BEARINGS FOR WEB-DRIVEN ROLLERS

By

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BEARINGS FOR WEB-DRIVEN ROLLERS

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

C_o Basic static load rating $[kg]$

d_o Pitch–circle diameter of the set of rolling element [mm]

F_a Axial component of dynamic bearing load $[kg]$

F_r Radial component of dynamic bearing load $[kg]$

f_1 Factor depending on bearing design and load

f_o Factor depending on bearing design and lubrication method

M_o Friction torque affected by lubricant $[kg \cdot mm]$

M_I Friction torque for bearing I $[kg \cdot mm]$

M_{II} Friction torque for bearing II $[kg \cdot mm]$

M_t Friction torque influenced on two bearings $[kg \cdot mm]$

$M_{\exp}$ Friction torque for experiment $[kg \cdot mm]$

M_{load} Friction torque in case of load-dependent $[kg \cdot mm]$

P_o Static equivalent bearing load $[kg]$

P_1 Load ruling M_{load} $[kg]$

p Difference between atmospheric pressure and the vaporization pressure of the oil $[kg / mm^2]$

ω Angular velocity of the bearing rings in relation to each other $[rad/sec]$

X_o Radial load factor for the bearing

Y_o Axial load factor for the bearing

η Dynamic viscosity of the lubricant $[kg \cdot sec / mm^2]$

CHAPTER I

INTRODUCTION

1.1 Definition of the Problem

The following experiments have been focused on the relationship between the applied load, the rotating speed, and the lubricants. Bearing manufacturer and design texts are primarily concerned with loads consistent with reasonable fatigue life of the bearing. The relationship of the turning torque of oil and grease lubricated bearings are considered. However, drag from seals and lubricants may be greater than the drag from loading of bearings in idlers, where size is often determined by design for accidents and malfunction, not by the operating load. The design of an entire process line may hinge on the choice between dead-shaft and live-shaft idlers, and this choice may be determined by the turning torque as a function of the type of bearing, type of seal, and lubrication. Avoiding scratching the web is important. If the thickness of the entrained air at the roller surface is large, then the turning torque of bearings is important in avoiding scratching the web.

1.2 Objectives of the Study

The major objectives of this study are

(1) To determine the turning torque over a wide range of mounted bearing assemblies as a function of load, rotating speed and viscosity of the lubricants used.

(2) These experiments will be done on readily available commercial bearings.

(3) To recommend lubricants and lubrication procedures for minimizing the turning torque

(4) To develop an understanding of the mechanism of friction torque of rolling element bearings at lightly loaded conditions.

1.3 Methods of Approach

In order to avoid repetition of prior work and to ensure an appropriate method of mounting and acceptable lubrication of the bearings, a review of technical papers and literature created by bearing manufacturers was done. A test stand was laid out and built. A variable-speed motor was used to drive the bearing shaft, and a method for loading and measuring friction torque was developed. A Palmgren equation, Eq (0.1), will be introduced for comparison with experimental results to test whether the results can be reliable and predictable.

CHAPTER II

LITERATURE REVIEW

2.1 Friction Torque

Friction torque is one of the most significant characteristics of ball bearings to be considered in the field of web handling. The rotating speed, load, and the viscosity are common factors causing the friction torque to change.

Effect of Rotating Speed

Mabie (1965) [4] performed high speed torque tests with several bearings such as R2, R3, and R4 ball bearings lubricated with MIL-L-6085A oil and MIL-G-3278A grease over a speed range of 1,000 to 40,000 rpm at ambient temperature. The conclusion is based on the experimental observation that the rotating speed does not correlate with the speed of the retainer. Lindeman (1966) [2] tested size 204 ball bearing with small radial and axial loads to find the characteristics of friction torque at rotating speeds from 1 to 10,000 rpm. It was noted that the friction torque at high speed is proportional to spindle speed at $250^o F$, while it does not increase linearly with speed at temperatures ranging from $80^o F$ to $160^o F$.

Effect of Load

Wikström and Höglund (1995) [7] studied friction torque of rolling element bearings lubricated by grease at low temperatures. They attempted to classify the parameters affecting the friction torque and concluded that the load is a trivial parameter. Lawrence (1996) [3] also observed the effect of load applied to R-2 and R-3 size ball bearings. At all test conditions, considering all tested greases and cage shapes, the thrust load ranging from 1 to 3 pounds did not remarkably change the magnitude of friction torque.

Effect of Viscosity

Styri (1940) [6] presented summaries showing that for a low viscosity lubricant, the rotating speed has a small effect on the torque, but on the other hand for a high viscosity lubricant, the torque increases with rotating speed.

CHAPTER III

EXPERIMENTS

3.1 Experimental Setup

Test Setup for Grease-Lubricated Bearings

Some parts of the apparatus for performing a grease-lubricated bearings test have been changed as desired. Figure 2 shows the setup for grease-lubricated bearings such as ER16 MKFF, ER20S MKFF, and ER24 MKFF manufactured by MB. The test bearing mounted in the test block was fixed by a screw. A steel shaft thirty inches in length with a $1\frac{7}{16}$ inch diameter is shown in Figure 2. Two single row deep groove ball bearings manufactured by SKF have been used for supporting the driven shaft. To set the equilibrium position of the mounting block, two rectangular aluminum balancing masses, which are mounted on the extension rods on both sides, two (2) inches wide, two (2) inches in height and 1.3 inches deep were used. One of the balancing masses is not moved throughout the whole test period and held at a fixed radial position from the center, while the other's position being able to be adjusted is changed to set the pillow block at an equilibrium state by rotating the plate as shown in Figure 1. In order to indicate the distance of the balancing mass, a circular flat plate attached to the balancing mass was designed to have seventy two (72), five degree (5^o) segment lines. The actual distance of each segment is equal to $(5^o/360 \cdot 1/13)'' = 0.001068''$ along the extension rod. For example, if the 111 segments are rotated, the actual distance of balancing mass along the extension rod is equal to $0.001068'' \cdot 111 = 0.119''$. The test bearing is mounted on the shaft and can be readily changed to various sizes of bearings. The shaft inserted into pillow block bearings I and II, and had two machined diameters at the extremity to mount the smaller bearings. The greased bearing inserted into the mounting block is driven by an electric motor. The electric motor is powered by an external power supply through the line cord. It is coupled to a driven shaft by a timing belt.

Motor specifications:

Manufacturer: GE Motors & Industrial System

Type	: D-C motor
HP	: 1/4
RPM	: 1725
Volt	: 90
AMP	: 3

For measuring the spindle speed, a tachometer with an indicator was connected to the motor shaft. The control panel controls spindle speed. Temperature is one of the major factors to be taken into consideration in the test. However, the thermocouple to measure the temperature of oil near the outer race of bearing has not been equipped yet.

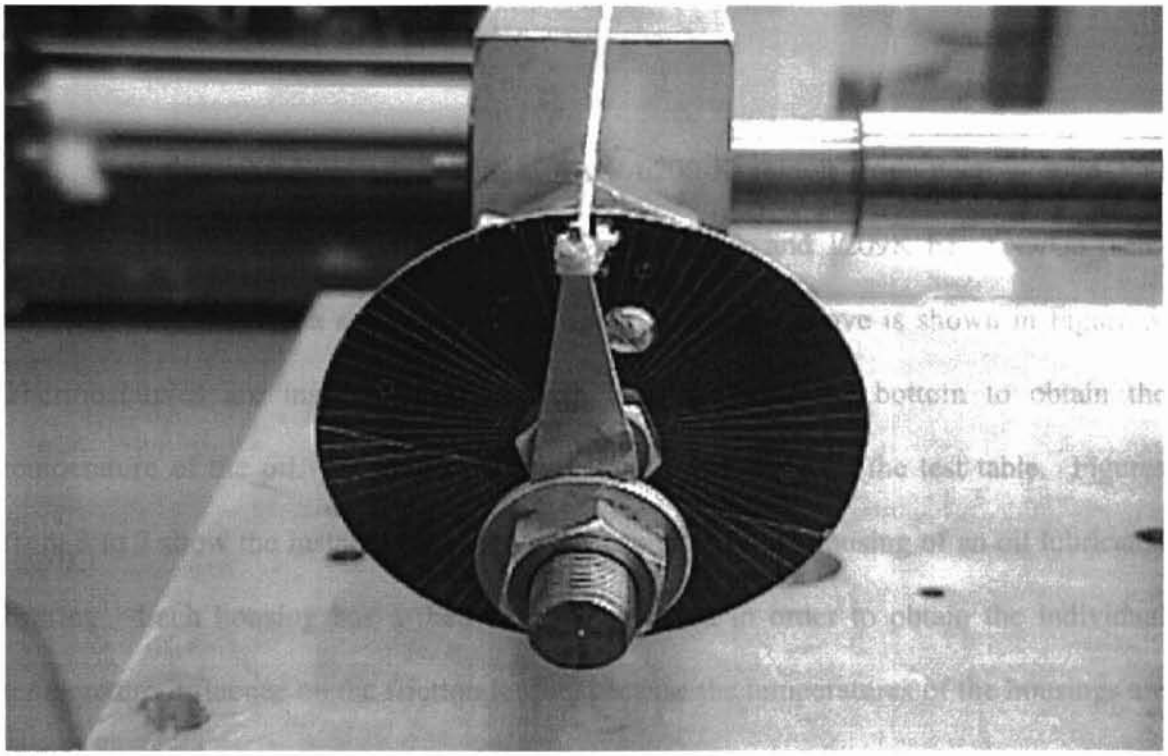

Figure 1. The device for measuring distance of balancing mass

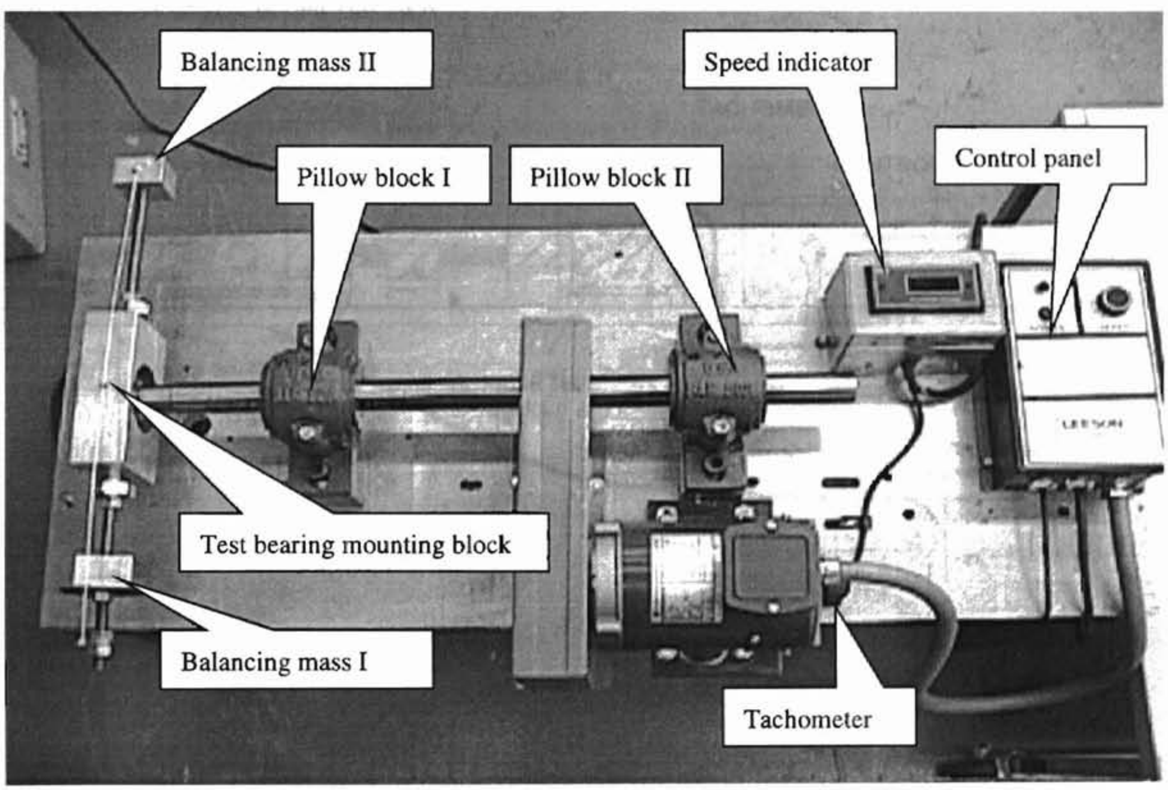

Figure 2. Test Setup 1

Test Setup for Oil-lubricated Bearings

For the oil-lubricated bearings, 6AK 6209-K (single row deep groove ball bearing), 22209 CCK/C3W33 (spherical roller bearing), and 1209K EK TN9/C3 (self-aligning ball bearing), a schematic of the setup mentioned above is shown in Figure 3. Thermocouples are installed through both housings near the bottom to obtain the temperature of the oil. The temperature readout is installed on the test table. Figures from 3 to 7 show the installation of the thermocouples in the housing of an oil lubricated bearing. Each housing has a thermocouple installed in order to obtain the individual temperature influence on the friction torque, because the temperatures of the housings are different.

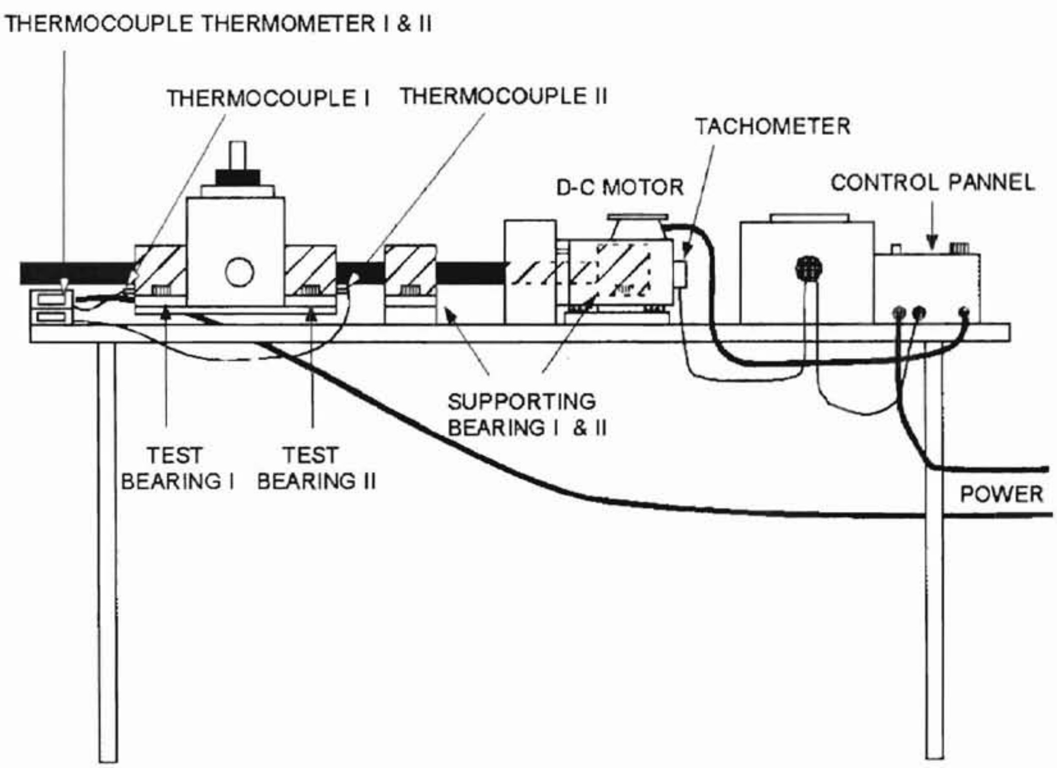

Figure 3. Schematic of test rig for oil-lubricated bearing

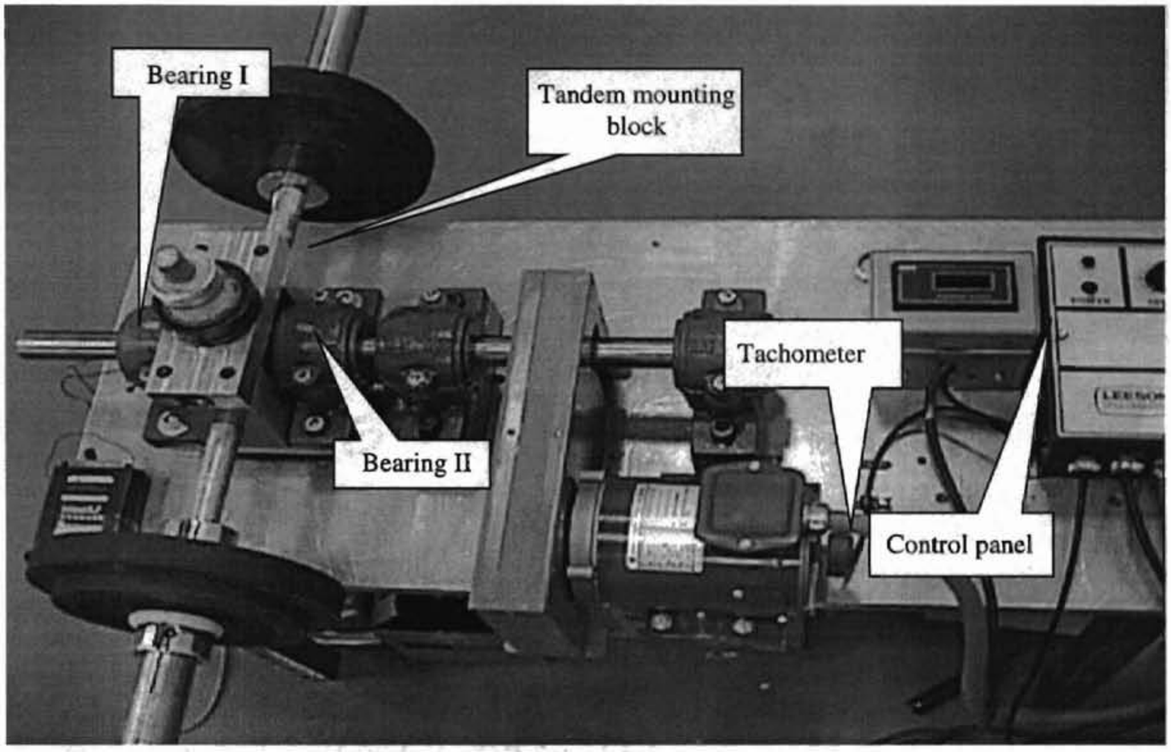

Figure 4. Test Setup 2

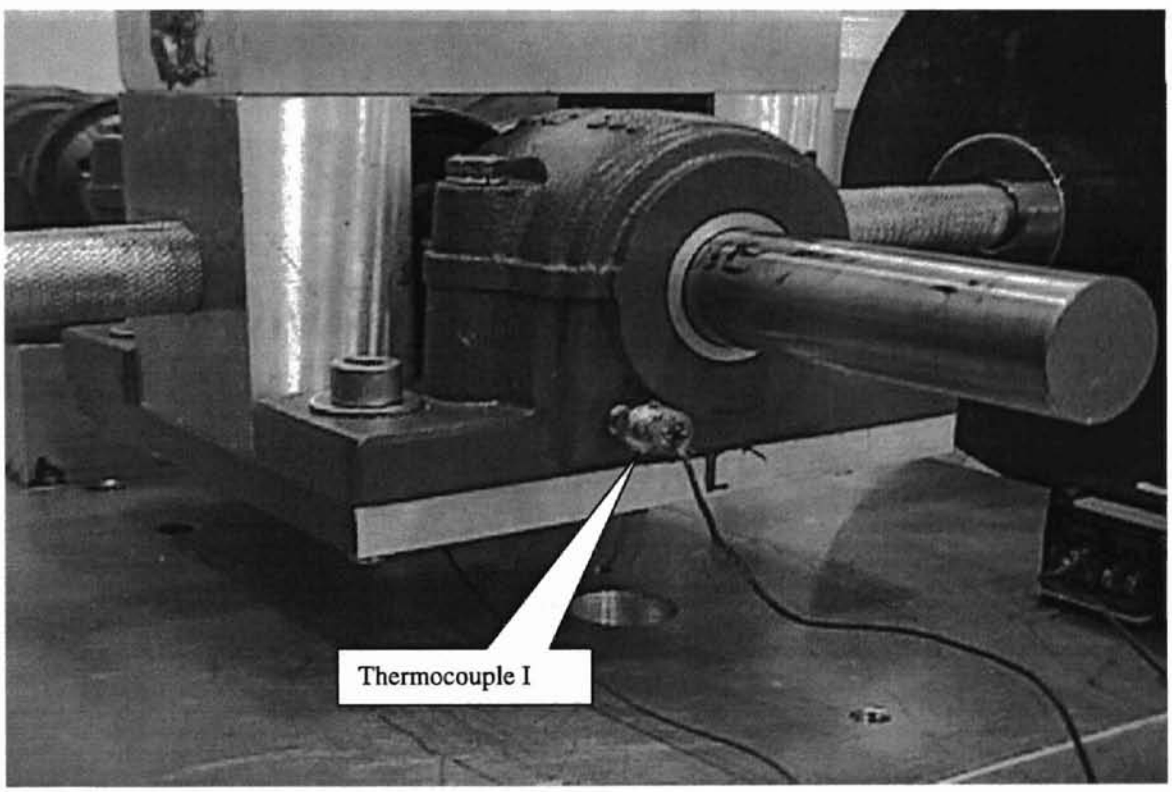

Figure 5. Installation of thermocouple I

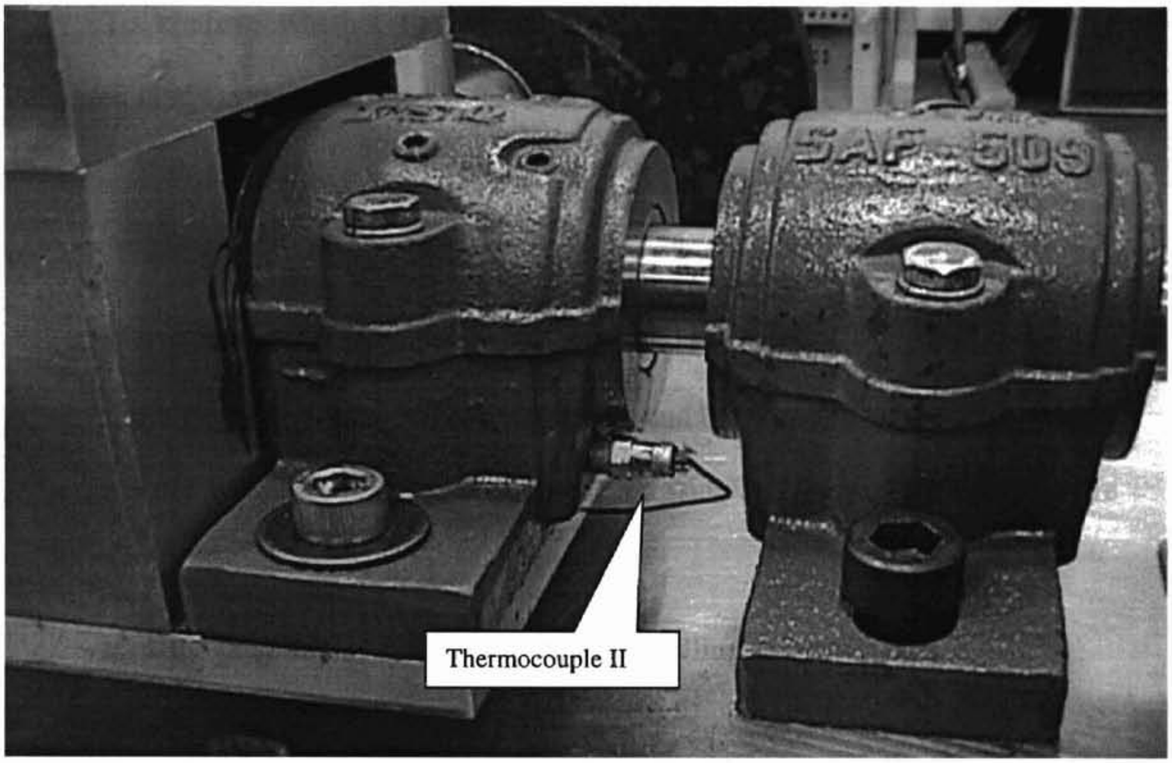

Figure 6. Installation of thermocouple II

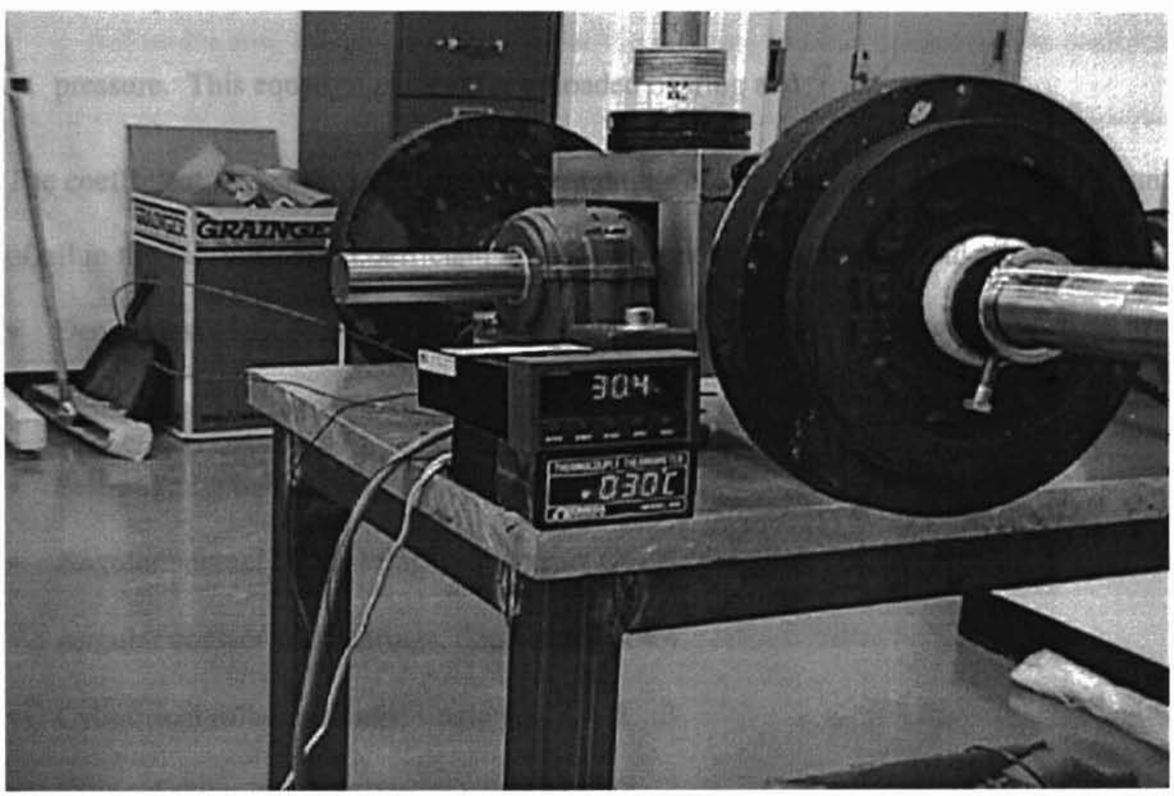

Figure 7. Installation of thermometer display

To confirm whether the experimental result was reliable, an equation from Palmgren (1954) [5] was studied:

$$M_0 = f_0 \times p \times d_m^{\ 3} \times (\eta \times \omega / p)^{2/3} \text{ [kg-mm]} \qquad \text{Eq (0.1)}$$

Where,

M_0 = a friction torque effected by lubricant, $[kg \cdot mm]$

f_o = a factor depending on bearing design and lubrication method

p = the difference between atmospheric pressure and the vaporization pressure of the oil, $[kg / mm^2]$

d_m = the pitch-circle diameter of the set of rolling element, [*mm*]

η = the dynamic viscosity of the lubricant, $[kg \cdot sec / mm^2]$

ω = the angular velocity of the bearing rings in relation to each other, [*rad/sec*]

- The vaporization pressure is so low that p can be put equal to the atmospheric pressure. This equation is valid for unloaded bearing and $\eta \cdot \omega / p = 2 \cdot 10^{-6}$.

