.2604	29.89	37.95	1.2697

Table 2 The temperature rise where the interstitial media was mechanical oil

T_A			T_B			
	8W	12W		8W	12W	
i	T_{A8}	T_{A12}	K_A	T_{B8}	T_{B12}	K_B
1	4.40	4.20	0.9545	5.74	6.29	1.0958
2	5.56	6.32	1.1367	7.08	8.25	1.1653
3	6.86	8.21	1.1968	8.36	10.07	1.2045
4	8.13	9.92	1.2202	9.58	11.72	1.2234
5	9.47	12.05	1.2724	10.76	13.57	1.2612
6	10.59	13.75	1.2984	12.20	14.58	1.1951
7	11.88	14.58	1.2273	13.26	15.78	1.1900
8	12.91	16.28	1.2610	14.15	17.45	1.2332
9	14.03	17.91	1.2766	14.41	19.05	1.3220
10	14.47	19.21	1.3276	15.46	20.46	1.3234
11	15.18	20.67	1.3617	16.66	21.79	1.3079
12	16.16	22.10	1.3676	17.56	23.09	1.3149
13	16.99	23.33	1.3732	18.23	24.20	1.3275
14	18.12	24.76	1.3664	19.25	25.28	1.3132
15	18.85	26.01	1.3798	20.06	26.72	1.3320
16	19.57	27.47	1.4037	20.80	27.83	1.3380
17	20.31	28.78	1.4170	21.47	29.06	1.3535
18	21.16	30.07	1.4211	22.21	30.20	1.3597
19	21.88	30.60	1.3985	22.78	30.94	1.3582
20	22.56	32.03	1.4198	23.51	32.33	1.3752
21	23.02	33.25	1.4444	23.92	33.25	1.3901
22	23.64	33.68	1.4247	24.53	33.88	1.3812
23	24.37	34.83	1.4292	25.16	35.01	1.3915
24	24.74	36.74	1.4850	25.57	35.92	1.4048

Table 3 The temperature rise where the interstitial media was water

2.3 The Linearity Research on the Temperature Rise of the Contact Face

The goal of the project was to use the *t-hypothesis* test to determine whether the estimations of K_{Air} and K_{Bair} , K_{Aoil} and

K_{Boil} , and K_{Awater} and K_{Bwater} were equal. The hypothesis to be tested was, at the significance level, α , whether to accept the null hypothesis $H_0 : \mu_1 = \mu_2$, or the alternative hypothesis, $H_1 : \mu_1 \neq \mu_2$. In both cases, μ_1 and μ_2 were the estimations of K_A and K_B , respectively.

From table 1, we knew $\overline{K_{Air}} = 1.0625$, $\overline{K_{Bair}} = 1.1231$, $S_{Air}^2 = 0.0006$, $S_{Bair}^2 = 0.0198$ and $S_{\omega}^2 = 0.85$, so the region of rejection was $|\overline{K_{Air}} - \overline{K_{Bair}}| \geq 0.01694$ (10)

But $|\overline{K_{Air}} - \overline{K_{Bair}}| = 0.0606 > 0.01694$, so it was in the region of rejection. Therefore, when $\alpha = 0.05$, we rejected the null hypothesis, indicating that there was a thermal nonlinear relationship of the temperature rise between the contact face when the interstitial media was air.

From table 2, $\overline{K_{Aoil}} = 1.3238$, $\overline{K_{Boil}} = 1.2875$, $S_{Aoil}^2 = 0.0198$, $S_{Boil}^2 = 0.0081$ and $S_{\omega}^2 = 0.01395$, so the region of rejection was $|\overline{K_{Aoil}} - \overline{K_{Boil}}| \geq 0.06864$ (11)

This time, $|\overline{K_{Aoil}} - \overline{K_{Boil}}| = 0.0363 < 0.06864$, so it was out of the region of rejection. It was therefore concluded that, when $\alpha = 0.05$, the null hypothesis was valid and the thermal relationship of the temperature rise was linear when the interstitial media was mechanical oil.

Finally, Table 3 shows that $\overline{K_{AWater}} = 1.3277$, $\overline{K_{BWater}} = 1.2984$, $S_{AWater}^2 = 0.0154$, $S_{BWater}^2 = 0.0074$ and $S_{\omega}^2 = 0.0114$, so the region of rejection was $|\overline{K_{AWater}} - \overline{K_{BWater}}| \geq 0.06205$ (12)

Again, $|\overline{K_{AWater}} - \overline{K_{BWater}}| = 0.0293 < 0.06205$, so it was out of the region of rejection. It was therefore concluded that for $\alpha = 0.05$, the null hypothesis was valid and that the temperature rise was linear between the contact face when the interstitial media was water.

The thermal conduction of the contact face was related to the thermal conductivity of the interstitial media and the thickness of the interstitial media. The thickness of the media was dependent on the roughness, geometrical accuracy, and contact pressure of the contact face. In our experiments, the thermal conductivity of the steel ring was $K = 46.5 \text{ w/m.k}$, of the air 0.023 w/m.k , of the mechanical oil 0.14 w/m.k , and of the water 0.58 w/m.k . The thermal conductivities of the oil and water were much smaller than that of the steel ring, although still an order of magnitude greater than that of air.

3. Conclusions:

Several conclusions have been reached and are listed below.

- (1) The thermal conduction of the contact face is dependent on the thermal conductivity of the interstitial media and the thickness of the interstitial media. The interstitial media thickness is in turn dependent on the ring roughness, geometric accuracy, and the contact pressure of the contact face.
- (2) At the specified roughness and normal working conditions, the heat transfer is nonlinear when the interstitial media is air, but it is linear when the interstitial media is mechanical oil or water.
- (3) When the interstitial media is mechanical oil or water, we can monitor the temperature rise of one side of the contact face and accurately predict the thermal condition of the other side.
- (4) When the interstitial media is mechanical oil or water, thermal excitation can be applied on one side of the contact face to predictably control the temperature distribution of the other side.

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