The coefficient f_o is specified as a dependent on the bearing identification and the amount of oil in the bearing. This coefficient is used corresponding to the particular bearings.

- Deep groove ball bearings, single row f_o = 1.5…2
- Filling slot ball bearings, single row f_o = 2
- Self-aligning ball bearings, double row f_o = 1.5…2
- Angular contact ball bearings, single row f_o = 2
- Angular contact ball bearings, double row f_o = 4
- Cylindrical roller bearings, single row f_o = 2…3
- Tapered roller bearings, single row f_o = 3…4

- Spherical roller bearings, double row $f_o = 4 \ldots 6$
- Thrust ball bearing $f_o = 1.5 \ldots 2$
- Spherical roller thrust bearings $f_o = 3 \ldots 4$

3.2 Experimental Procedure (Oil-Lubricated Bearings)

Calibration of the thermometers was performed before the test. When two wires composed of dissimilar metals, Iron and Constantan, are welded at the ends and the two ends are at different temperatures, there is a continuous current in the circuit. In order to obtain the reference temperature, ice water and boiling water were used at $0^o C$ and $100^o C$, respectively. In this procedure the Iron-Constantan thermocouple is connected to a digital readout.

Before the run, the center of gravity of the pivoting bearing assembly was centered on the center of the shaft, to ensure that the state is neutrally stable. The measured torque should not have any additional torque caused by a change of angle of the pivoting assembly. The test oil was added to the housing up to the center of the bottom ball.

(1) The equilibrium position of the balancing mass was set without running the motor.

(2) The motor was run at a desired rotating speed such as 1000 rpm, 2000 rpm and 3000 rpm and the time was recorded.

(3) The balancing mass was moved to find its new location for equilibrium, and the location of the mass, time, spindle speed and temperature were recorded.

(4) The spindle speed was adjusted if it had changed from the desired speed.

(5) Steps 3 and 4 were repeated every 5 minutes for the first one hour of testing.

(6) Data was taken following steps 3 and 4 with 20 minutes of time interval for two more hours.

(7) Data was sometimes taken for longer periods with different time intervals.

3.3 Results

In most tests, a high startup torque has been observed. The friction torque at startup is relatively high because of the low temperature, resulting in a high lubricant viscosity and a high shear stress. The following two figures (referred to V. Wikström and E. Höglund [8]) show, the behavior of viscosity with changing temperature and type of oil.

V. Wikström and E. Höglund said "If a high friction torque was registered at start-up, it means that also the shear stresses in the grease were high during the starting".

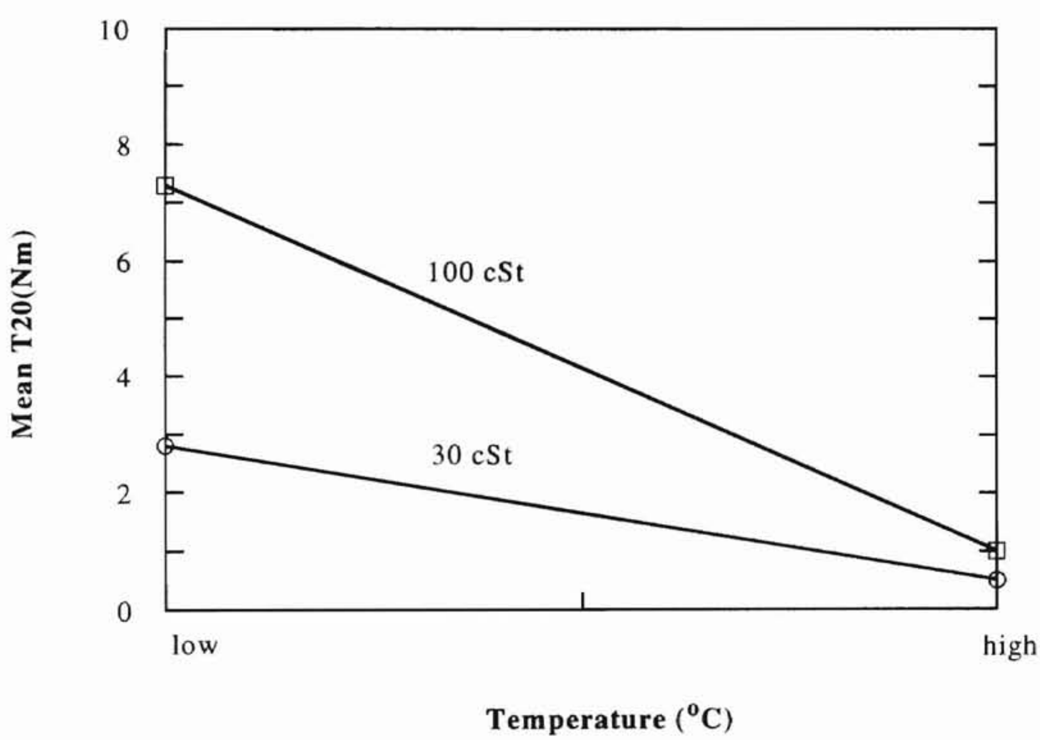

Figure 8. Viscosity-temperature effect

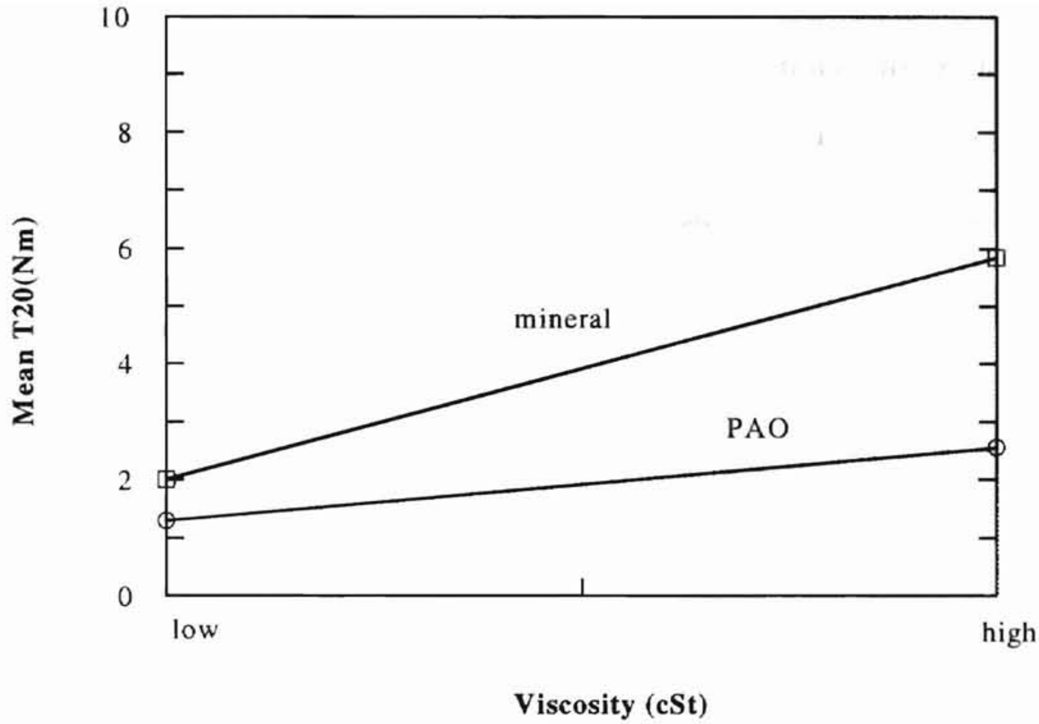

Figure 9. Viscosity and oil type effect

3.3.1 Results for Grease-Lubricated Ball Type Bearings

In order to find the effect of the bearing sizes, three sizes of grease-lubricated bearings were used. The following figures show the effect of rotating speed on the friction torque for the bearings lubricated with grease. These tests were run at a very light load at speeds ranging from 1000 to 3000 rpm.

3.3.1.1 ER16 MKFF, MB

Figure 10 shows the effect of increasing temperature of the grease on the torque of the bearing, ER16 MKFF, at 1000 rpm at room temperature and also shows that the start-up torque was observed for the first 30 to 60 minutes before the steady state torque was reached. During about 45 minutes, the torque dropped from 0.08 $lb \cdot in$ to 0.065 $lb \cdot in$, then slowly converged to the steady state. According to Figure 13, the effect of rotating was not predictable, with much scattering of data. It is suspected that the non-negligible vibration caused the friction torque data to be scattered.

Table 1. Effect of the elapsed time on bearing friction torque

Unloaded condition		
Time elapsed (min)	* Displacement (in)	Measured torque (lbf*in)
5	0.114	0.074
10	0.123	0.080
15	0.107	0.069
20	0.104	0.067
25	0.099	0.065
30	0.097	0.063
35	0.101	0.066
40	0.098	0.064
45	0.098	0.064
50	0.099	0.065
55	0.099	0.065
60	0.098	0.064
80	0.098	0.064
100	0.099	0.065
120	0.098	0.064
140	0.099	0.065
160	0.099	0.065
180	0.097	0.063

* Rotation of the 0.65 lb balancing mass in increment of 5 degree on ½-13 threaded rod.
Test date: 09/05/98

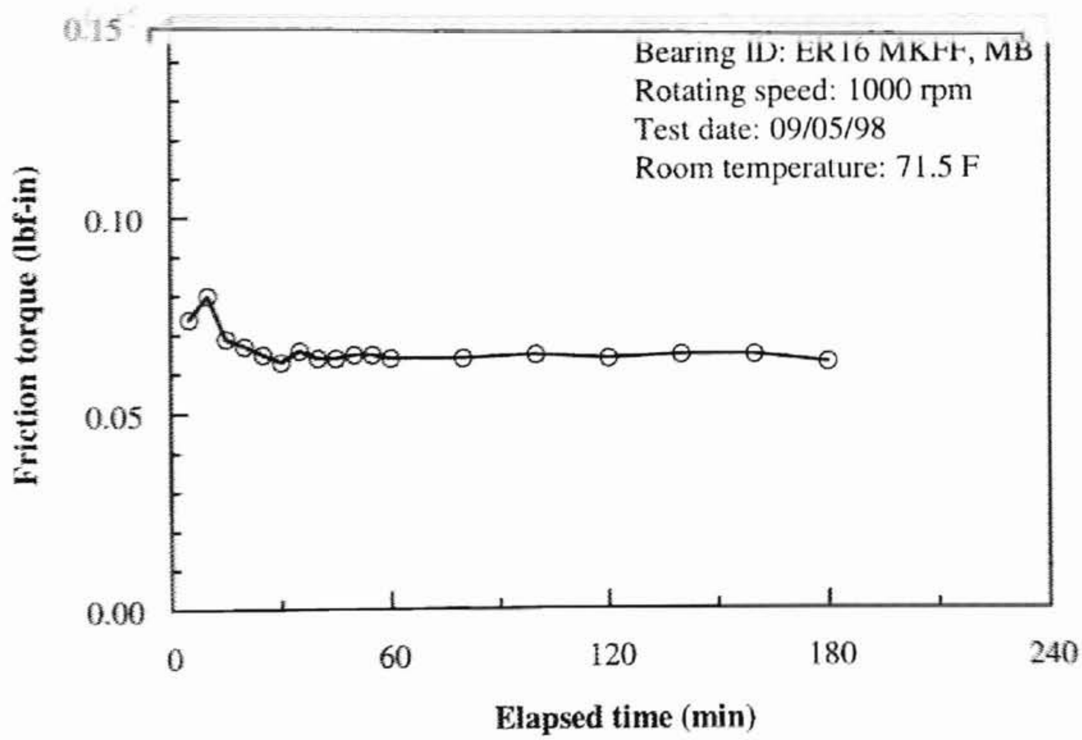

Figure 10. Effect of the elapsed time on bearing friction torque

Table 1. Effect of the elapsed time on bearing friction torque

Unloaded condition		
Time elapsed (min)	* Displacement (in)	Measured torque (lbf*in)
5	0.114	0.074
10	0.123	0.080
15	0.107	0.069
20	0.104	0.067
25	0.099	0.065
30	0.097	0.063
35	0.101	0.066
40	0.098	0.064
45	0.098	0.064
50	0.099	0.065
55	0.099	0.065
60	0.098	0.064
80	0.098	0.064
100	0.099	0.065
120	0.098	0.064
140	0.099	0.065
160	0.099	0.065
180	0.097	0.063

* Rotation of the 0.65 lb balancing mass in increment of 5 degree on ½-13 threaded rod.
Test date: 09/05/98

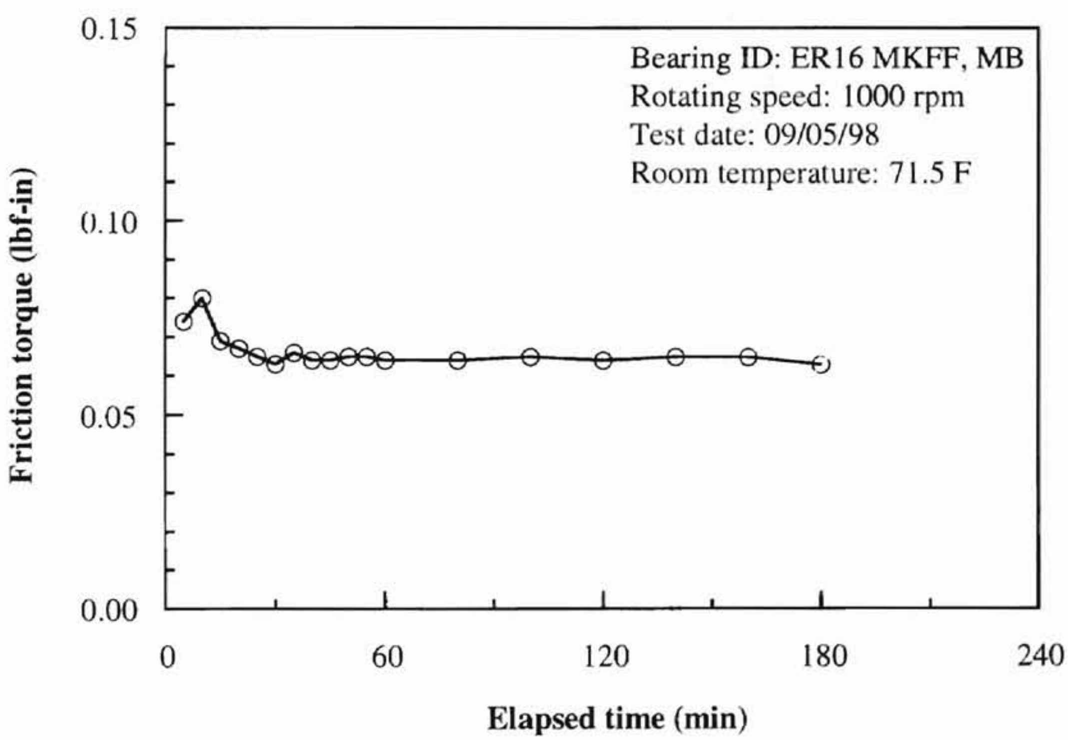

Figure 10. Effect of the elapsed time on bearing friction torque

Table 2. Effect of the elapsed time on bearing friction torque

Unloaded condition		
Time elapsed (min)	* Displacement (in)	Measured torque (lbf*in)
5	0.119	0.077
10	0.114	0.074
15	0.109	0.071
20	0.104	0.067
25	0.099	0.065
30	0.093	0.060
60	0.098	0.064
90	0.090	0.058
120	0.085	0.056
150	0.095	0.062
180	0.097	0.063
210	0.106	0.069
240	0.094	0.061

* Rotation of the 0.65 lb balancing mass in increment of 5 degree on ½-13 threaded rod.
Test date: 09/06/98

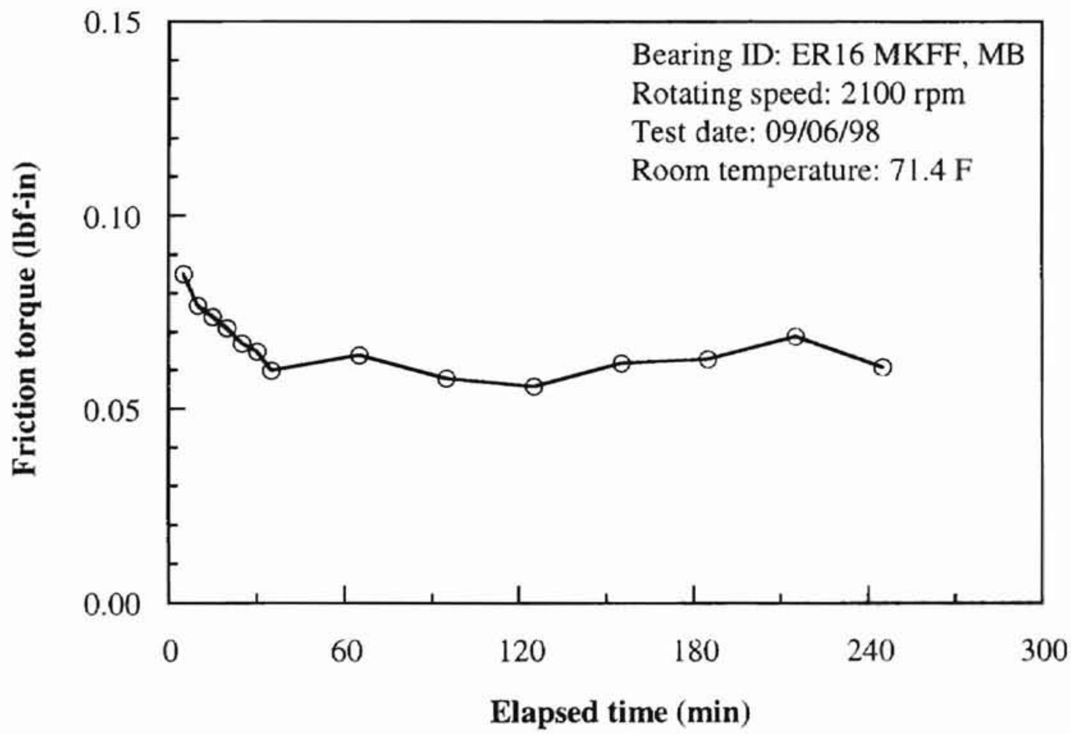

Figure 11. Effect of the elapsed time on bearing friction torque

Table 3. Effect of the elapsed time on bearing friction torque

Unloaded condition		
Time elapsed (min)	* Displacement (in)	Measured torque (lbf*in)
10	0.192	0.125
18	0.149	0.097
24	0.123	0.080
30	0.088	0.057
36	0.109	0.071
41	0.058	0.038
47	0.051	0.033
460	0.035	0.023
493	0.045	0.029
523	0.044	0.028
553	0.056	0.036
583	0.049	0.032

* Rotation of the 0.65 lb balancing mass in increment of 5 degree on ½-13 threaded rod.
Test date: 09/14/98

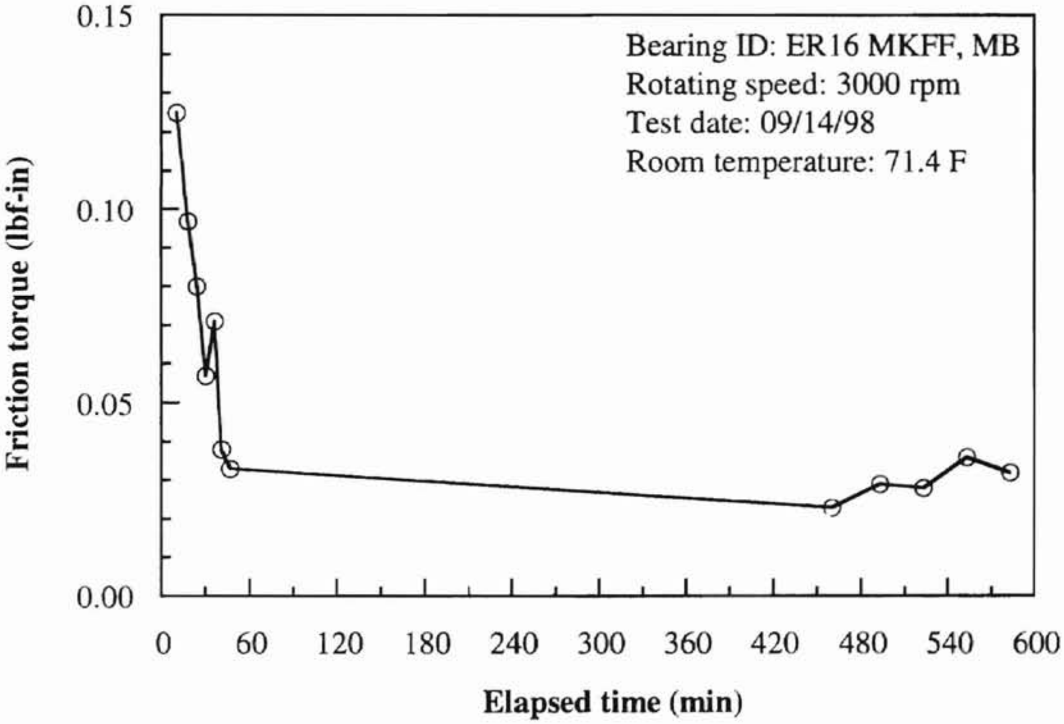

Figure 12. Effect of the elapsed time on bearing friction torque

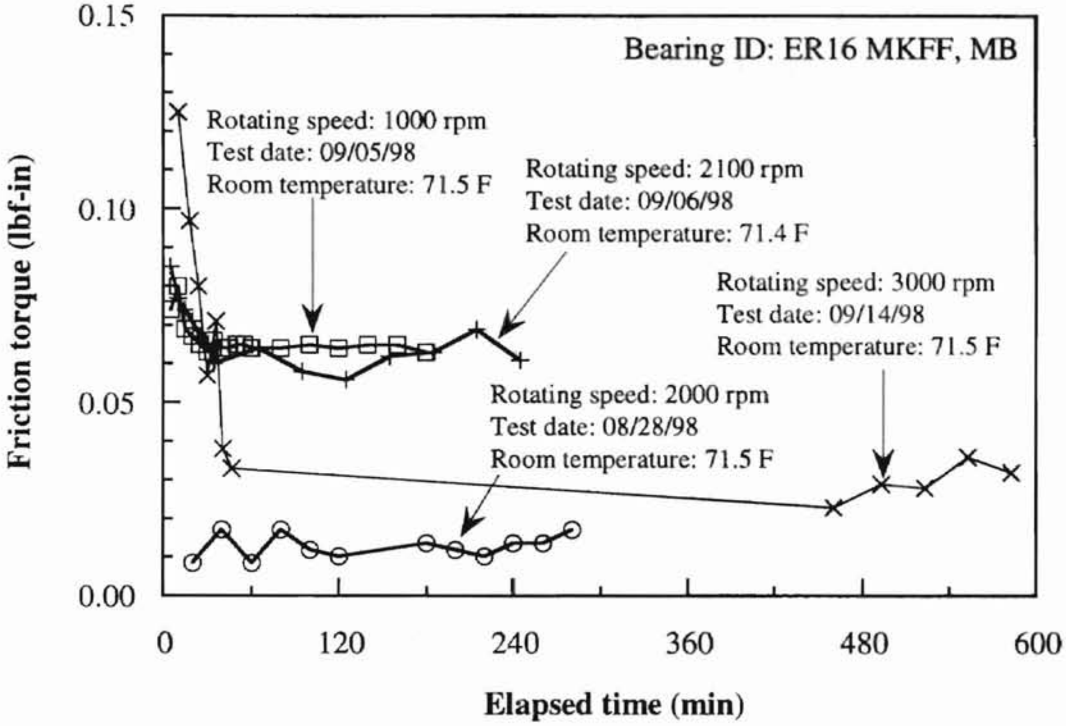

Figure 13. Effect of the elapsed time and speed on bearing friction torque

3.3.1.2 ER20S MKFF, MB

Table 4. Effect of the elapsed time on bearing friction torque

Unloaded condition		
Time elapsed (min)	* Displacement (in)	Measured torque (lbf*in)
8	0.194	0.126
13	0.162	0.106
18	0.143	0.093
25	0.127	0.083
30	0.128	0.083
36	0.121	0.078
41	0.121	0.078
47	0.113	0.074
57	0.107	0.069
78	0.101	0.066
111	0.100	0.065
131	0.099	0.065
151	0.096	0.063
171	0.099	0.065

* Rotation of the 0.65 lb balancing mass in increment of 5 degree on ½-13 threaded rod.
Test date: 09/17/98

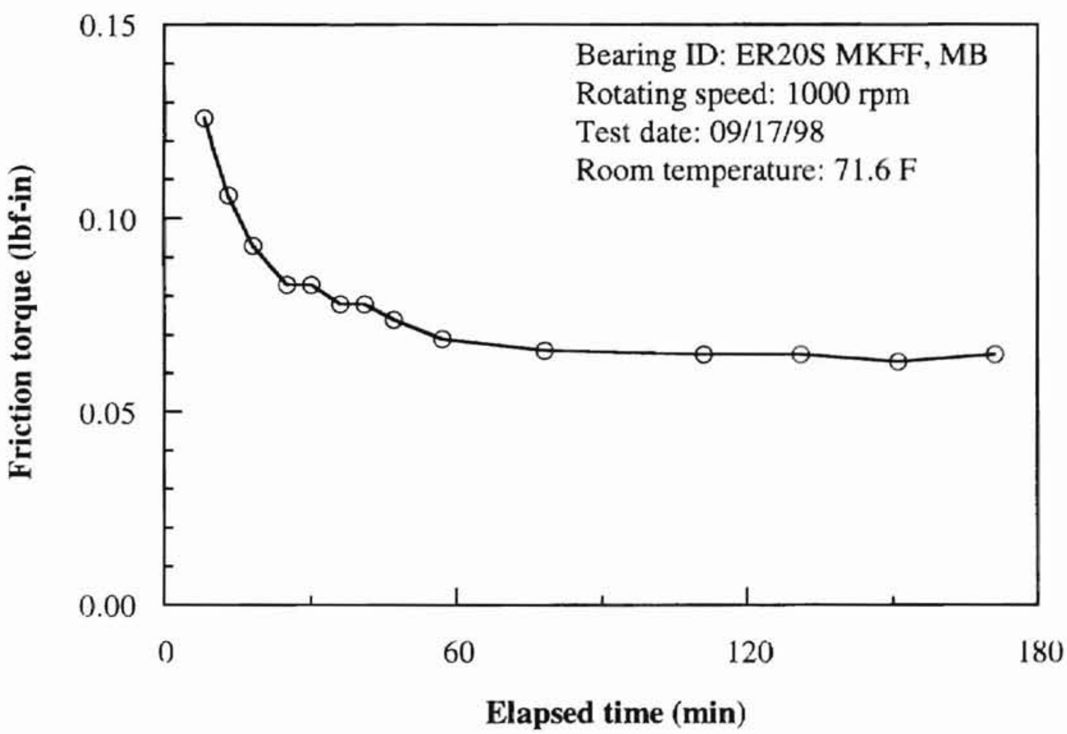

Figure 14. Effect of the elapsed time on bearing friction torque

Table 5. Effect of the elapsed time on bearing friction torque

Unloaded condition		
Time elapsed (min)	* Displacement (in)	Measured torque (lbf*in)
10	0.134	0.087
16	0.109	0.071
28	0.098	0.064
125	0.089	0.058
165	0.095	0.062
187	0.062	0.040
200	0.065	0.042
215	0.048	0.031
230	0.050	0.033
245	0.049	0.032
270	0.054	0.035

* Rotation of the 0.65 lb balancing mass in increment of 5 degree on ½-13 threaded rod.
Test date: 09/18/98

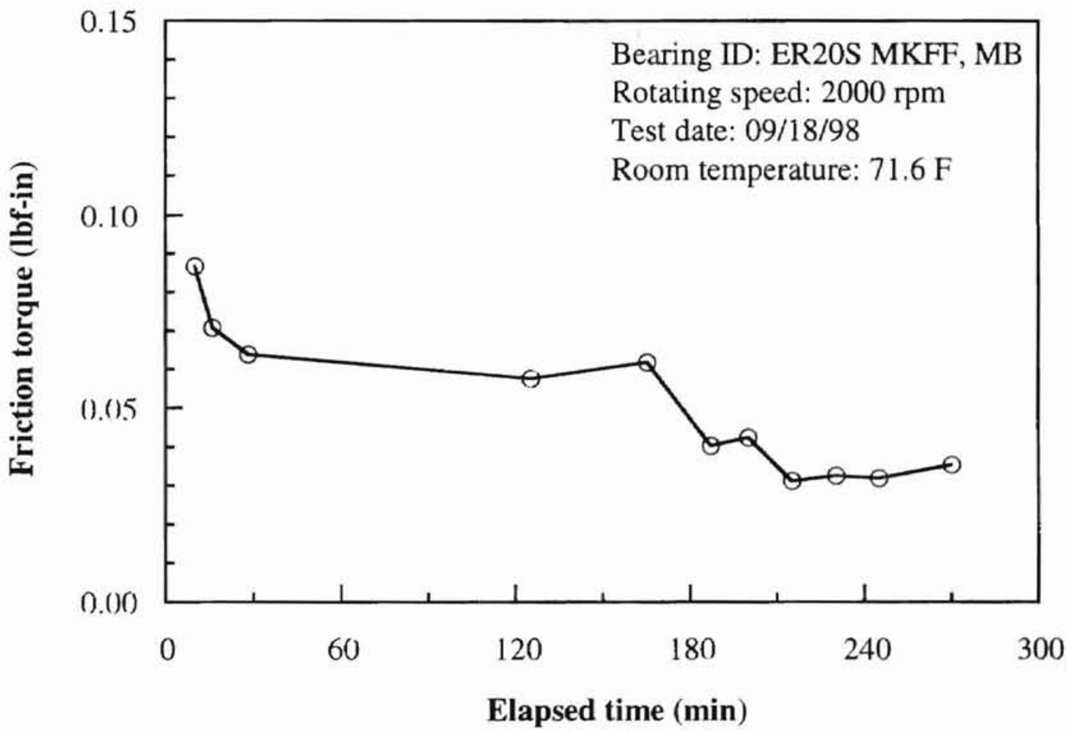

Figure 15. Effect of the elapsed time on bearing friction torque

Table 6. Effect of the elapsed time on bearing friction torque

Unloaded condition		
Time elapsed (min)	* Displacement (in)	Measured torque (lbf*in)
5	0.114	0.074
10	0.192	0.125
15	0.187	0.122
30	0.135	0.088
35	0.127	0.083
40	0.126	0.082
47	0.147	0.096
52	0.147	0.096
90	0.099	0.065
120	0.085	0.056
150	0.075	0.049
160	0.079	0.051
165	0.076	0.049
170	0.075	0.049
175	0.075	0.049
180	0.075	0.049
455	0.075	0.049

* Rotation of the 0.65 lb balancing mass in increment of 5 degree on ½-13 threaded rod.
Test date: 09/23/98

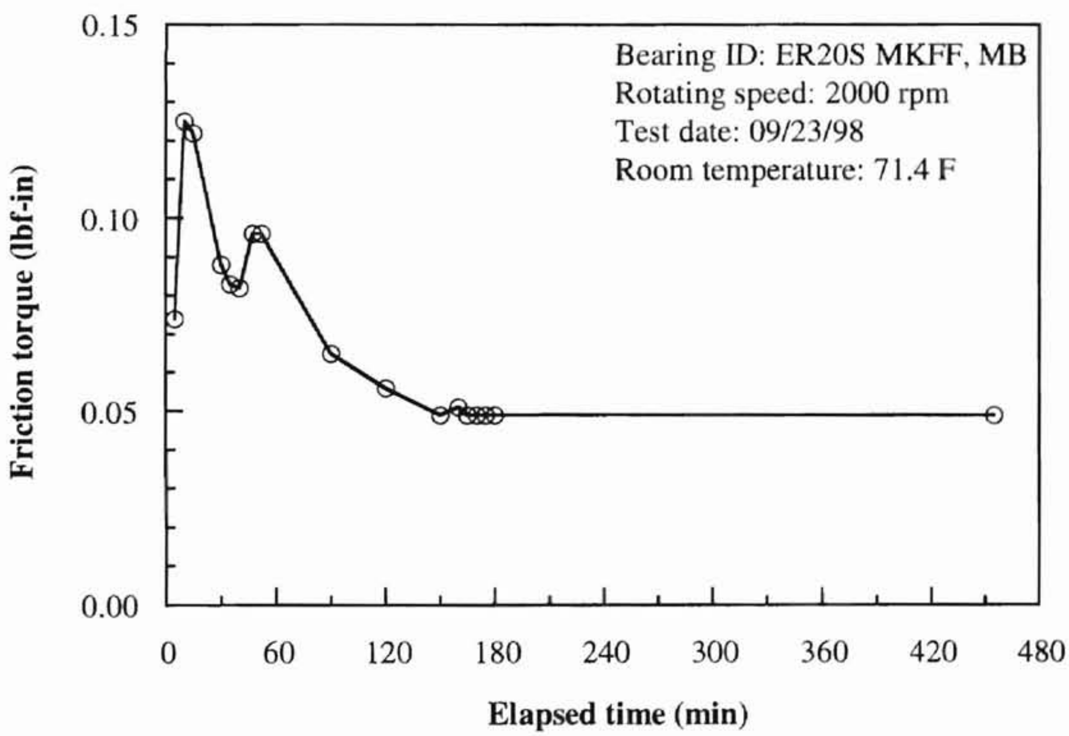

Figure 16. Effect of the elapsed time on bearing friction torque

Table 7. Effect of the elapsed time on bearing friction torque

Unloaded condition		
Time elapsed (min)	* Displacement (in)	Measured torque (lbf*in)
3	0.114	0.074
8	0.130	0.085
16	0.103	0.067
20	0.176	0.115
26	0.112	0.073
32	0.105	0.068
34	0.179	0.117
42	0.122	0.079
52	0.098	0.064
62	0.096	0.063
97	0.099	0.065
120	0.085	0.056
140	0.125	0.081
145	0.163	0.106
158	0.093	0.060
170	0.080	0.052
180	0.087	0.056

* Rotation of the 0.65 lb balancing mass in increment of 5 degree on ½-13 threaded rod.
Test date: 09/24/98

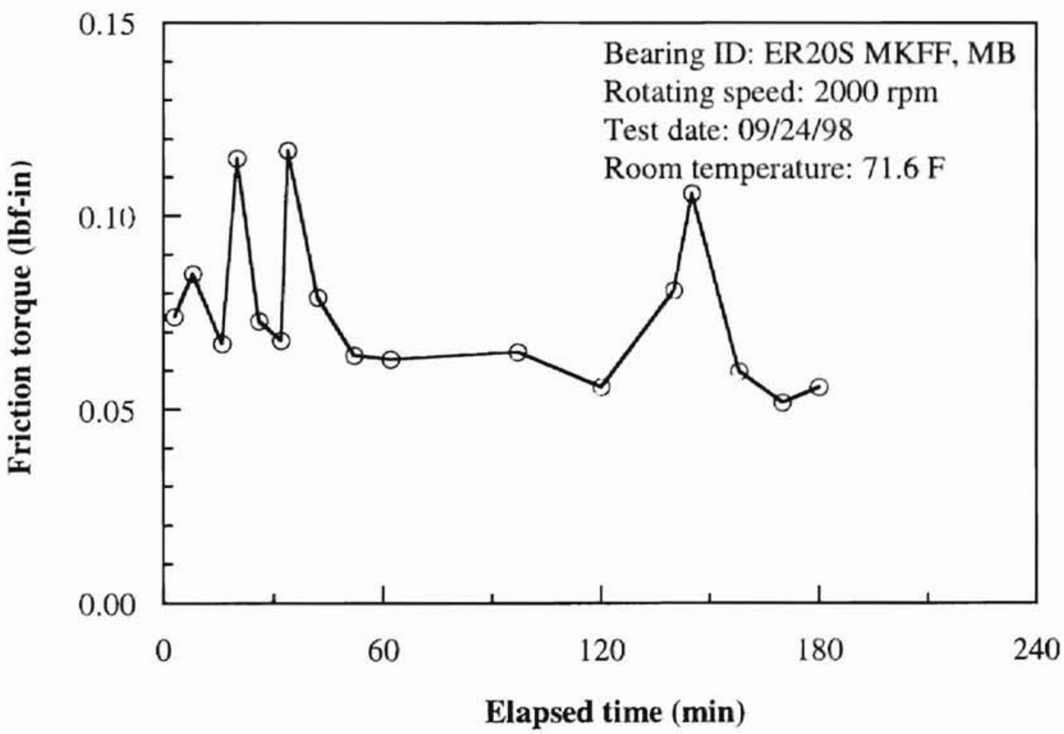

Figure 17. Effect of the elapsed time on bearing friction torque

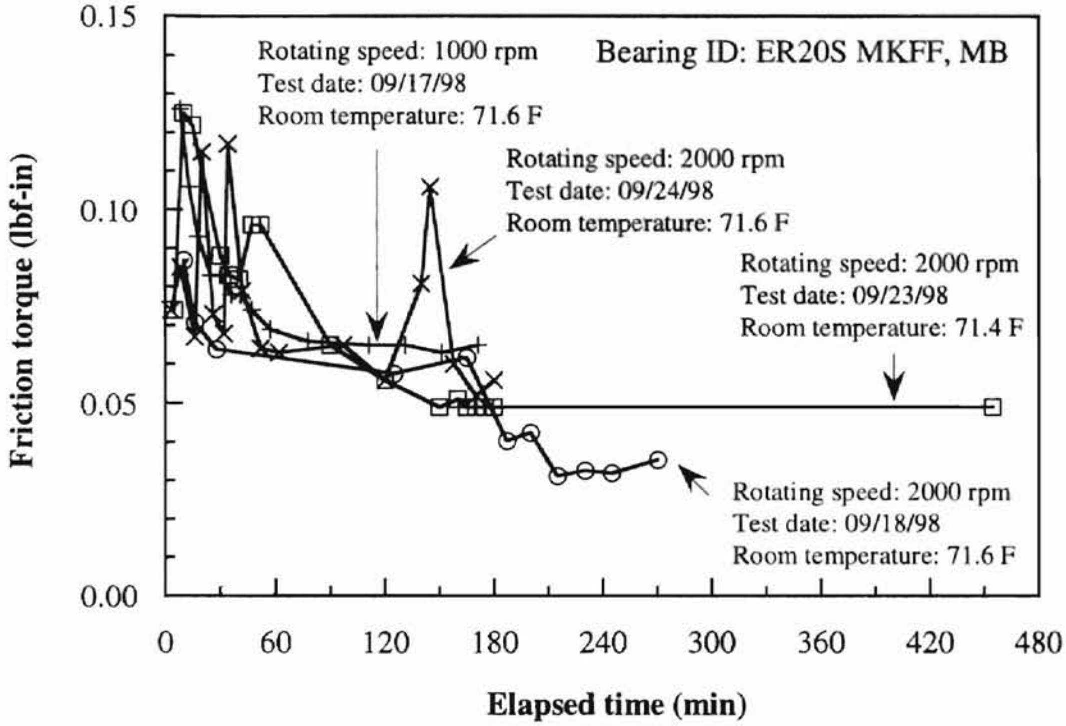

Figure 18. Effect of the elapsed time on bearing friction torque

3.3.1.3 ER24 MKFF, MB

Table 8. Effect of the elapsed time on bearing friction torque

Unloaded condition		
Time elapsed (min)	* Displacement (in)	Measured torque (lbf*in)
5	0.624	0.406
10	0.534	0.347
17	0.557	0.362
22	0.507	0.330
29	0.557	0.362
35	0.535	0.348
40	0.526	0.342
47	0.531	0.345
220	0.478	0.310
225	0.459	0.299
232	0.442	0.288
245	0.442	0.288
250	0.442	0.288

* Rotation of the 0.65 lb balancing mass in increment of 5 degree on ½-13 threaded rod.
Test date: 10/03/98

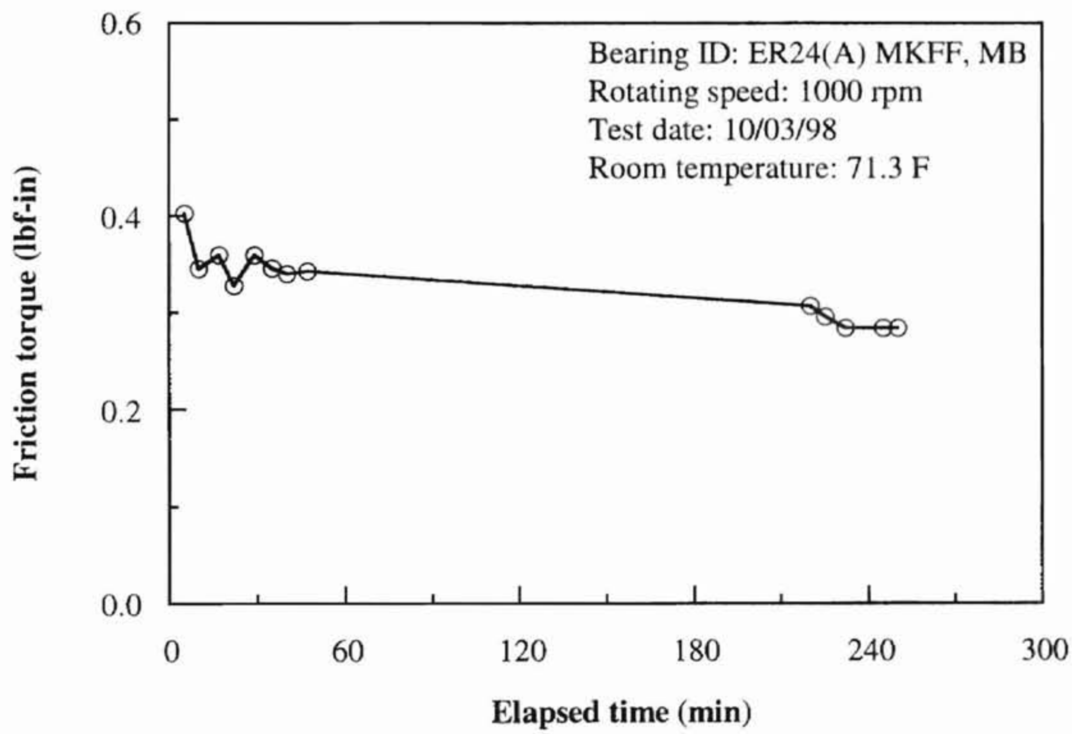

Figure 19. Effect of the elapsed time on bearing friction torque

Table 9. Effect of the elapsed time on bearing friction torque

Unloaded condition		
Time elapsed (min)	* Displacement (in)	Measured torque (lbf*in)
2	0.835	0.543
7	0.779	0.506
14	0.730	0.474
16	0.845	0.549
19	0.706	0.459
30	0.681	0.442
50	0.777	0.505
70	0.683	0.444
72	0.650	0.422
74	0.637	0.414
75	0.778	0.506
77	0.624	0.406
100	0.572	0.372
145	0.604	0.392
146	0.824	0.535
150	0.747	0.485
152	0.728	0.473
154	0.668	0.434
155	0.636	0.413
158	0.621	0.403
161	0.621	0.403
166	0.626	0.407
167	0.686	0.446
168	0.628	0.408
180	0.607	0.394
212	0.628	0.408
270	0.774	0.503
271	0.686	0.446
273	0.675	0.439
274	0.665	0.432
295	0.625	0.406
321	0.632	0.411

* Rotation of the 0.65 lb balancing mass in increment of 5 degree on ½-13 threaded rod.
Test date: 10/04/98

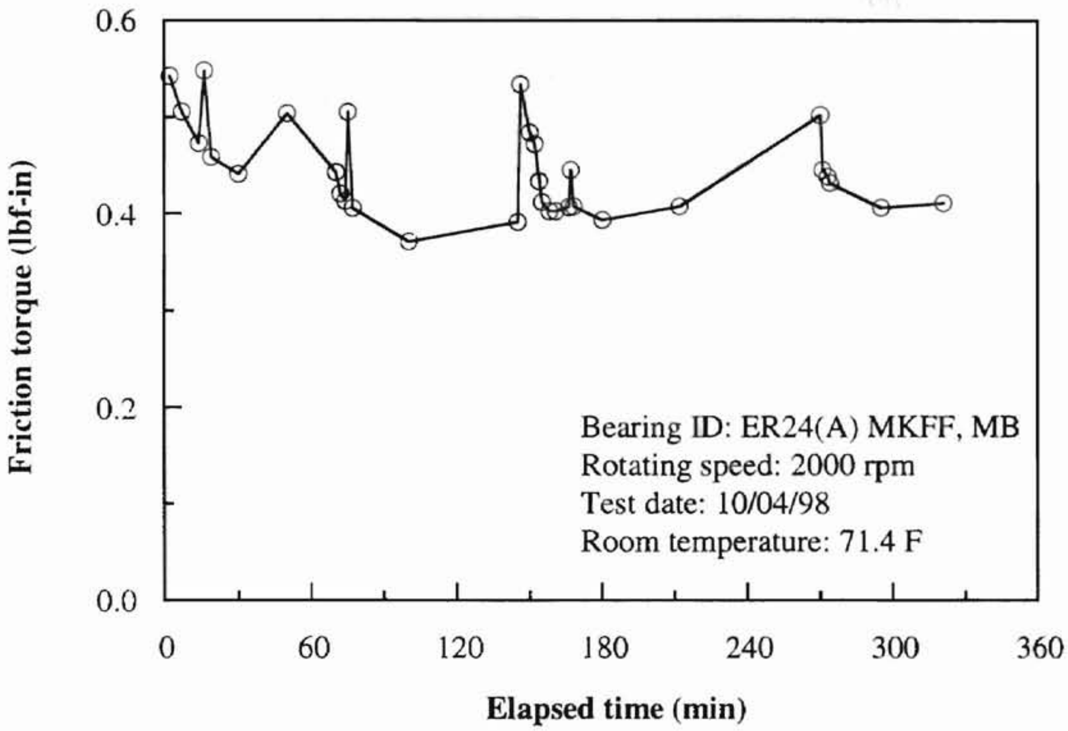

Figure 20. Effect of the elapsed time on bearing friction torque

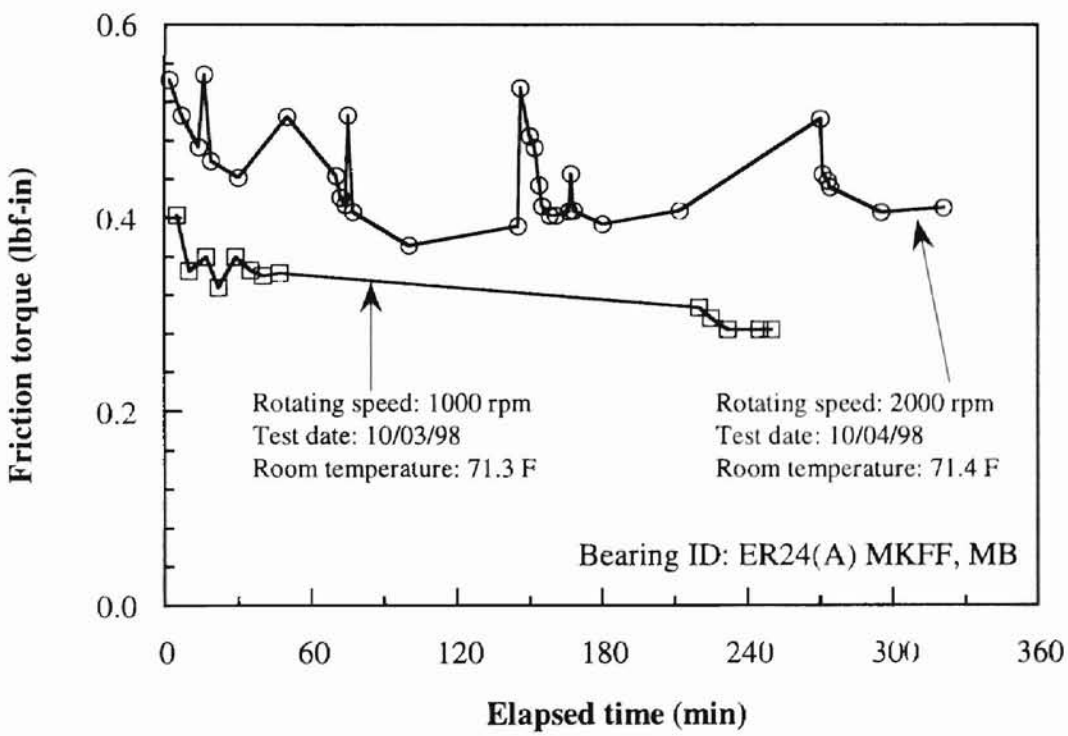

Figure 21. Effect of the elapsed time on bearing friction torque

Table 10. Effect of the elapsed time on bearing friction torque

Unloaded condition		
Time elapsed (min)	* Displacement (in)	Measured torque (lbf*in)
5	1.311	0.852
10	0.484	0.315
12	0.946	0.615
14	0.426	0.277
30	0.253	0.165
33	0.196	0.127
42	0.129	0.084
55	0.080	0.052
65	0.061	0.040
68	0.078	0.051
69	0.234	0.152
71	0.061	0.040
85	0.042	0.027
100	0.056	0.036
120	0.069	0.045
125	0.048	0.031
135	0.032	0.021
150	0.964	0.626
157	0.214	0.139
158	0.521	0.339
165	0.156	0.101
166	0.098	0.064
177	0.028	0.018
182	0.029	0.019

* Rotation of the 0.65 lb balancing mass in increment of 5 degree on ½-13 threaded rod.
Test date: 10/08/98

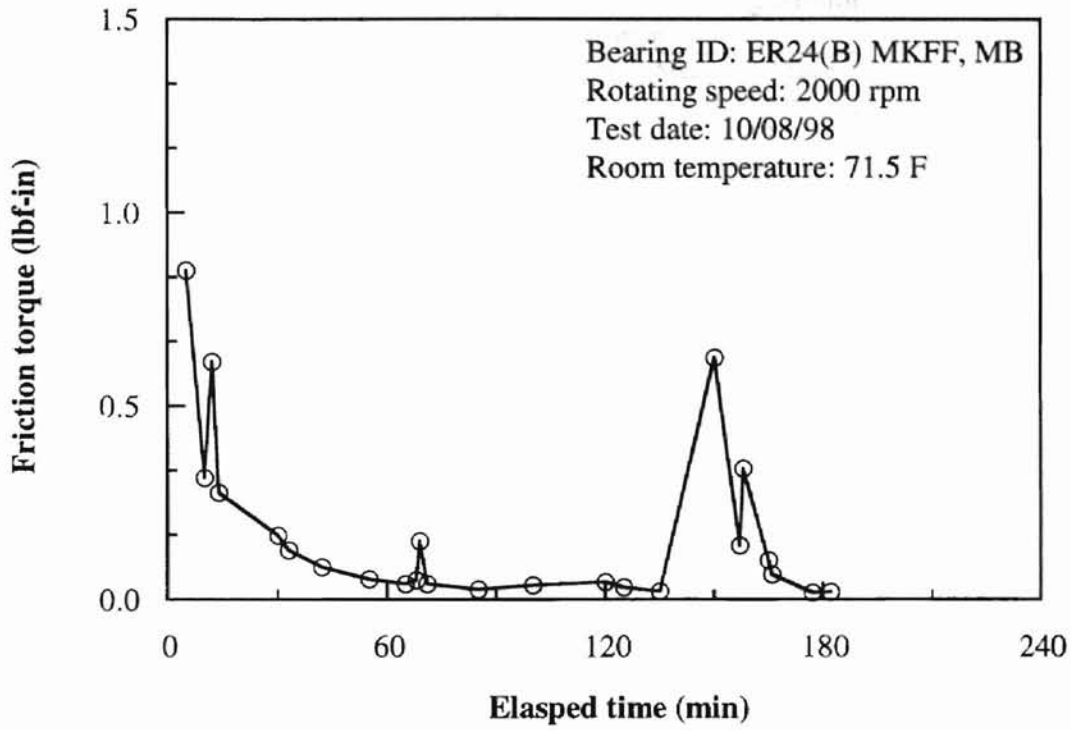

Figure 22. Effect of the elapsed time on bearing friction torque

Table 11. Effect of the elapsed time on bearing friction torque

Unloaded condition		
Time elapsed (min)	* Displacement (in)	Measured torque (lbf*in)
3	0.783	0.852
5	0.591	0.727
9	0.418	0.615
11	0.802	0.865
15	0.544	0.697
16	0.843	0.891
17	0.537	0.715
19	0.630	0.654
25	0.543	0.597
30	0.598	0.633
32	0.746	0.729
42	1.167	1.003
48	0.782	0.753
54	0.698	0.698
64	0.596	0.632
84	0.627	0.652
104	0.637	0.658
114	0.502	0.571
119	0.497	0.567
125	0.500	0.569

* Rotation of the 0.65 lb balancing mass in increment of 5 degree on ½ 13 threaded rod.
Test date: 10/11/98

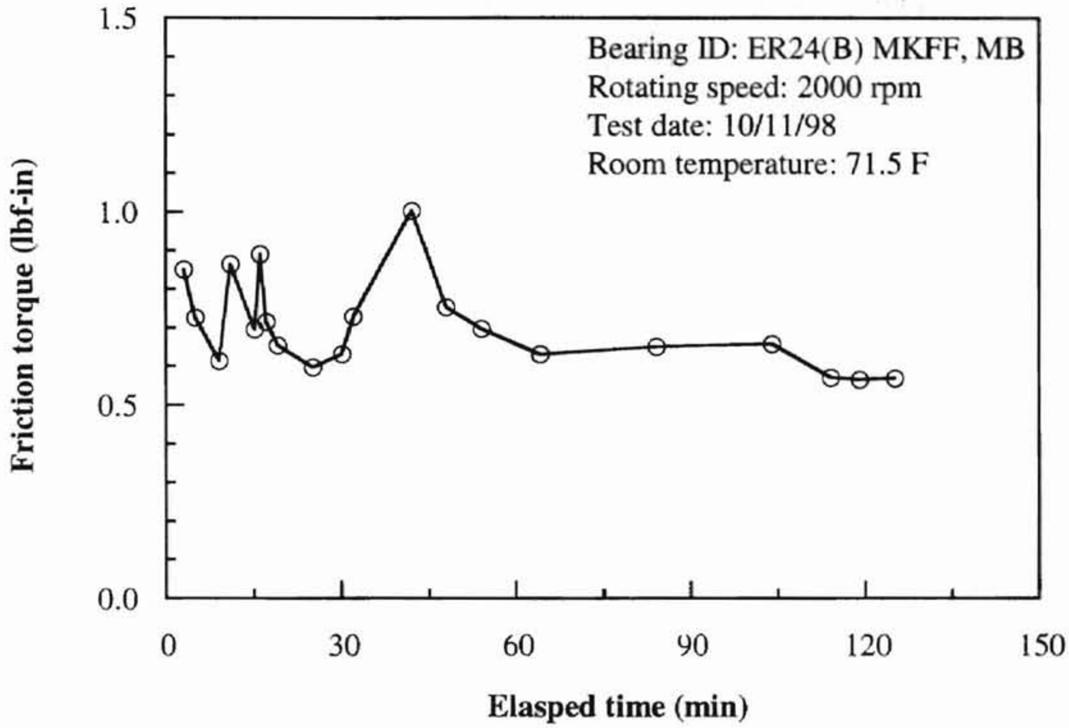

Figure 23. Effect of the elapsed time on bearing friction torque

Table 12. Effect of the elapsed time on bearing friction torque

Unloaded condition		
Time elapsed (min)	* Displacement (in)	Measured torque (lbf*in)
2	1.654	1.075
3	1.154	0.750
5	0.577	0.375
6	0.731	0.475
11	0.254	0.165
17	0.212	0.138
18	0.222	0.144
19	0.607	0.394
24	0.068	0.044
25	0.415	0.269
27	0.991	0.644
32	0.491	0.319
39	0.589	0.383
42	0.204	0.133
72	0.031	0.020
97	0.059	0.038
117	0.050	0.033
137	0.050	0.033
172	0.080	0.052

* Rotation of the 0.65 lb balancing mass in increment of 5 degree on ½ 13 threaded rod.
Test date: 10/12/98

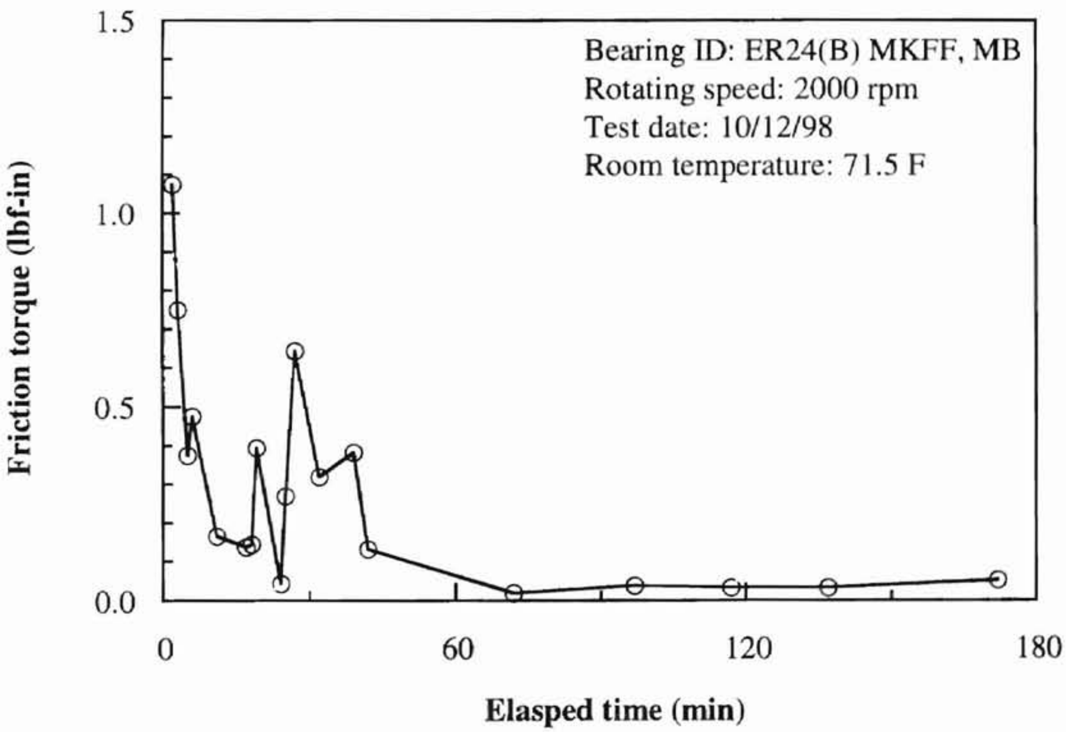

Figure 24. Effect of the elapsed time on bearing friction torque

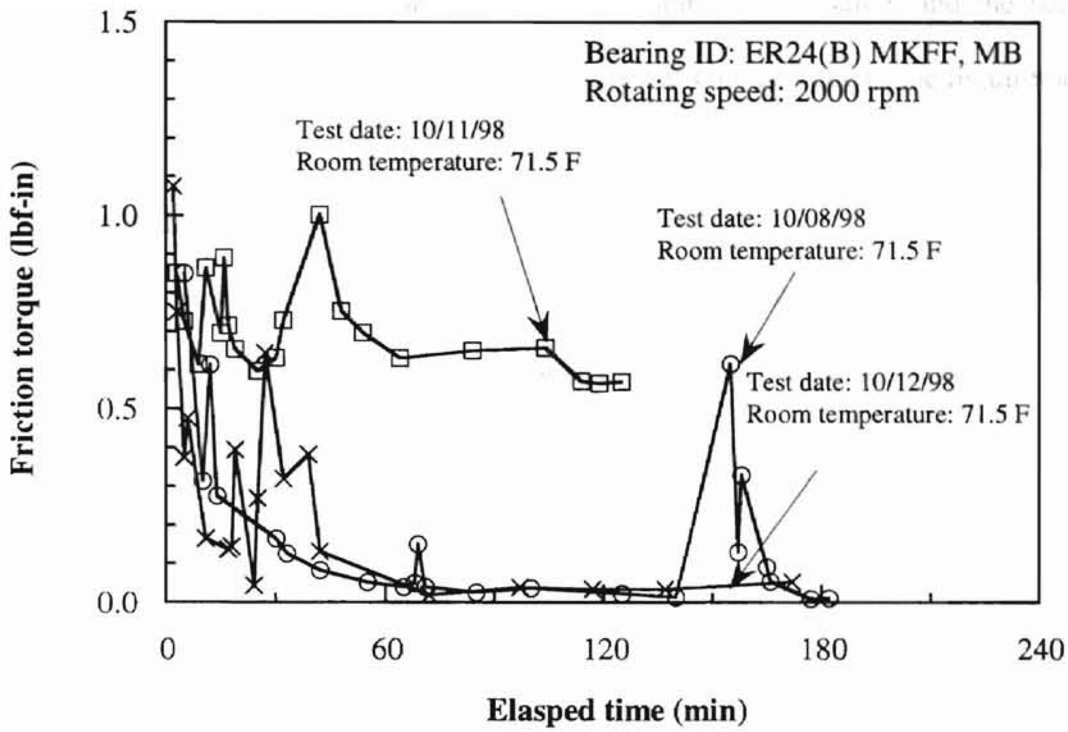

Figure 25. Effect of the elapsed time on bearing friction torque

3.3.2 Results for oil-lubricated bearings

3.3.2.1 6AK 6209-K (Single row deep groove ball bearing, SKF)

6AK 6209-K (Single row deep groove ball bearing) manufactured by SKF has been tested at speeds ranging from 1000 rpm to 3000 rpm. An appreciable effect of the viscosity of the lubricant was observed. If the light lubricant was used, the friction torque was smaller than that of the thick lubricant with the same load. The start-up torque increased considerably when the speed was increased. This phenomenon can be observed in Figure 28. It can be observed that the experimental results of 02/06/99 were different from those of 07/24/99 to 07/29/99. The applied conditions were as follows: the loading condition was slightly different, the lubricant was the same, and the bearings were identical. On the other hand, the driver shaft was changed due to the requirement of avoiding the large vibration from the bent shaft. Consequently, the friction torque was reduced after changing the driven shaft.

Because the thermocouple was not installed before 03/03/99, calculation could not be done due to the absence of equipment to measure the temperature of an outer race. It would be beneficial to compare the experimental results with the calculated results, helping to verify that the experiment was appropriately set up.

Table 13. Effect of elapsed time on bearing friction torque

Loaded weight: 135 lb		
Time elapsed (min)	Spindle speed (rpm)	Total torque (lbf*in)
3	1000	3.575
7	1015	3.231
14	1005	3.163
22	1014	2.991
28	1018	2.888
34	1004	2.819
49	1015	2.613
97	1029	2.475
112	1002	2.338
127	1003	2.338
212	1010	2.338

The first measured distance of the balancing mass from the extremity of the wing was 1.375".
Lubricant: PENNZOIL 20W-50 (Motor oil)
Test date: 02/02/99

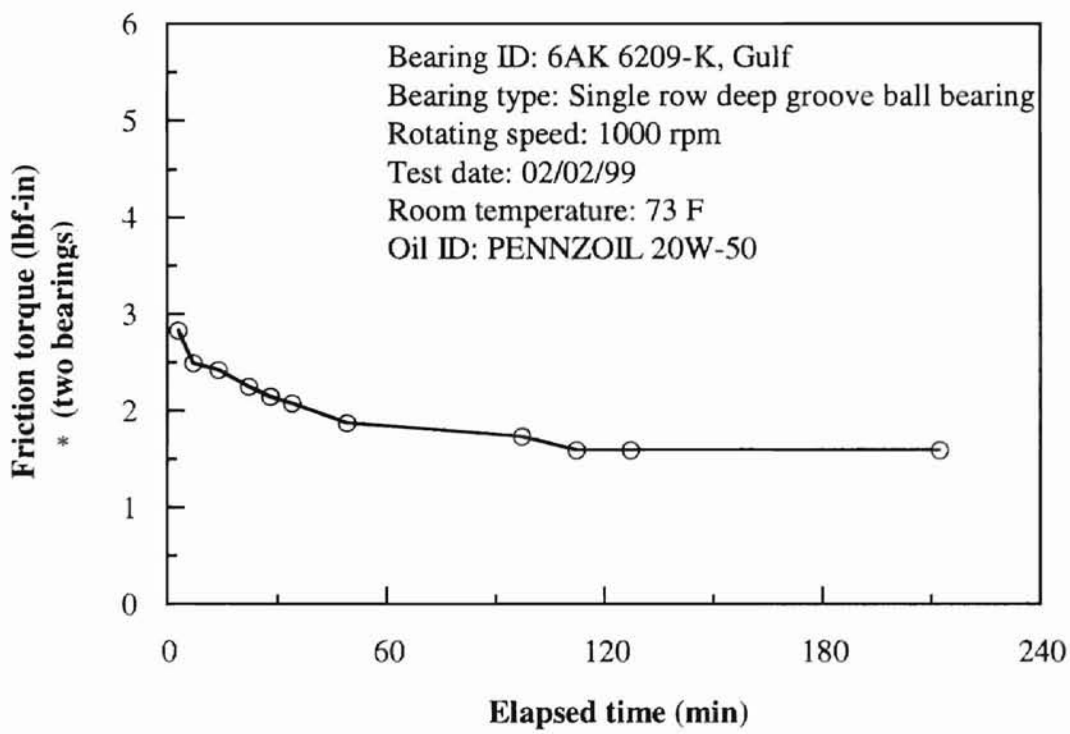

Figure 26. Effect of the elapsed time on bearing friction torque

* Friction torque in y-axis shown in the graph indicates that the torque results from two bearings.

Table 14. Effect of elapsed time on bearing friction torque

Loaded weight: 135 lb		
Time elapsed (min)	Spindle speed (rpm)	Total torque (lbf*in)
2	2002	5.156
7	2012	4.331
12	1999	3.506
24	2000	3.197
34	2027	3.025
51	2011	2.784
66	2028	2.750
99	2021	2.613
134	1998	2.509
159	2000	2.475
192	2005	2.475
212	2002	2.475

The first measured distance of the balancing mass from the extremity of the wing was 1.375".
Lubricant: PENNZOIL 20W-50 (Motor oil)
Test date: 02/03/99

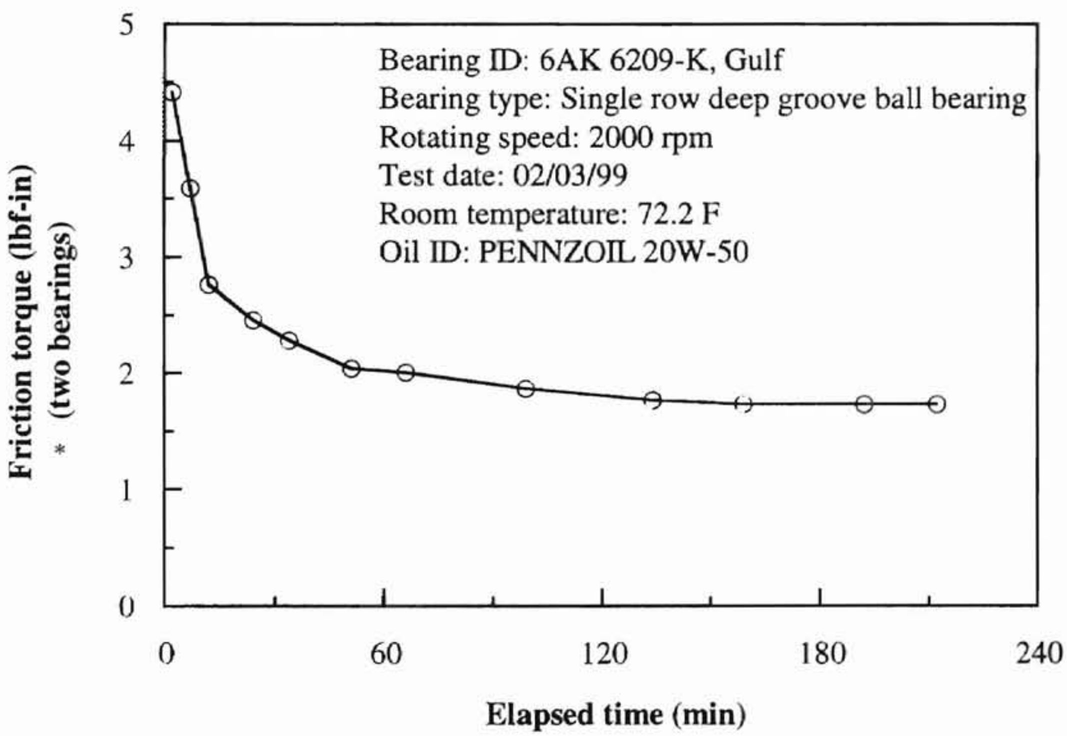

Figure 27. Effect of the elapsed time on bearing friction torque

Table 15. Effect of elapsed time on bearing friction torque

Loaded weight: 135 lb		
Time elapsed (min)	Spindle speed (rpm)	Total torque (lbf*in)
4	3002	6.188
9	3081	4.813
14	3048	4.159
20	3038	3.747
26	3000	3.506
31	3027	3.369
40	3009	3.197
54	2950	2.956
74	2996	2.819
113	3008	2.681
133	3015	2.681
168	3003	2.681

The first measured distance of the balancing mass from the extremity of the wing was 1.375".
Lubricant: PENNZOIL 20W-50 (Motor oil)
Test date: 02/06/99

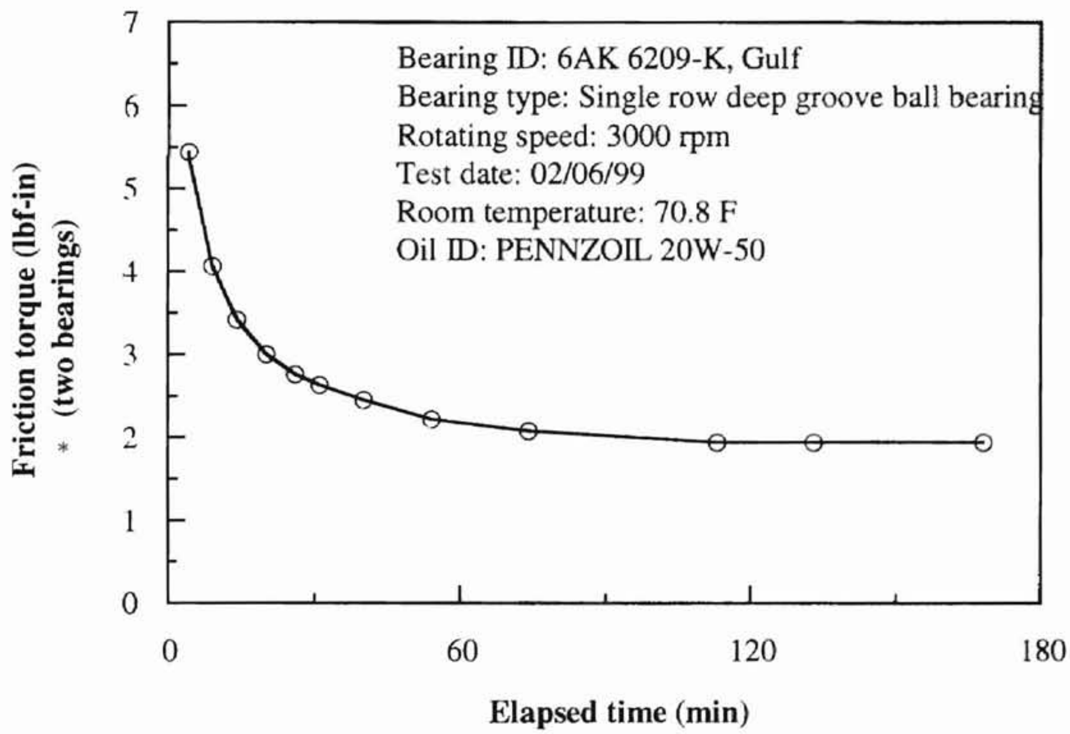

Figure 28. Effect of the elapsed time on bearing friction torque

Figure 28 shows the effect of rotating speed on bearing friction torque when PENNZOIL 20W-50 was used as a lubricant. As the rotating speed is increased, the friction torque in the steady state is slightly increased.

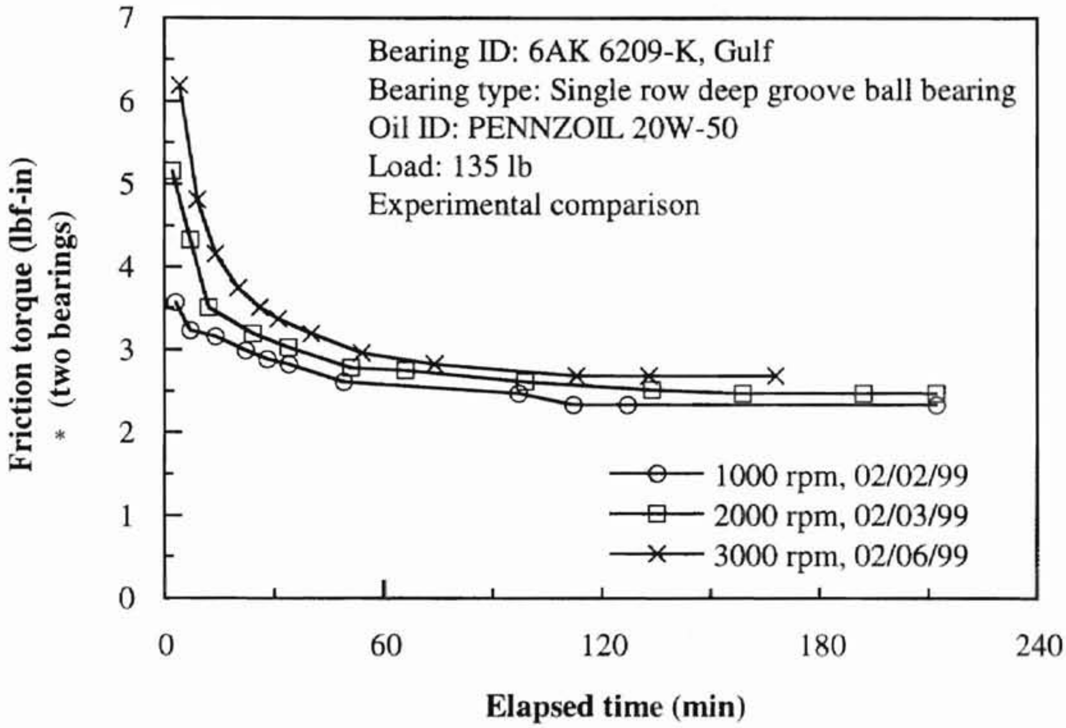

Figure 29. Effect of the elapsed time on bearing friction torque

Installation of the thermocouple near the outer race of the first bearing enabled the measurement of the temperature for comparison to Eq (0.1). However, one possible cause of a difference between experiment and calculation was the difference between the temperatures of the bearing surfaces. It would be ideal to install another thermocouple near the other bearing in order to reduce the error resulting from the approximation of temperature.

Table 16. Effect of elapsed time on bearing friction torque

Loaded weight: 136.6 lb		Bearing			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp(C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
2	1044	22.8	68.9	0.651	1.302	0.963
7	1047	22.8	68.9	0.652	1.305	0.877
20	1052	23.8	65.1	0.630	1.259	0.859
40	1045	24.8	61.2	0.602	1.204	0.842
85	1050	25.8	59.3	0.591	1.182	0.825
348	1054	27.9	53.6	0.553	1.106	0.825
398	1054	27.9	53.6	0.553	1.106	0.825

The first measured distance of the balancing mass from the extremity of the wing was 1.3".
Lubricant: PENNZOIL DEXRON III (Automatic transmission oil)
Pitch diameter: 65mm, Factor f_o: 1.5
Test date: 03/03/99

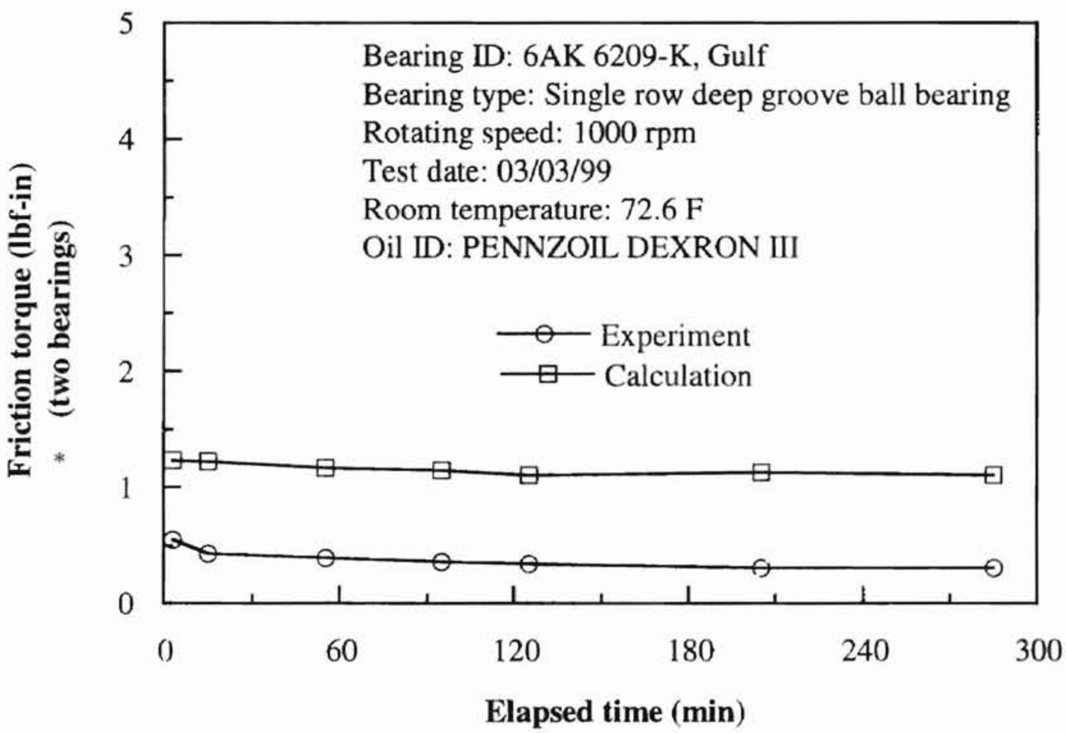

Figure 30. Effect of the elapsed time on bearing friction torque

Table 17. Effect of elapsed time on bearing friction torque

Loaded weight: 136.6lb		Bearing			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp(C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
3	1999	22.3	360	1.004	2.008	1.547
10	2010	23.8	340	0.970	1.939	1.409
23	1992	25.8	310	0.906	1.811	1.341
45	2021	27.9	280	0.853	1.707	1.203
93	2030	30.9	250	0.793	1.585	1.066
148	2021	32.9	230	0.747	1.493	0.997
253	2034	35.0	205	0.693	1.386	0.928
363	2037	35.0	205	0.694	1.388	0.928

The first measured distance of the balancing mass from the extremity of the wing was 0.47".
Lubricant: PENNZOIL DEXRON III (Automatic transmission oil)
Pitch of bearing: 65mm, Factor f_o: 1.5
Test date: 03/12/99

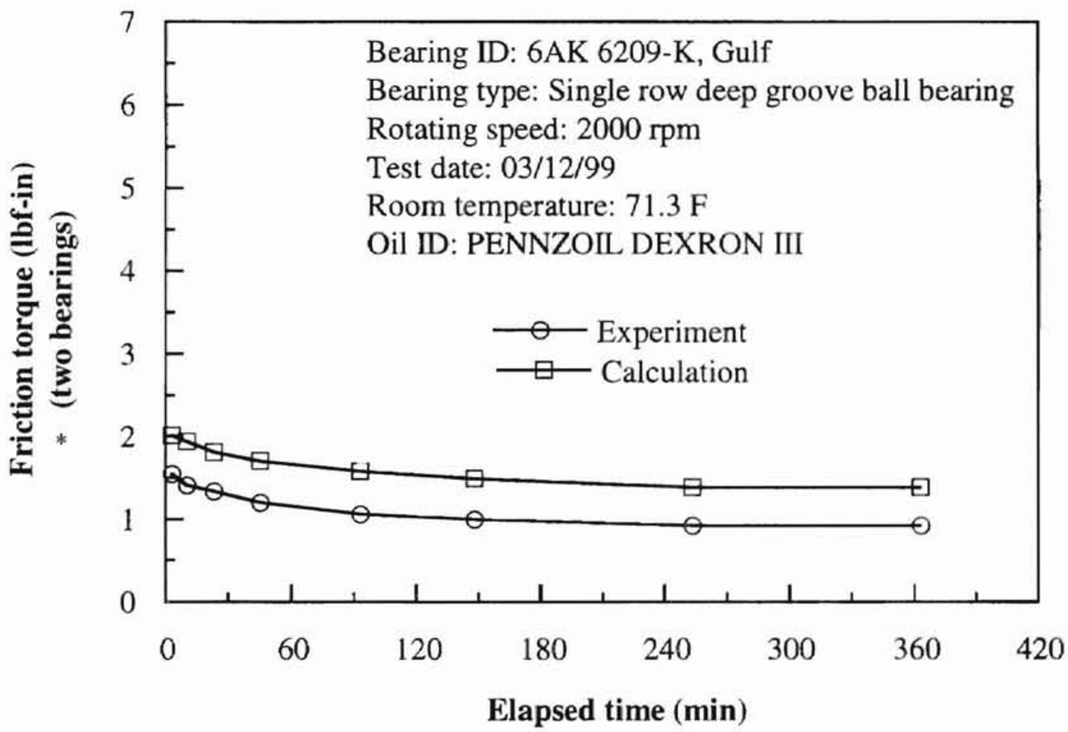

Figure 31. Effect of the elapsed time on bearing friction torque

Table 18. Effect of elapsed time on bearing friction torque

Loaded weight: 136.6 lb		Bearing			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp(C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
2	2993	23.9	340	1.264	2.529	1.891
6	3103	26.9	300	1.190	2.380	1.684
15	3016	29.9	280	1.115	2.229	1.513
25	3025	32.0	240	1.006	2.012	1.409
40	2989	34.0	225	0.955	1.910	1.323
69	3031	38.1	190	0.858	1.716	1.306
104	2990	40.1	180	0.819	1.639	1.238
154	3007	41.1	155	0.741	1.482	1.169
394	3016	42.1	150	0.726	1.451	1.100
494	3016	42.1	150	0.726	1.451	1.100

The first measured distance of the balancing mass from the extremity of the wing was 1".
Lubricant: PENNZOIL DEXRON III (Automatic transmission oil)
Pitch of bearing: 65mm, Factor f_o: 1.5
Test date: 03/09/99

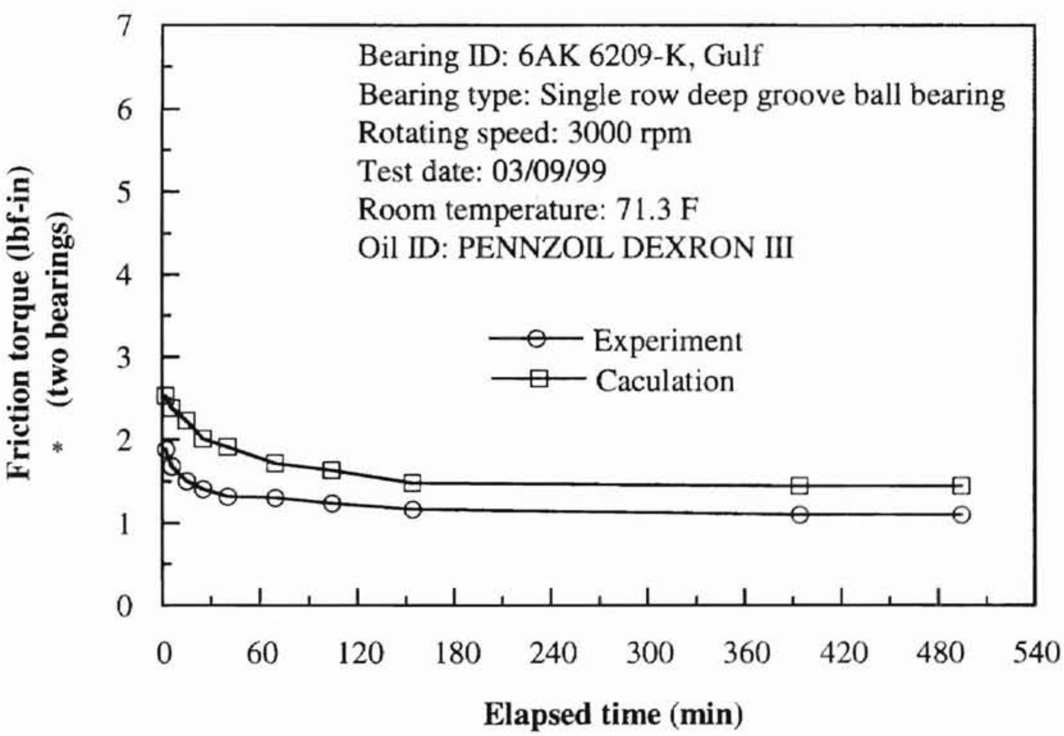

Figure 32. Effect of the elapsed time on bearing friction torque

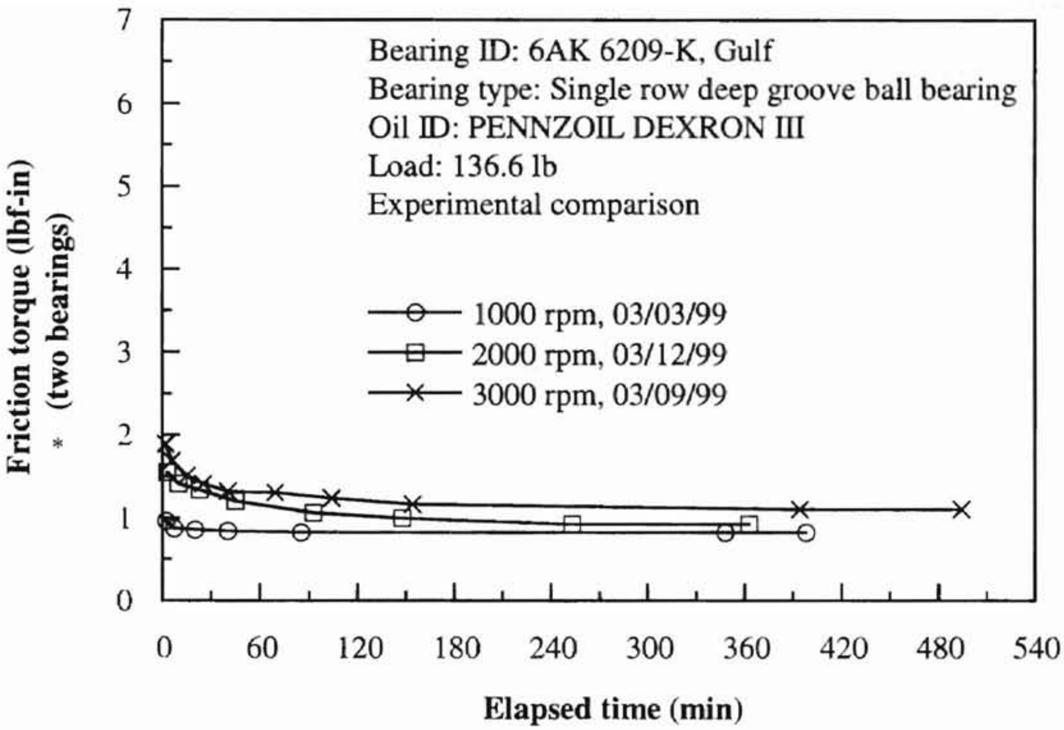

Figure 33. Effect of the elapsed time on bearing friction torque

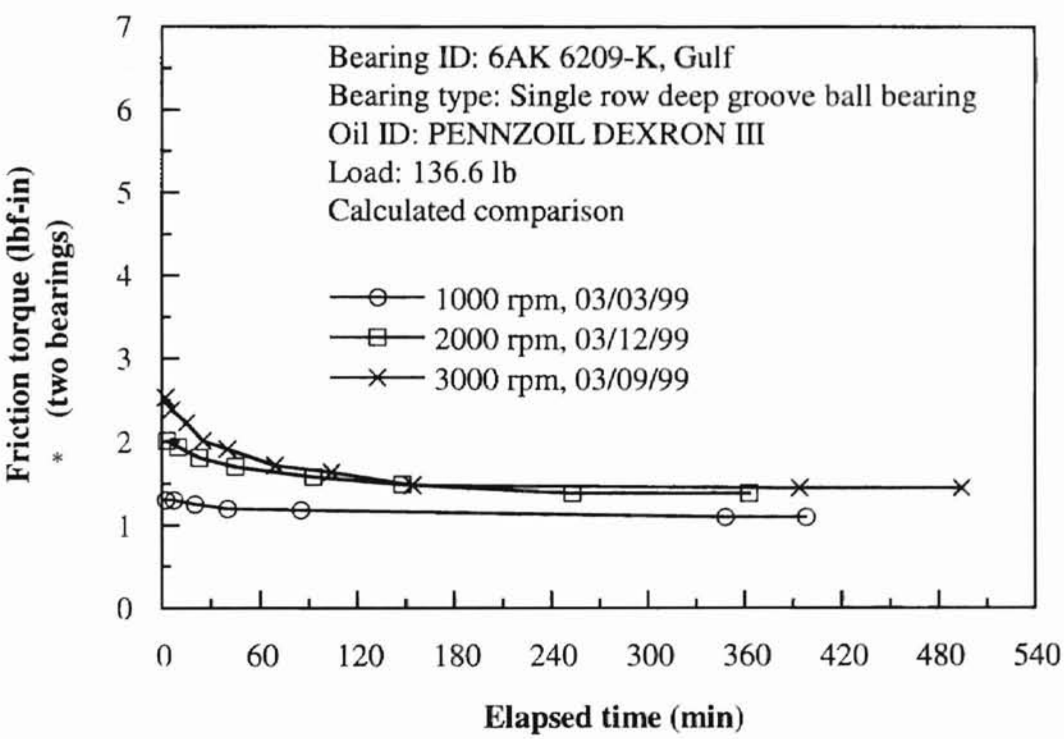

Figure 34. Effect of the elapsed time on bearing friction torque

At this time, a thermocouple was installed in the other bearing housing to measure the temperature near the outer race of the bearing, so that the total calculated torque could be compared to the experimental result. One reason the temperatures were different from each other may have been the mounting blocks were not centered on the mounting plate. Also, the dynamic loading caused by the curved shaft may have been different on the two bearings, and the clearances of the bearings in their operating condition undoubtedly varied.

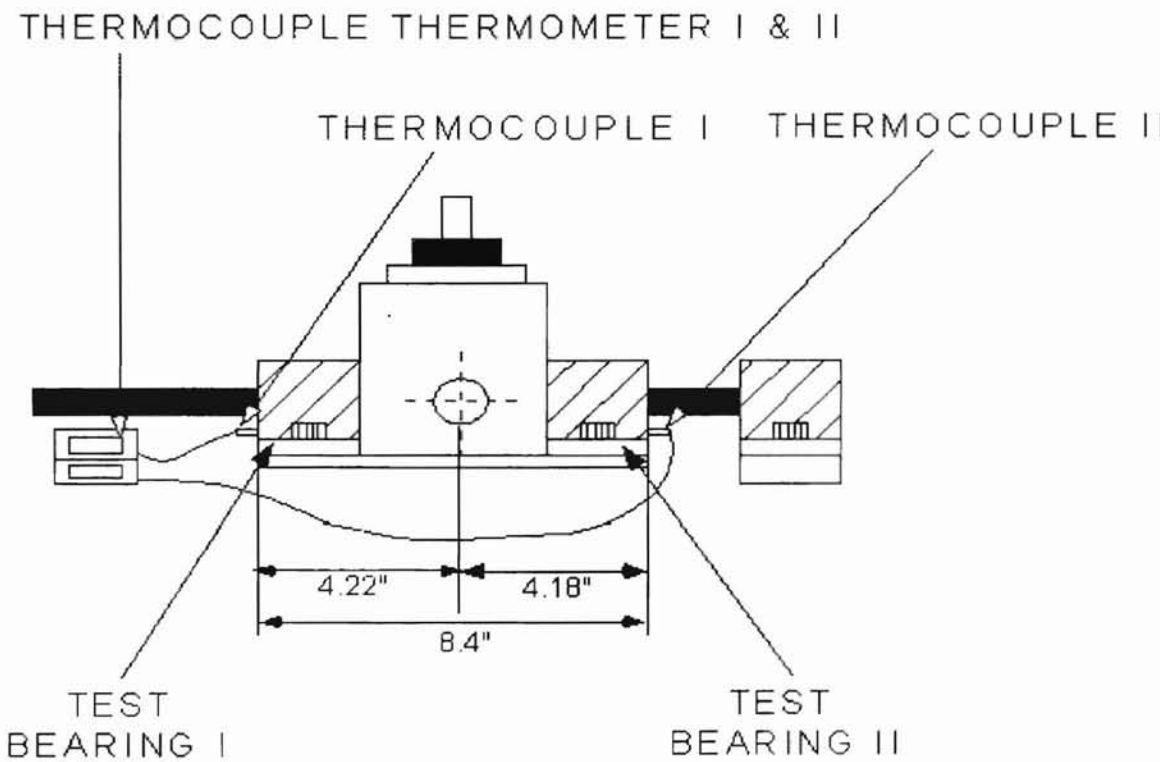

Figure 35. Unbalance

Table 19. Effect of elapsed time on bearing friction torque

Loaded weight: 60.8 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
5	1155	26.8	1600	1.888	23.9	1800	2.043	3.931	3.609
12	1168	29.7	1350	1.699	24.9	1700	1.981	3.679	3.197
34	1090	33.2	1140	1.449	28.9	1350	1.622	3.071	2.372
67	1110	34.3	1100	1.432	31.0	1250	1.560	2.992	2.131
117	1122	35.1	1000	1.354	31.0	1250	1.571	2.924	1.994
165	1126	35.2	995	1.352	32.0	1185	1.520	2.872	1.925
217	1130	35.3	992	1.353	32.0	1185	1.523	2.876	1.856
273	1129	35.2	995	1.355	32.0	1185	1.522	2.877	1.856

The first measured distance of the balancing mass from the extremity of the wing was 5".
Lubricant: PENNZOIL 20W-50 (Motor oil)
Pitch of bearing: 65mm, Factor f_o: 1.5
Test date: 07/18/99

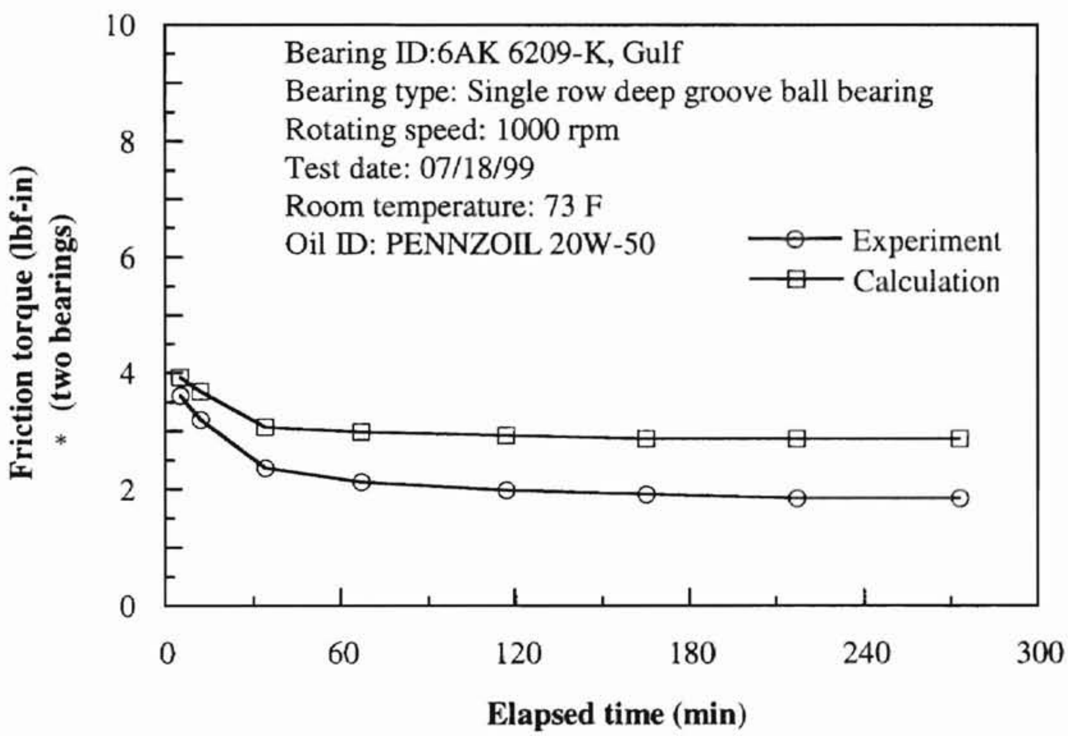

Figure 36. Effect of the elapsed time on bearing friction torque

Table 20. Effect of elapsed time on bearing friction torque

Loaded weight: 60.8 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
4	2264	30.3	1200	2.441	23.9	1900	3.317	5.758	3.163
20	2231	37.9	875	1.958	27.9	1500	2.805	4.763	1.959
50	2284	40.7	775	1.834	32.0	1200	2.455	4.289	1.856
95	2330	44.0	720	1.769	35.0	1000	2.203	3.972	1.667
130	2340	45.0	675	1.699	36.0	975	2.172	3.872	1.650
165	2303	45.2	635	1.614	37.1	925	2.075	3.689	1.650
206	2308	45.4	590	1.539	38.1	875	2.003	3.541	1.581
252	2306	45.3	595	1.547	38.1	875	2.001	3.548	1.581

The first measured distance of the balancing mass from the extremity of the wing was 4.7".
Lubricant: PENNZOIL 20W-50 (Motor oil)
Pitch of bearing: 65mm, Factor f_o: 1.5
Test date: 07/19/99

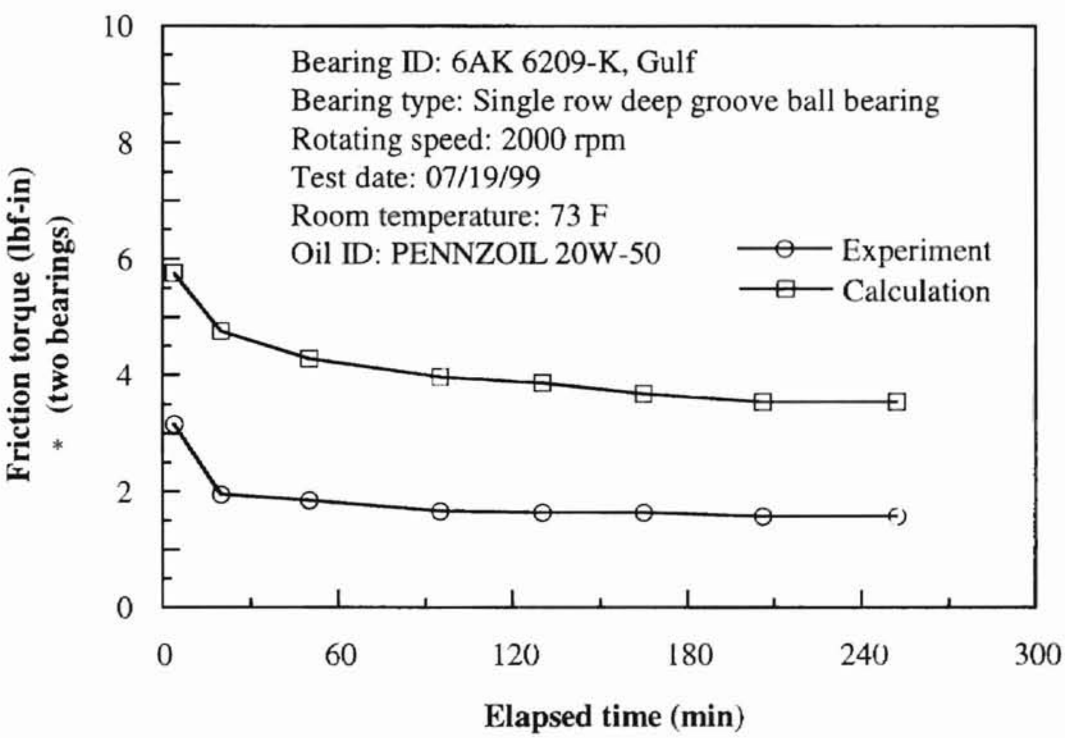

Figure 37. Effect of the elapsed time on bearing friction torque

Table 21. Effect of elapsed time on bearing friction torque

Loaded weight: 60.8 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
3	3351	32.9	1200	3.170	23.9	1850	4.232	7.402	3.266
7	3392	39.4	1100	3.016	24.9	1700	4.032	7.048	2.956
20	3453	45.2	640	2.126	27.9	1500	3.754	5.879	2.441
44	3440	49.8	520	1.845	34.0	1200	3.226	5.071	2.303
63	3513	53.1	440	1.673	39.1	850	2.599	4.272	2.166
105	3511	56.1	380	1.516	49.2	525	1.883	3.398	1.994
125	3469	57.7	360	1.450	51.3	500	1.807	3.257	1.959
163	3483	58.7	350	1.426	53.3	436	1.653	3.080	1.925
208	3490	58.7	350	1.428	53.3	436	1.656	3.084	1.925

The first measured distance of the balancing mass from the extremity of the wing was 4.5".
Lubricant: PENNZOIL 20W-50 (Motor oil)
Pitch of bearing: 65mm, Factor f_o: 1.5
Test date: 07/21/99

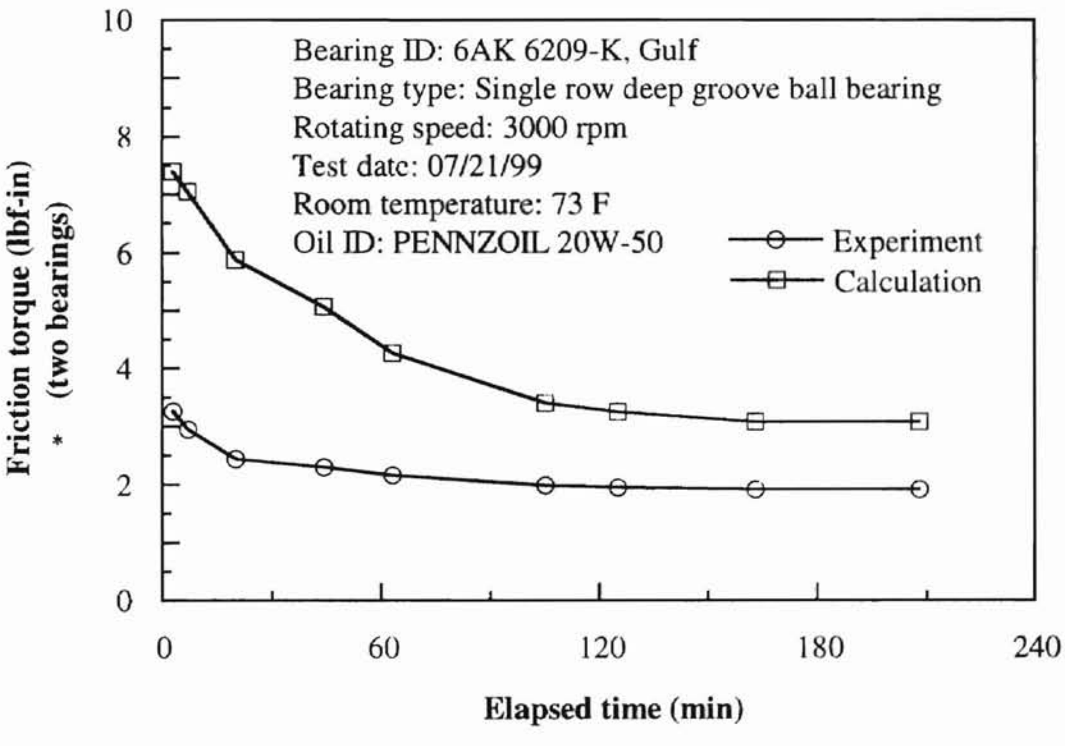

Figure 38. Effect of the elapsed time on bearing friction torque

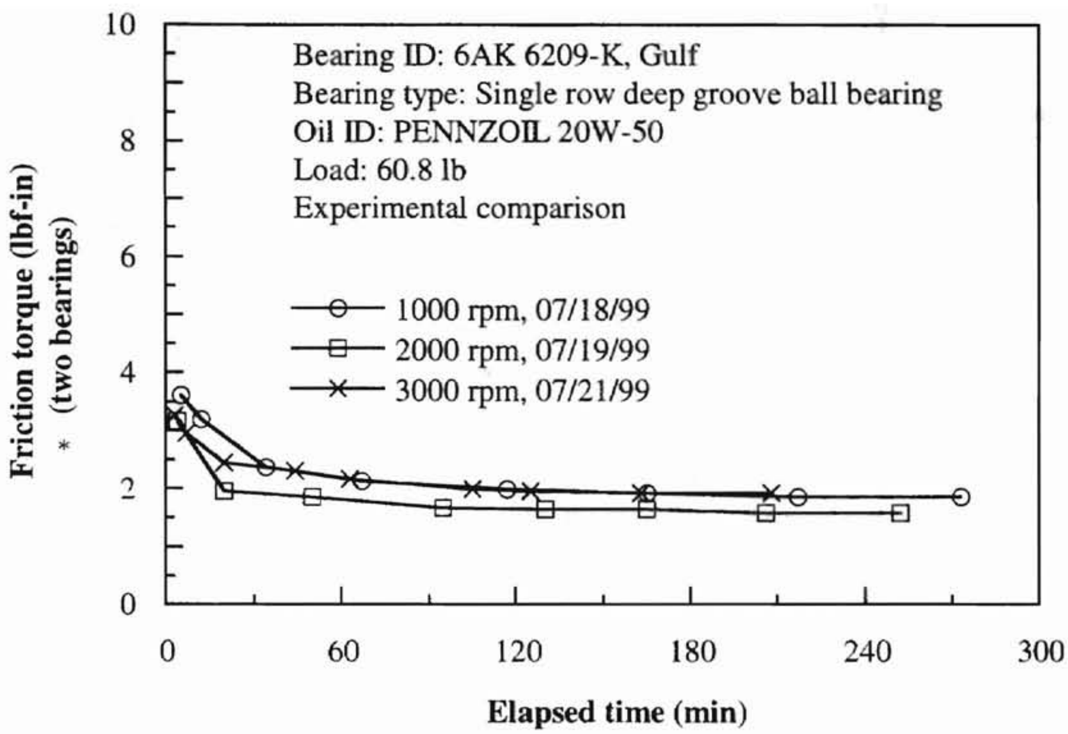

Figure 39. Effect of the elapsed time on bearing friction torque

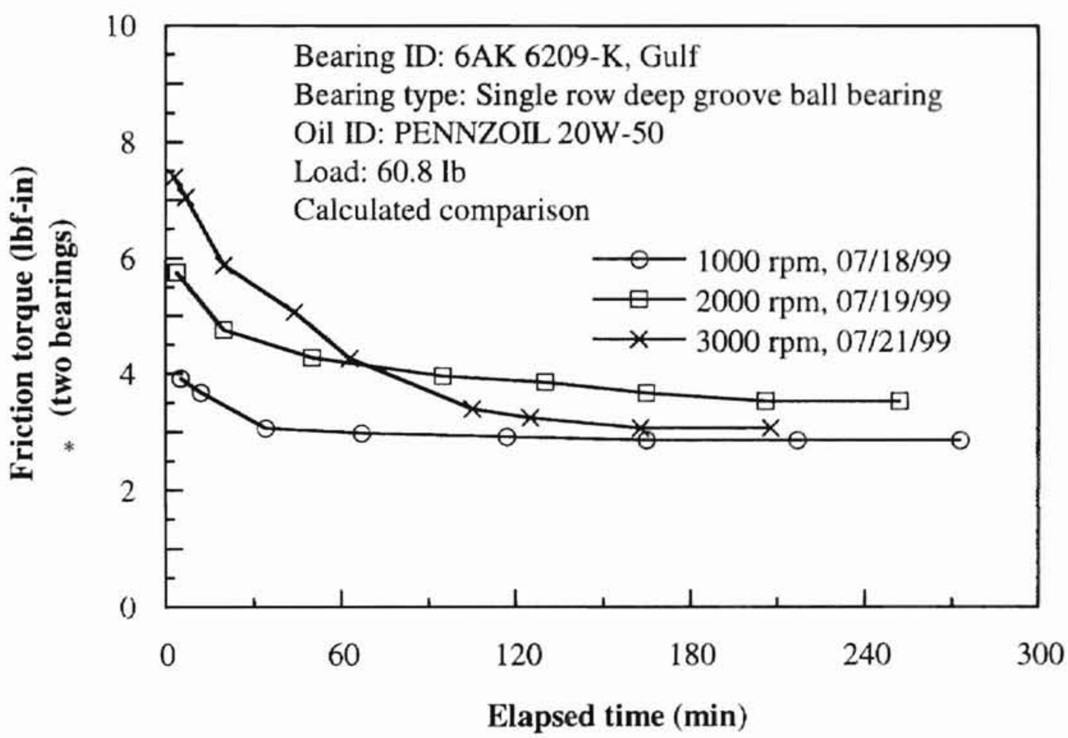

Figure 40. Effect of the elapsed time on bearing friction torque

Table 22. Effect of elapsed time on bearing friction torque

Loaded weight: 123.4 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
4	997	25.2	1800	1.852	22.8	2000	1.987	3.838	2.784
8	1004	26.5	1600	1.720	23.9	1900	1.929	3.649	2.613
17	1019	28.4	1400	1.589	24.9	1700	1.809	3.398	2.372
45	1019	31.4	1250	1.473	27.9	1500	1.664	3.137	2.063
75	1035	33.1	1150	1.408	29.9	1300	1.528	2.936	1.856
135	1084	34.6	1050	1.367	31.0	1250	1.535	2.902	1.788
195	1107	35.2	1010	1.350	32.0	1160	1.481	2.832	1.753
248	1037	35.1	1030	1.310	32.0	1160	1.418	2.728	1.753

The first measured distance of the balancing mass from the extremity of the wing was 0.25".
Lubricant: PENNZOIL 20W-50 (Motor oil)
Pitch of bearing: 65mm, Factor f_o: 1.5
Test date: 07/24/99

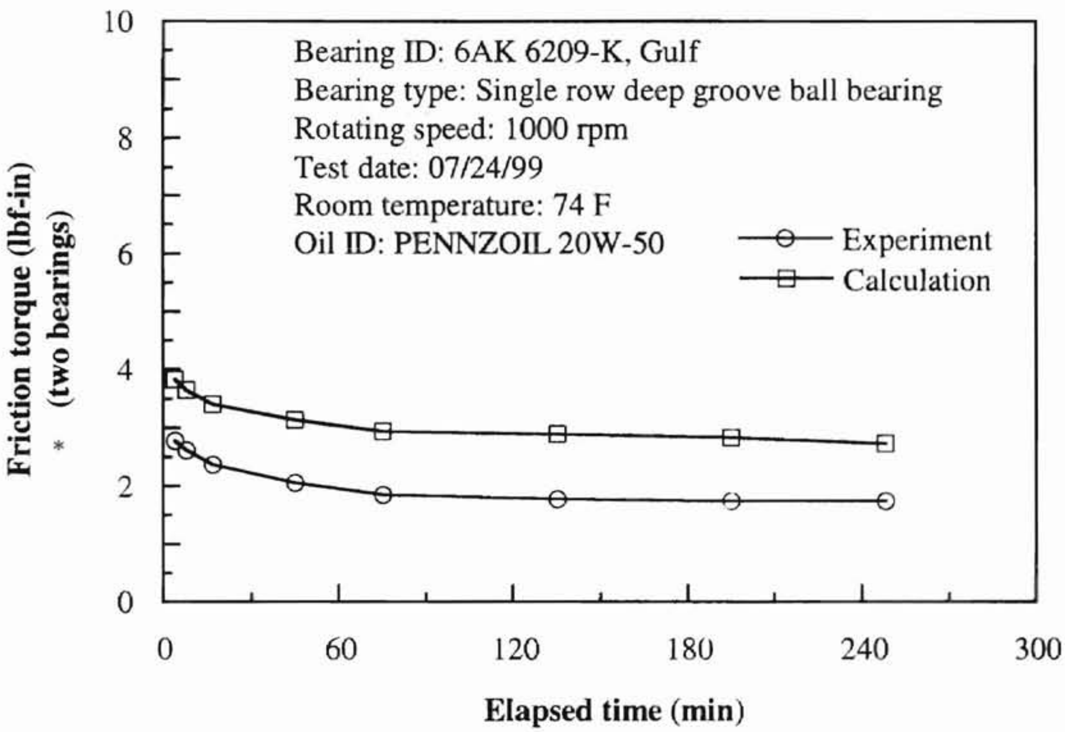

Figure 41. Effect of the elapsed time on bearing friction torque

Table 23. Effect of elapsed time on bearing friction torque

Loaded weight: 123.4 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
3	2111	28.4	1500	2.704	23.9	1900	3.165	5.869	4.469
6	2016	30.6	1300	2.383	24.9	1700	2.850	5.234	3.884
20	2087	37.4	900	1.908	29.9	1300	2.439	4.347	3.094
64	2070	43.3	675	1.566	38.1	875	1.862	3.428	2.544
112	2115	45.6	620	1.501	40.1	800	1.780	3.280	1.959
179	2010	45.2	625	1.459	39.1	850	1.791	3.250	1.856
286	1984	44.9	645	1.477	38.1	875	1.810	3.287	1.788
343	1988	45.0	640	1.471	39.1	850	1.778	3.249	1.788

The first measured distance of the balancing mass from the extremity of the wing was 0.375".
Lubricant: PENNZOIL 20W-50 (Motor oil)
Pitch of bearing: Factor f_o: 1.5
Test date: 07/28/99

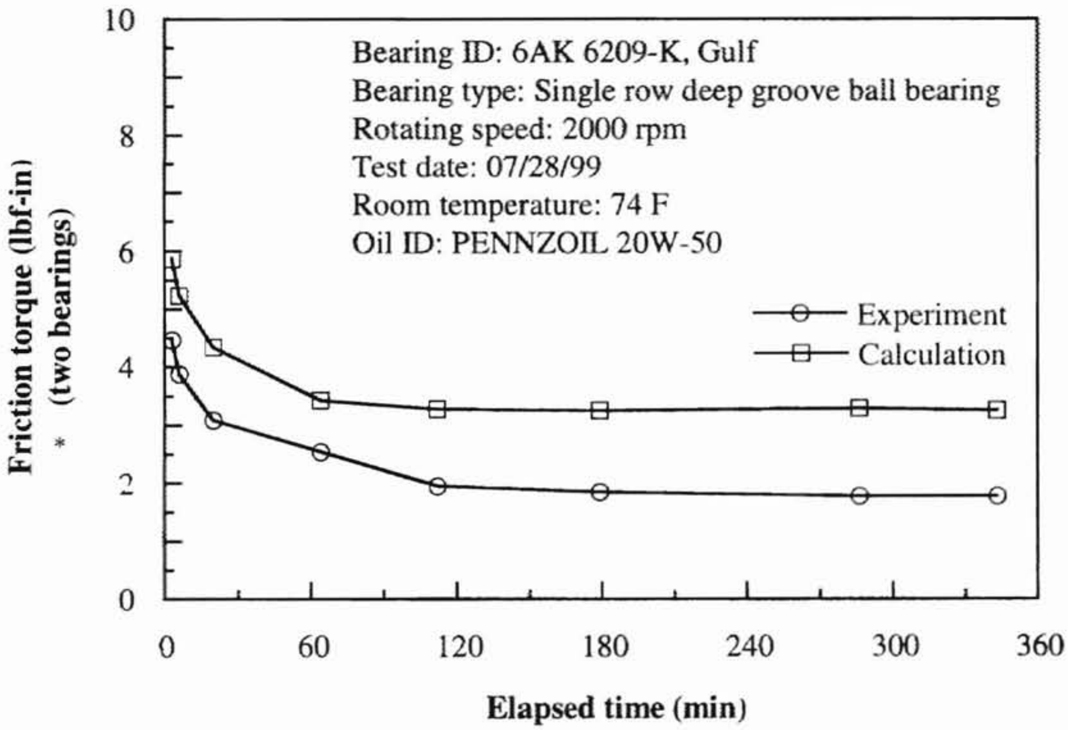

Figure 42. Effect of the elapsed time on bearing friction torque

Table 24. Effect of elapsed time on bearing friction torque

Loaded weight: 123.4 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
3	3026	30.8	1260	3.060	23.9	1900	4.024	7.084	4.125
6	3012	35.3	1000	2.614	25.9	1700	3.725	6.340	3.025
23	3012	45.8	620	1.900	33.0	1200	2.953	4.852	2.338
60	2961	51.6	475	1.571	41.1	1000	2.585	4.156	2.097
123	3016	53.8	410	1.441	44.2	660	1.983	3.424	1.788
153	3019	55.4	400	1.418	45.2	635	1.933	3.352	1.753
189	3021	55.6	390	1.395	46.2	600	1.862	3.257	1.753
237	2978	55.0	395	1.394	45.2	635	1.916	3.310	1.753

The first measured distance of the balancing mass from the extremity of the wing was 0.25".
Lubricant: PENNZOIL 20W-50 (Motor oil)
Pitch of bearing: 65mm, Factor f_o: 1.5
Test date: 07/29/99

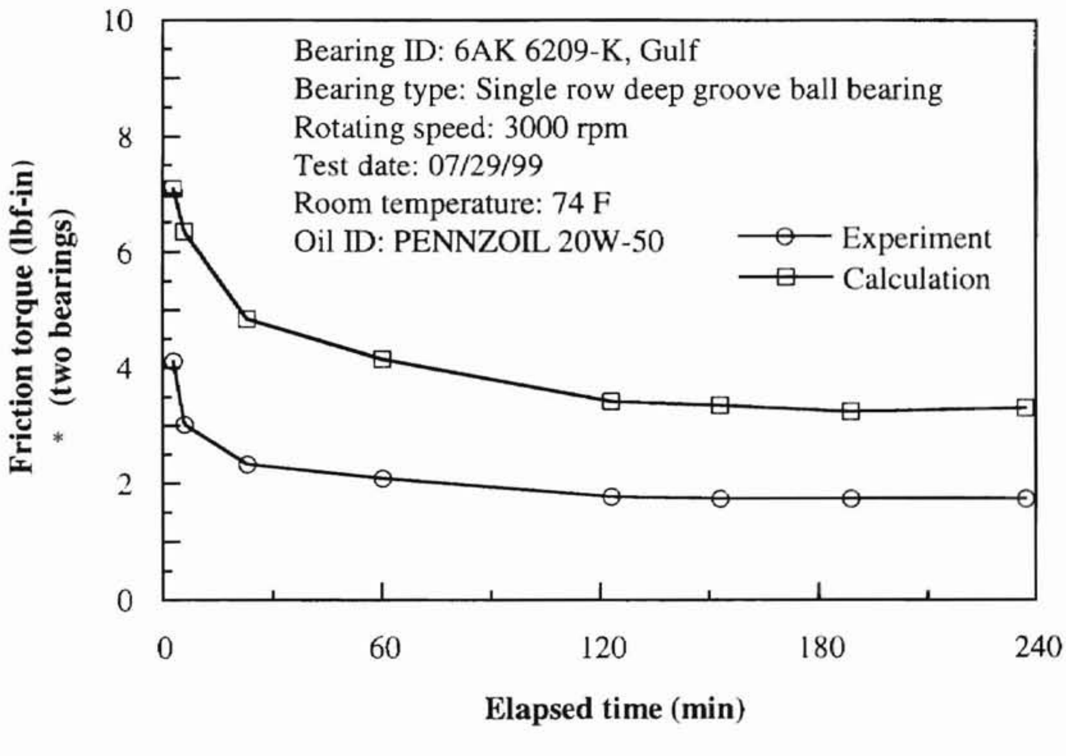

Figure 43. Effect of the elapsed time on bearing friction torque

As shown in Figure 44, the effect of rotating speed on the friction torque for single row deep groove ball bearings lubricated with PENNZOIL 20W-50 is not noteworthy. In addition, the effect of load is less important as presented in Figure 46. In Figure 47, it is evident that the effect of oil type on friction torque is substantial. The magnitude of friction torque for PENNZOIL 20W-50 is about two times as large as that for PENNZOIL DEXRON III. One single point in Figure 46 and 47 represents the steady state of friction torque.

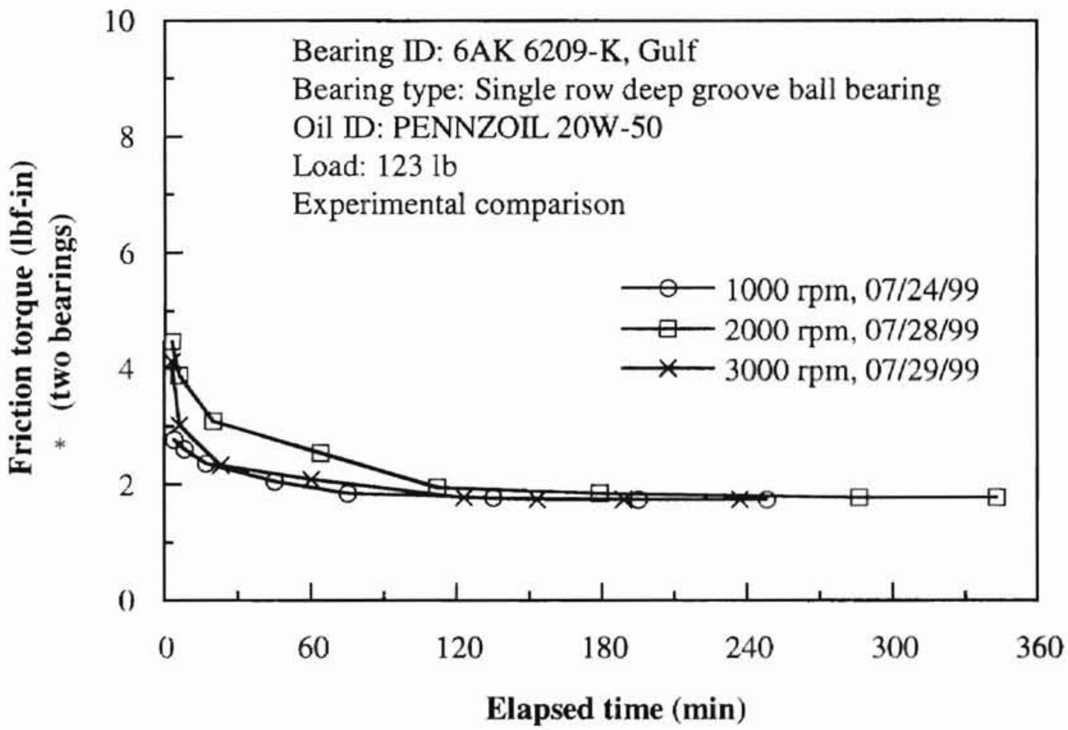

Figure 44. Effect of the elapsed time on bearing friction torque

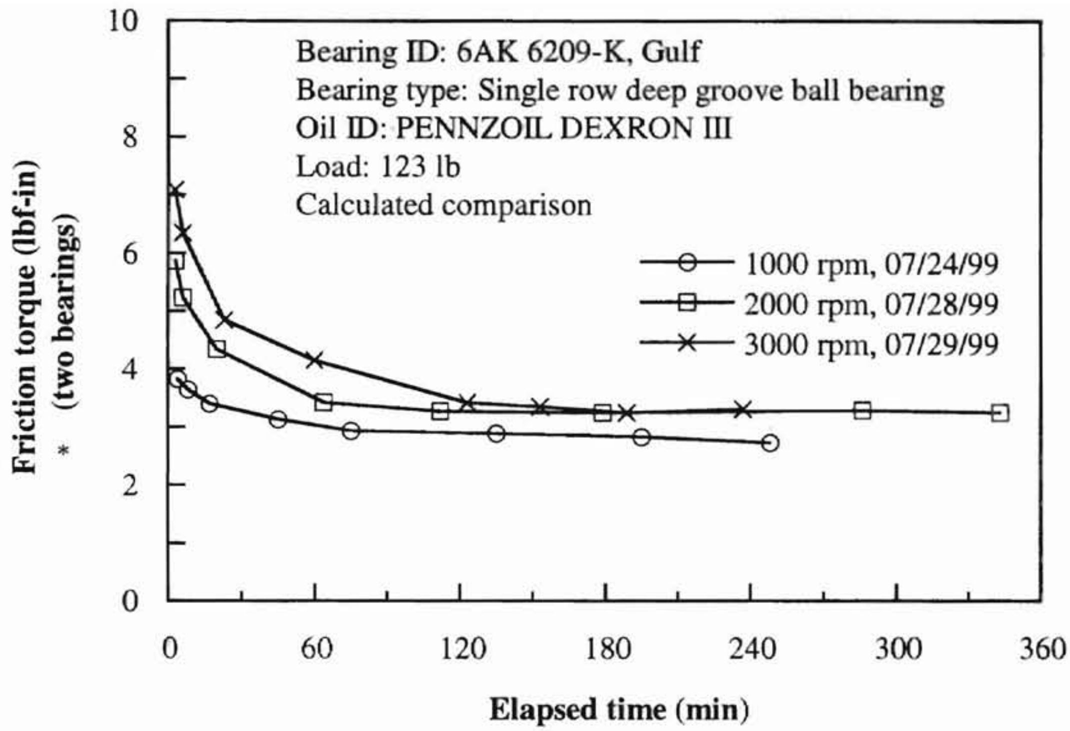

Figure 45. Effect of the elapsed time on bearing friction torque

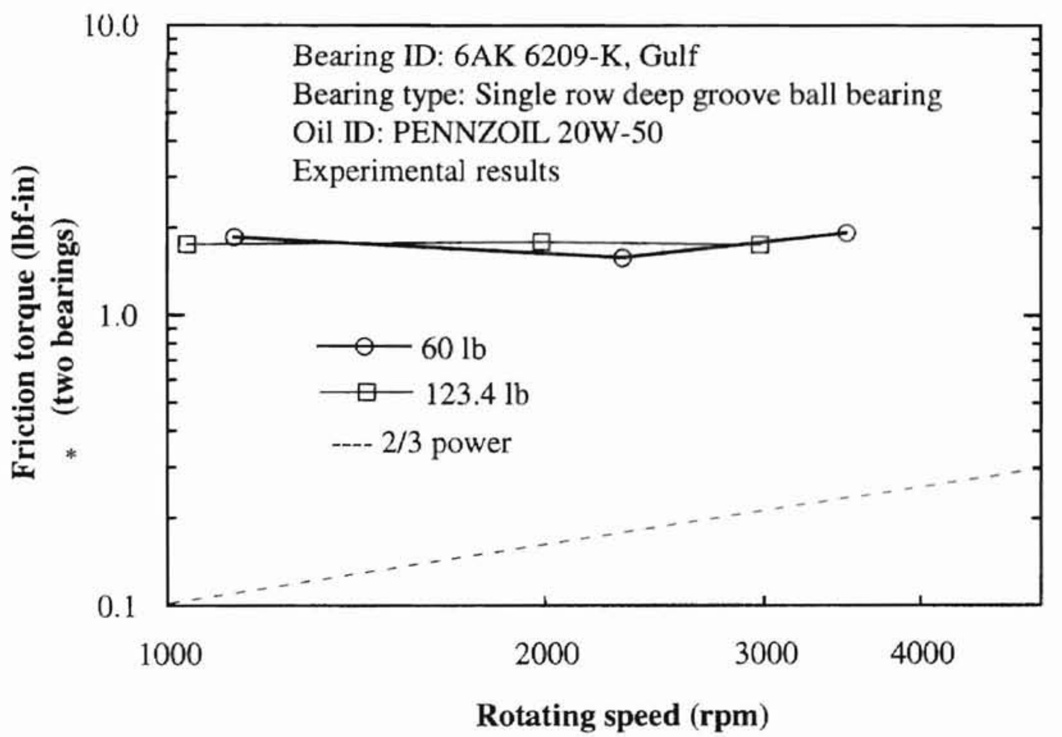

Figure 46. Effect of the elapsed time on bearing friction torque

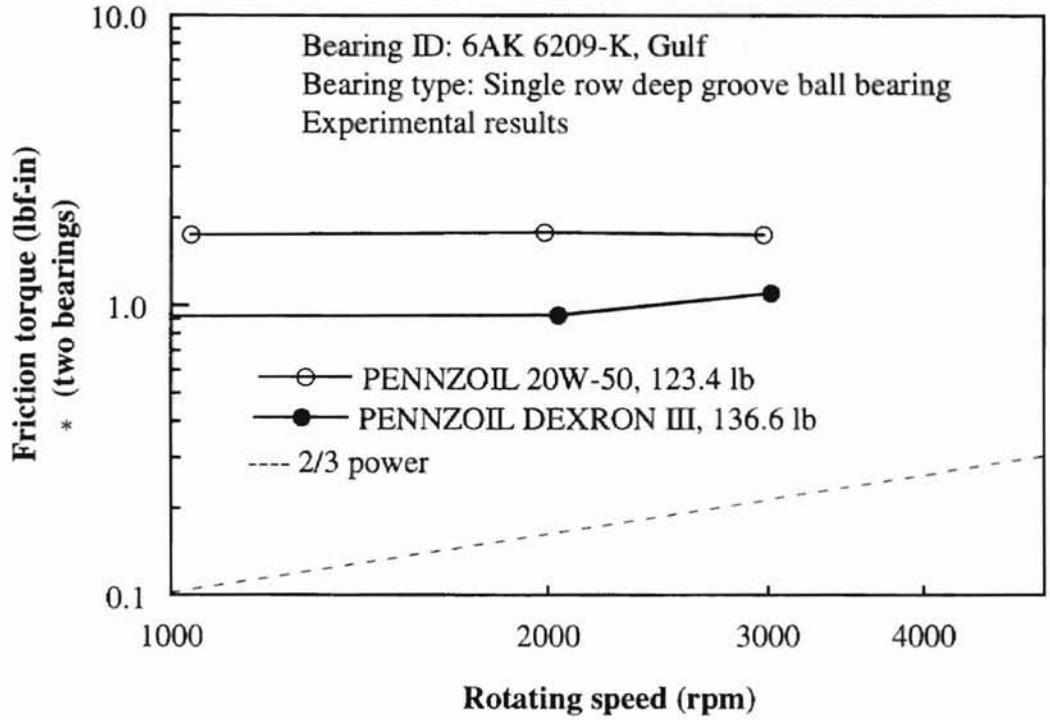

Figure 47. Comparison of different type of oil

3.3.2.2 2209 CCK/C 3W33 (Spherical roller bearing)

To find the effect of the rotating speed on the friction torque using spherical roller bearings in the same loading condition (135 *lb*), several tests were performed. Figures 47, 48, 49, and 50 show that the repeatability was good. The friction torque increased slightly with an increase in spindle speed up to 2000 rpm; however, no increase was observed when the speed was above 2000 rpm.

Table 25. Effect of elapsed time on bearing friction torque

Loaded weight: 135 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
5	980	23.3	330	1.570	23	330	1.570	3.139	2.166
20	994	25.6	307	1.509	25.2	305	1.503	3.012	1.959
35	1004	27.0	288	1.455	26.6	290	1.462	2.917	1.822
72	1017	28.9	272	1.412	28.5	270	1.405	2.817	1.684
105	1018	29.8	258	1.363	29.4	260	1.370	2.733	1.633
165	992	30.9	245	1.294	30.5	244	1.290	2.583	1.547
215	992	30.9	245	1.294	30.5	244	1.290	2.583	1.547

The first measured distance of the balancing mass from the extremity of the wing was 0.9063".
Lubricant: PENNZOIL DEXRON-III (Automatic transmission oil)
Pitch of bearing: 65mm, Factor f_o: 4
Test date: 05/14/99

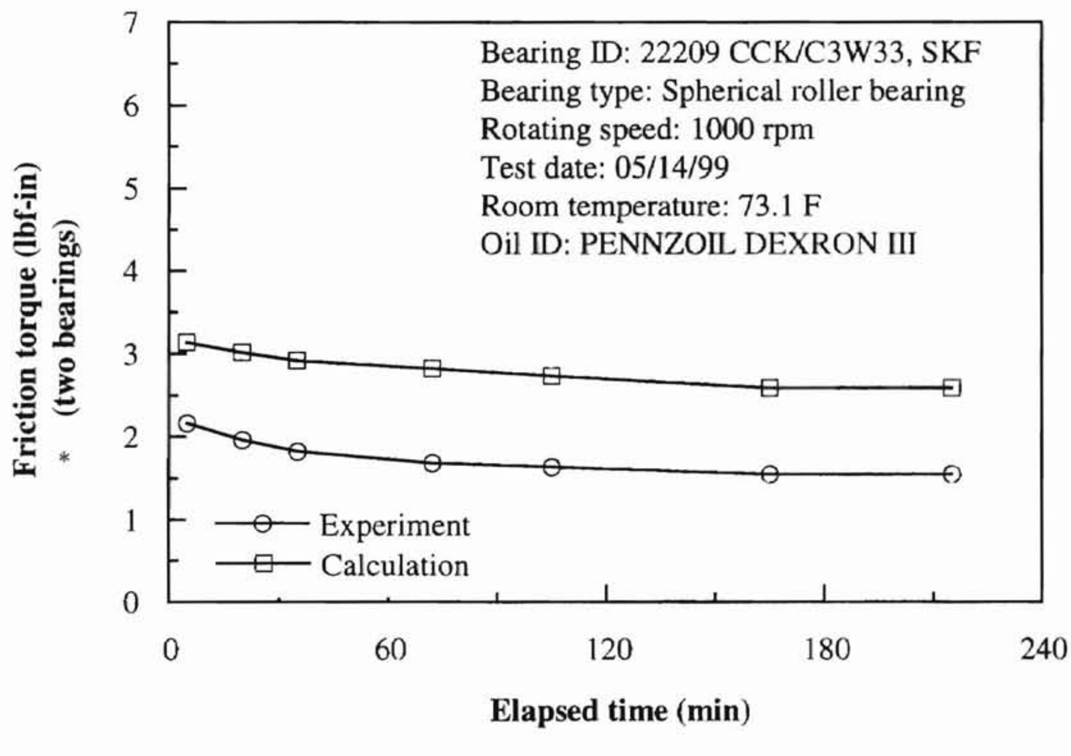

Figure 48. Effect of the elapsed time on bearing friction torque

Table 26. Effect of elapsed time on bearing friction torque

Loaded weight: 135 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
2	999	23.0	350	1.654	22.8	360	1.686	3.340	2.200
8	1003	24.0	327	1.584	23.9	330	1.594	3.179	2.131
25	1019	26.5	300	1.511	25.9	310	1.545	3.055	2.063
45	1005	27.9	282	1.435	27.9	280	1.429	2.864	2.028
80	986	29.4	270	1.376	29.9	260	1.341	2.718	1.959
135	990	30.6	257	1.334	31.0	247	1.299	2.633	1.891
165	990	30.8	250	1.310	31.0	247	1.299	2.609	1.891
225	998	31.5	242	1.288	32.0	240	1.281	2.569	1.856
265	999	31.5	242	1.289	32.0	240	1.281	2.570	1.856

The first measured distance of the moving mass from the extremity of the wing was 0.90".
Lubricant: PENNZOIL DEXRON III (Automatic transmission oil)
Pitch of bearing: 65mm, Factor f_o: 4
Test date: 05/22/99

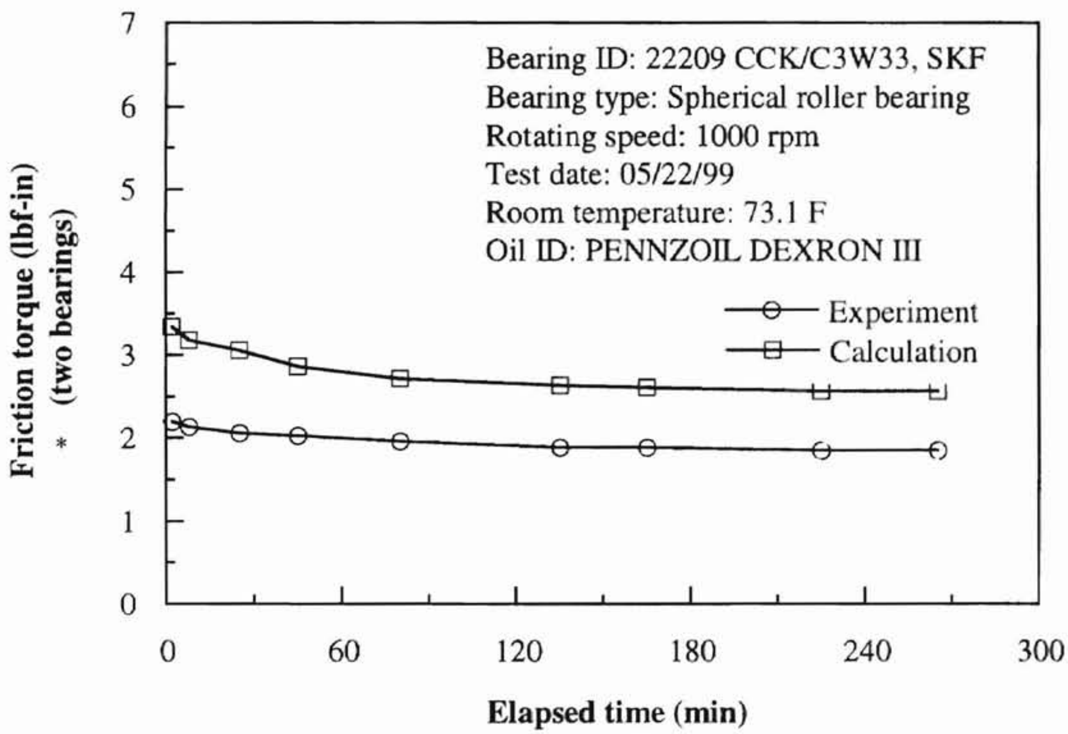

Figure 49. Effect of the elapsed time on bearing friction torque

Table 27. Effect of elapsed time on bearing friction torque

Loaded weight: 135 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
4	2009	24.0	315	2.455	24.9	320	2.481	4.936	2.956
10	2028	27.3	295	2.363	27.9	280	2.281	4.644	2.750
30	2024	32.2	220	1.934	33.0	230	1.993	3.927	2.509
115	2003	39.2	185	1.705	40.1	180	1.673	3.377	2.200
200	1991	43.0	160	1.535	44.2	155	1.501	3.036	2.063
260	2000	43.0	160	1.539	44.2	155	1.506	3.045	2.063

The first measured distance of the balancing mass from the extremity of the wing was 0.75".
Lubricant: PENNZOIL DEXRON III (Automatic transmission oil)
Pitch of bearing: 65mm, Factor f_o: 4
Test date: 05/16/99

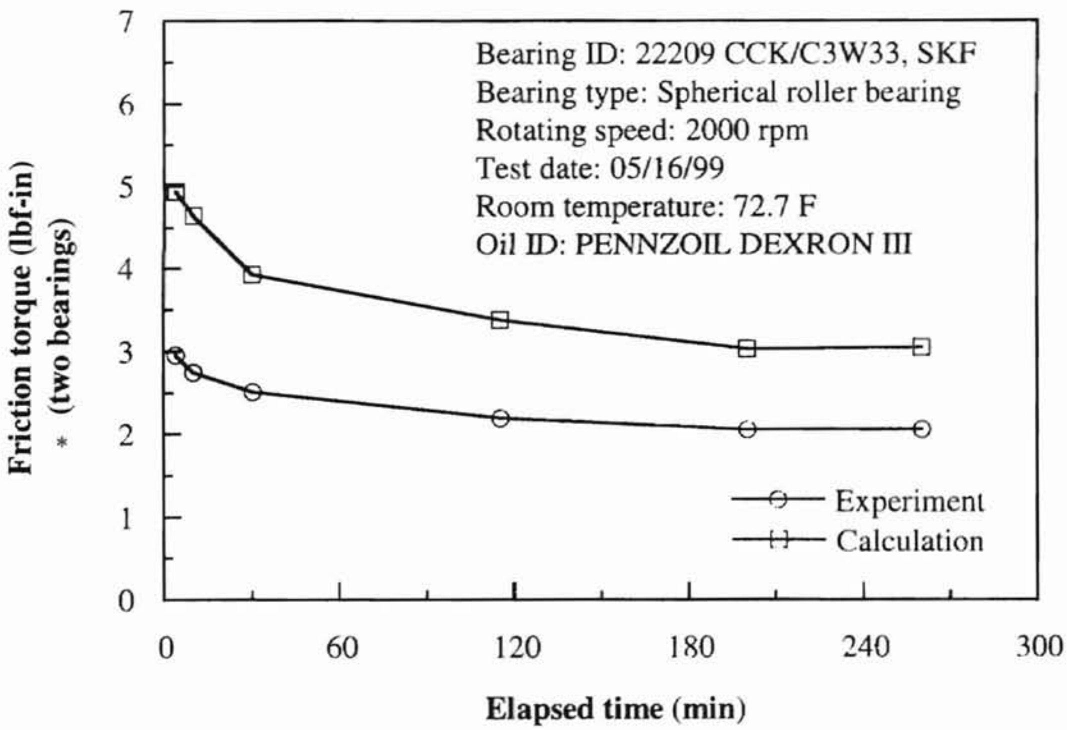

Figure 50. Effect of the elapsed time on bearing friction torque

Table 28. Effect of elapsed time on bearing friction torque

Loaded weight: 135 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
5	2085	25.3	315	2.516	24.9	320	2.543	5.060	3.094
10	2043	28.0	300	2.402	27.9	280	2.292	4.694	2.853
17	2006	29.9	280	2.265	31.0	247	2.080	4.345	2.681
28	2028	32.8	235	2.025	33.0	230	1.996	4.021	2.578
50	2033	37.4	185	1.722	38.1	190	1.754	3.475	2.406
90	1996	41.1	175	1.636	41.1	168	1.591	3.227	2.320
130	2006	42.9	162	1.556	43.1	162	1.556	3.112	2.200
180	2017	43.8	158	1.535	43.1	162	1.562	3.096	2.200
230	2015	44.4	155	1.513	43.1	162	1.561	3.074	2.166
260	2014	44.4	155	1.513	43.1	162	1.560	3.073	2.166

The first measured distance of the moving mass from the extremity of the wing was 1".
Lubricant: PENNZOIL DEXRON III (Automatic transmission oil)
Pitch of bearing: 65mm, Factor f_o: 4
Test date: 05/31/99

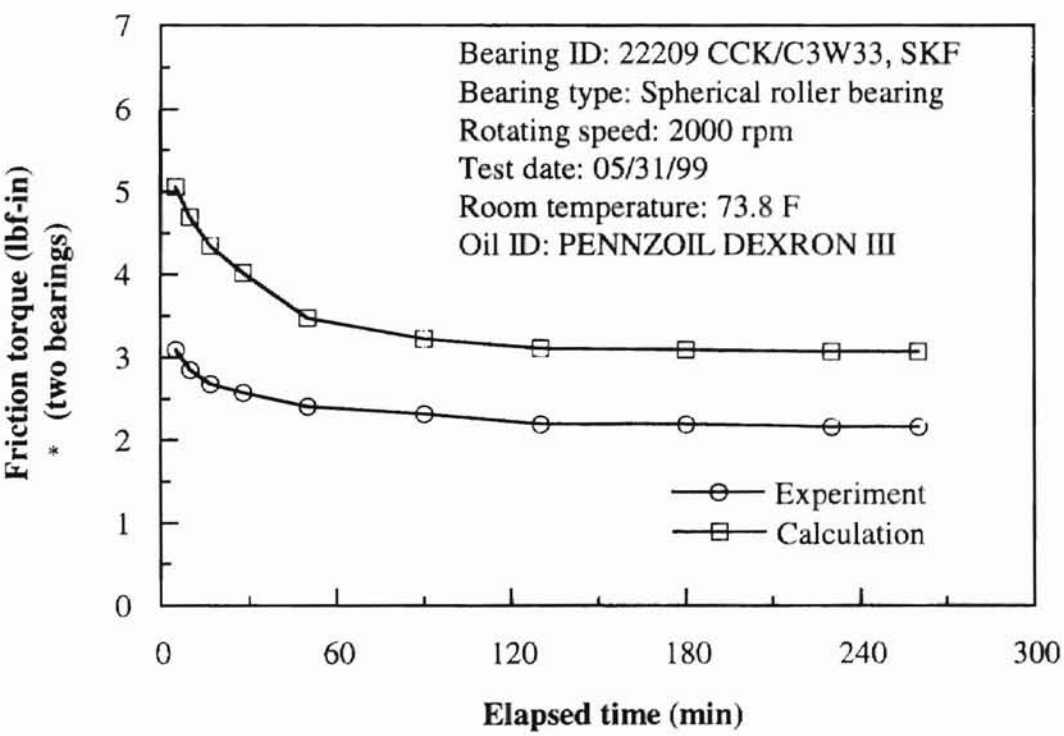

Figure 51. Effect of the elapsed time on bearing friction torque

Table 29. Effect of elapsed time on bearing friction torque

Loaded weight: 135 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
3	3484	27.3	295	3.390	29.9	260	3.112	6.502	3.059
11	3615	34.7	215	2.802	37.1	195	2.620	5.422	2.716
16	3649	39.4	183	2.524	40.1	178	2.476	4.999	2.441
21	3577	43.9	156	2.228	44.2	158	2.248	4.477	2.166
32	3633	48.4	132	2.001	47.2	140	2.086	4.087	2.028
52	3610	54.0	117	1.826	52.3	133	2.003	3.829	1.753
91	3557	60.6	98	1.585	59.4	100	1.609	3.195	1.478
128	3575	62.5	94	1.541	60.4	98	1.590	3.131	1.409
151	3569	62.7	94	1.539	60.4	98	1.589	3.128	1.409
176	3570	62.6	94	1.539	60.4	98	1.589	3.128	1.409

The first measured distance of the moving mass from the extremity of the wing was 0.78".
Lubricant: PENNZOIL DEXRON III (Automatic transmission oil)
Pitch of bearing: 65mm, Factor f_o: 4
Test date: 05/21/99

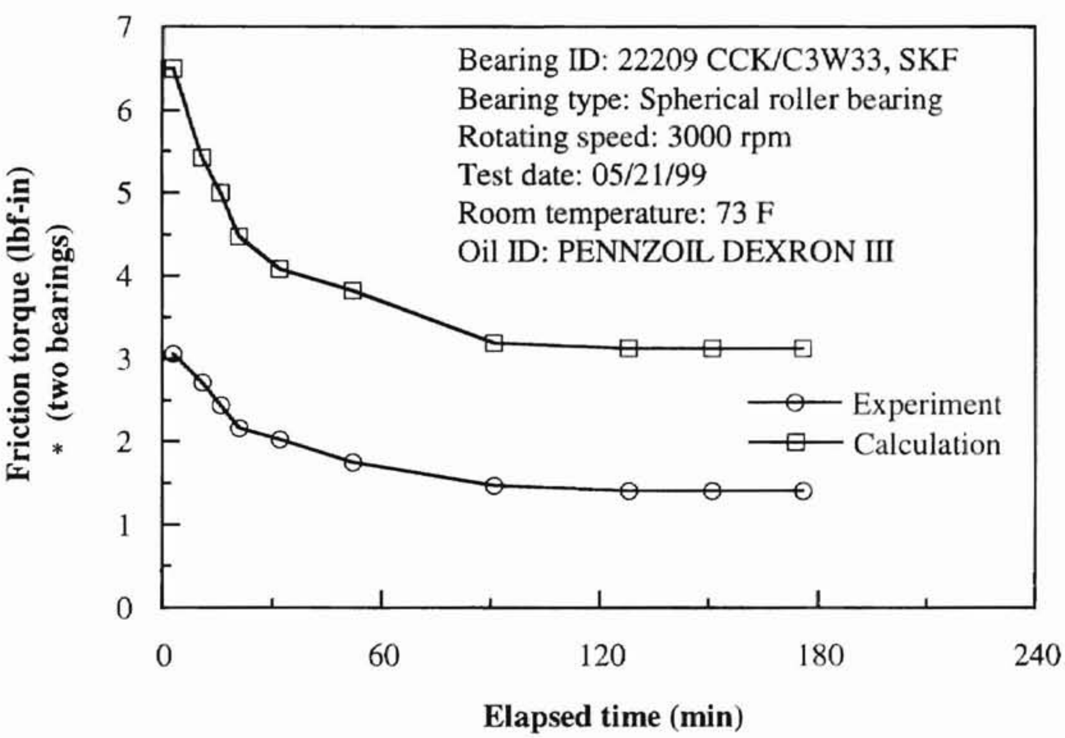

Figure 52. Effect of the elapsed time on bearing friction torque

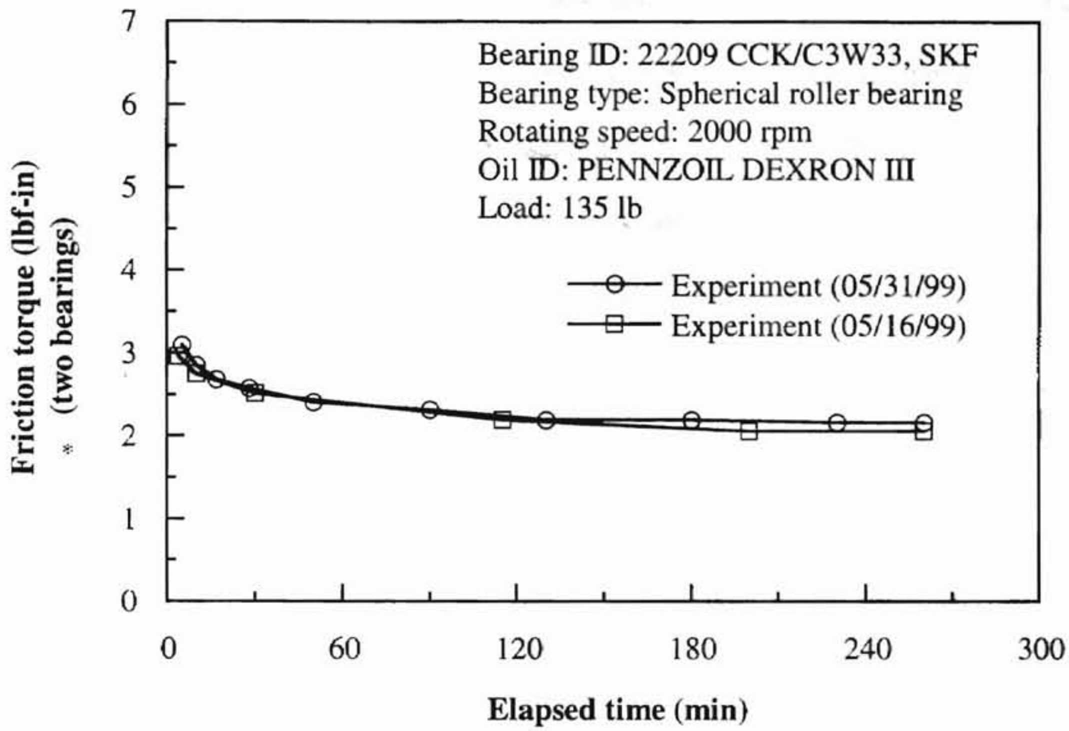

Figure 53. Effect of the elapsed time on bearing friction torque

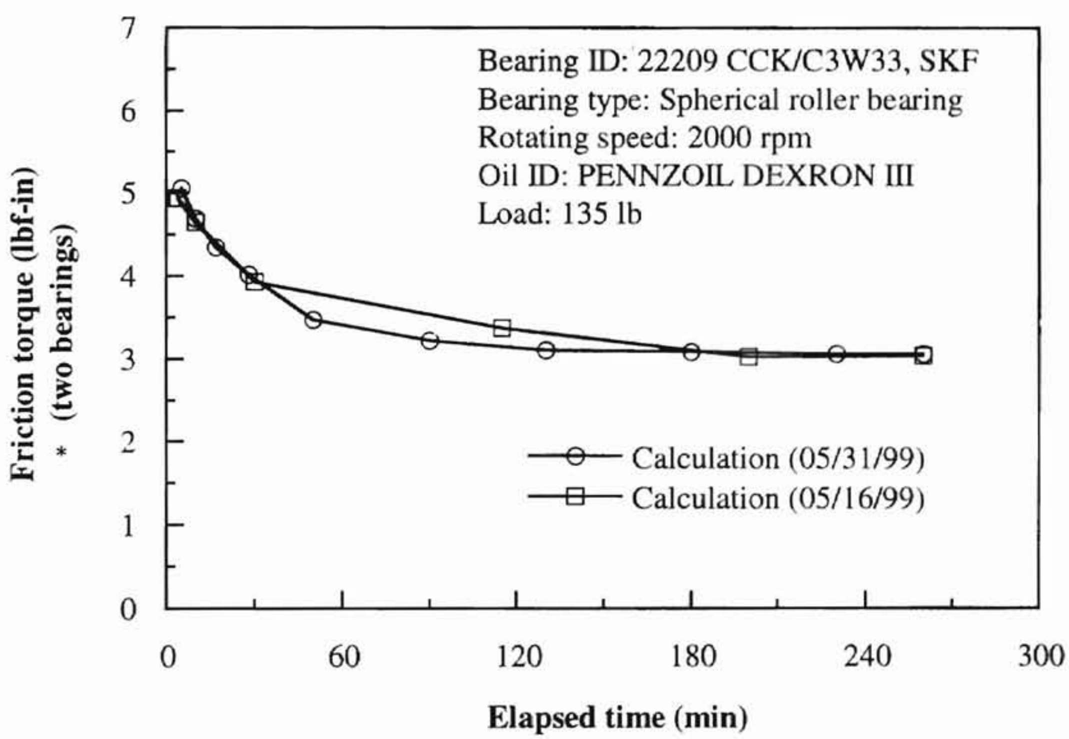

Figure 54. Effect of the elapsed time on bearing friction torque

The friction torque increased slightly with an increase in spindle speed up to 2000 rpm; however, this phenomenon did not continue when the rotating speed was above 2000 rpm in the experimental results presented in Figure 55. One single data point represents the steady state of friction torque. It is possible that the rotating speed does not play an important role on the friction torque, but it is difficult to draw any conclusions due to the data scatter.

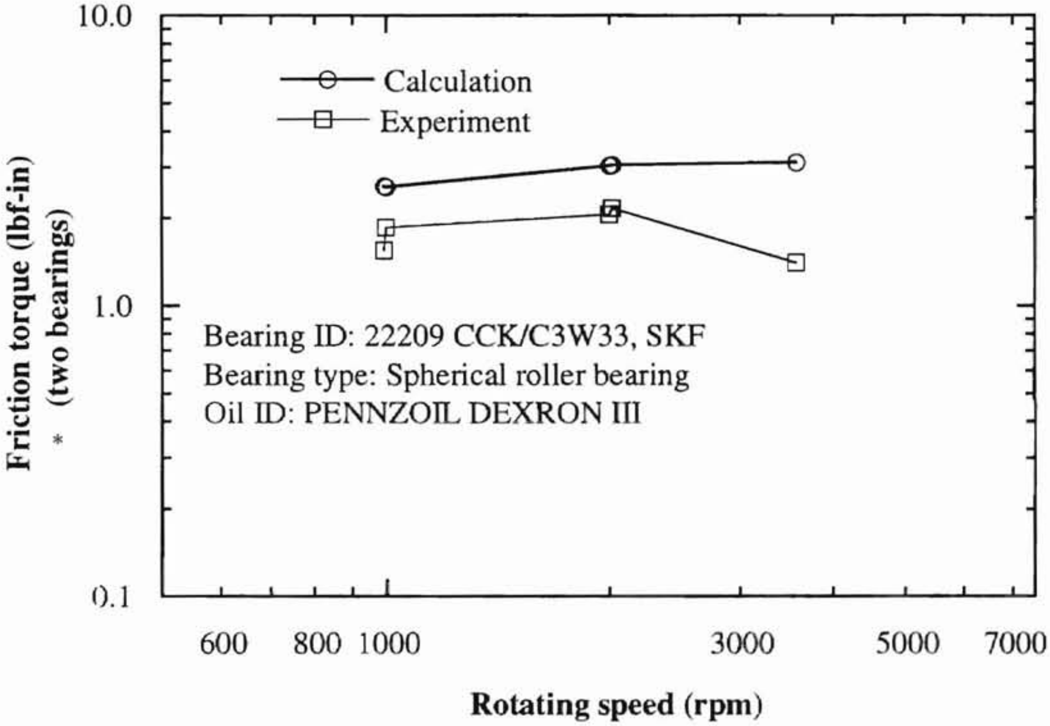

Figure 55. Effect of the elapsed time on bearing friction torque

3.3.2.3 NP-23 (Mounted pillow block)

Sealmaster Gold line mounted ball bearing units installed in pillow blocks were tested with loads from 50 *lb* to 203 *lb* as summarized in Figures 59 and 60. As expected, the friction torque dropped slowly when a light lubricant was used and approached a steady state.

Table 30. Effect of elapsed time on bearing friction torque

Loaded weight: 50 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
5	2498	24.4	325	0.629	23.9	337	0.613	1.242	0.756
15	2528	27.9	280	0.583	26.9	298	0.559	1.142	0.688
30	2551	29.3	265	0.549	28.9	270	0.542	1.091	0.619
75	2576	30.6	250	0.538	29.9	260	0.524	1.063	0.636
105	2518	30.3	260	0.530	29.9	260	0.530	1.061	0.636
140	2525	30.4	255	0.531	29.9	260	0.524	1.056	0.636
167	2530	30.5	258	0.532	29.9	260	0.529	1.061	0.636

The first measured distance of the moving mass from the extremity of the wing was 2.25".
Lubricant: PENNZOIL DEXRON III (Automatic transmission oil)
Pitch of bearing: 53.7mm, Factor f_o: 1.5
Test date: 07/06/99

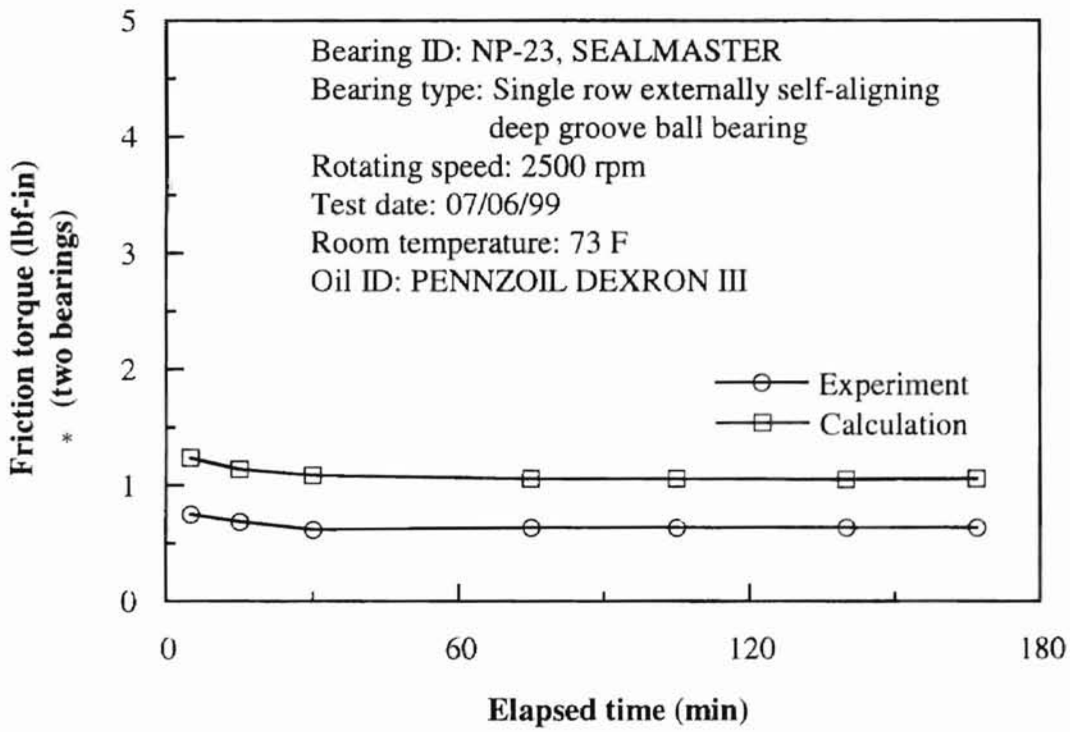

Figure 56. Effect of the elapsed time on bearing friction torque

Table 31. Effect of elapsed time on bearing friction torque

Loaded weight: 135 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
2	2001	23.8	330	0.534	23.9	330	0.534	1.069	0.997
14	2068	27.2	293	0.493	26.9	297	0.498	0.9910	0.928
47	2035	29.5	261	0.466	28.9	275	0.483	0.9490	0.859
122	2066	30.1	250	0.448	29.9	260	0.46	0.9080	0.928
182	1989	29.2	267	0.473	28.9	270	0.477	0.9500	0.928
262	1998	28.3	280	0.476	28.9	270	0.465	0.9410	0.928

The first measured distance of the moving mass from the extremity of the wing was 4".
Lubricant: PENNZOIL DEXRON III (Automatic transmission oil)
Pitch of bearing: 53.7mm, Factor f_o: 1.5
Test date: 06/27/99

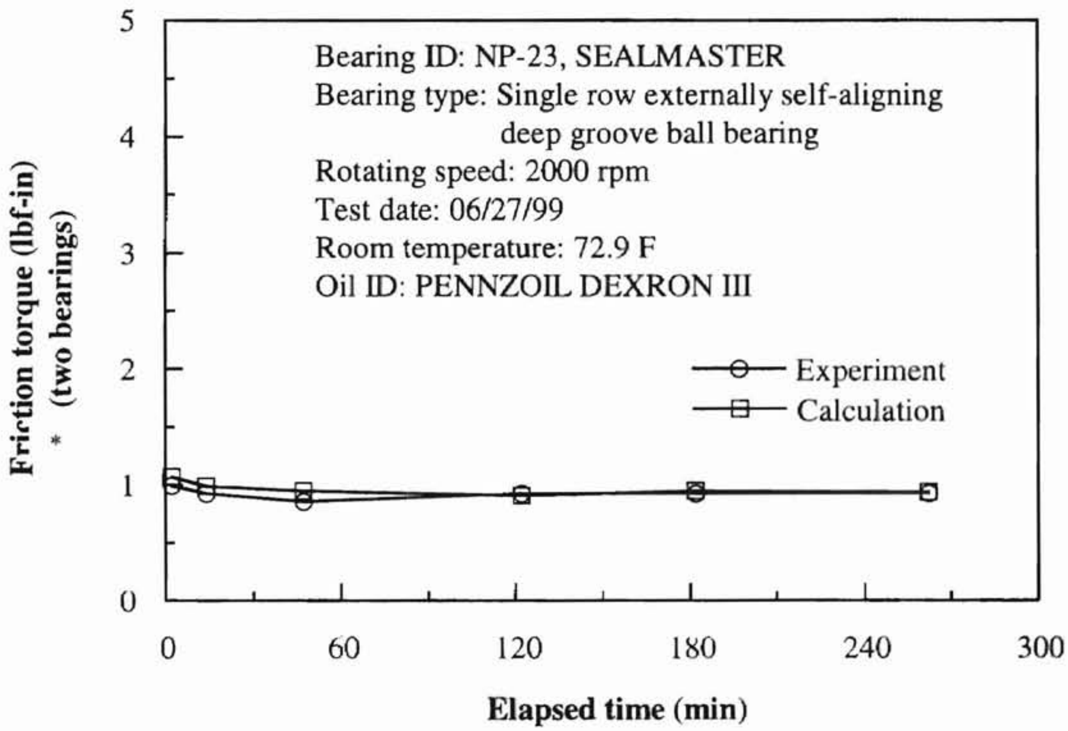

Figure 57. Effect of the elapsed time on bearing friction torque

Table 32. Effect of elapsed time on bearing friction torque

Loaded weight: 203.25 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
3	2488	25.2	320	0.605	23.9	335	0.624	1.230	0.825
12	2488	27.5	290	0.566	26.9	300	0.580	1.146	0.722
23	2516	29.0	270	0.544	28.9	272	0.546	1.090	0.653
49	2515	29.9	262	0.533	29.9	262	0.533	1.065	0.619
102	2513	30.7	248	0.513	31.0	244	0.507	1.020	0.619
147	2524	30.7	248	0.514	31.0	244	0.509	1.023	0.619

The first measured distance of the moving mass from the extremity of the wing was 1.8".
Lubricant: PENNZOIL DEXRON III (Automatic transmission oil)
Pitch of bearing: 53.7mm, Factor f_o: 1.5
Test date: 07/14/99

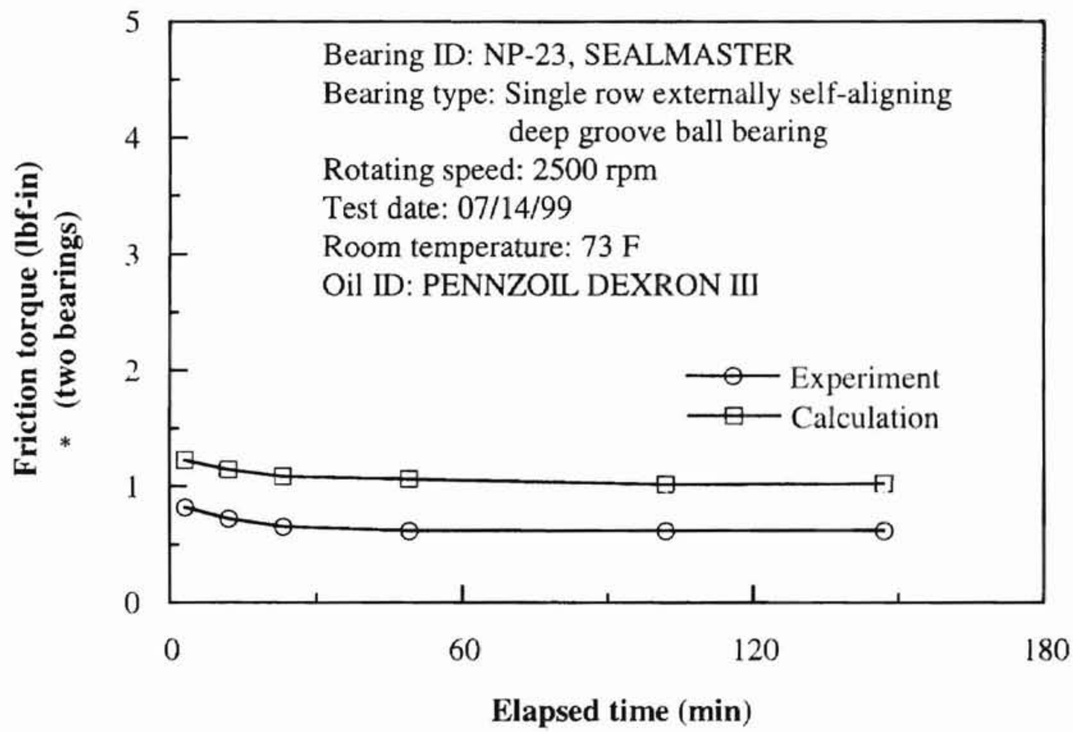

Figure 58. Effect of the elapsed time on bearing friction torque

Figure 58 shows the load effect indicating that if the load was increased from 50 *lb* to 203.25 *lb*, the friction torque did not consistently behave when the light lubricant was used. It is also not clear to see the trend.

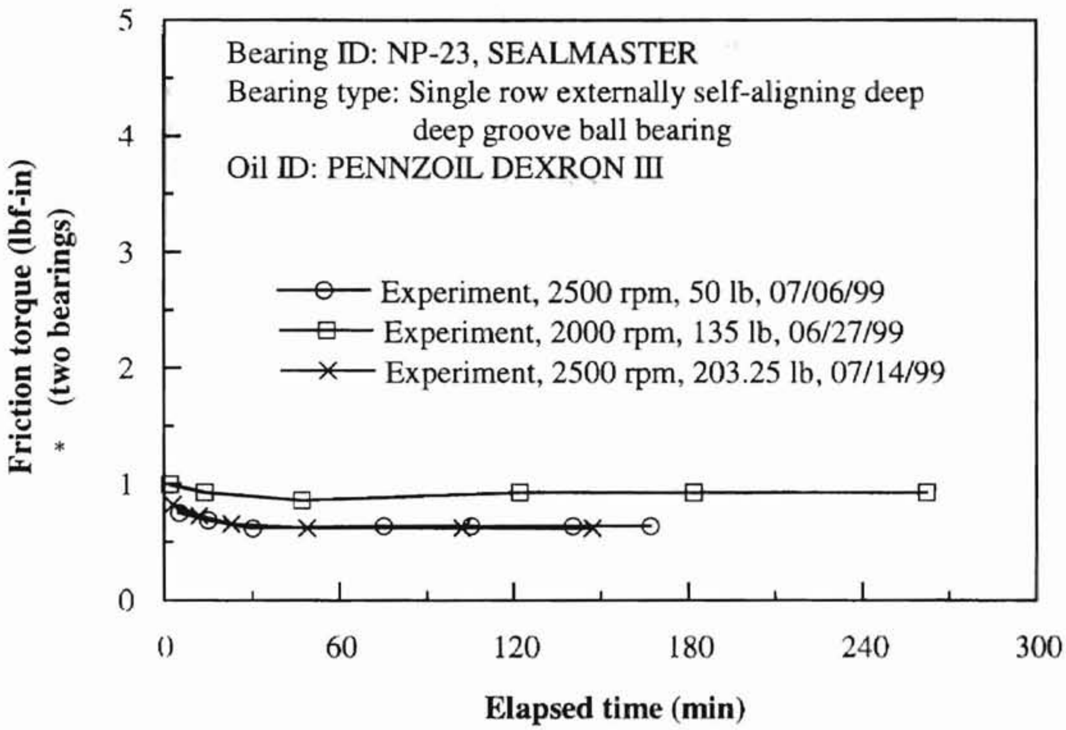

Figure 59. Effect of the elapsed time on bearing friction torque

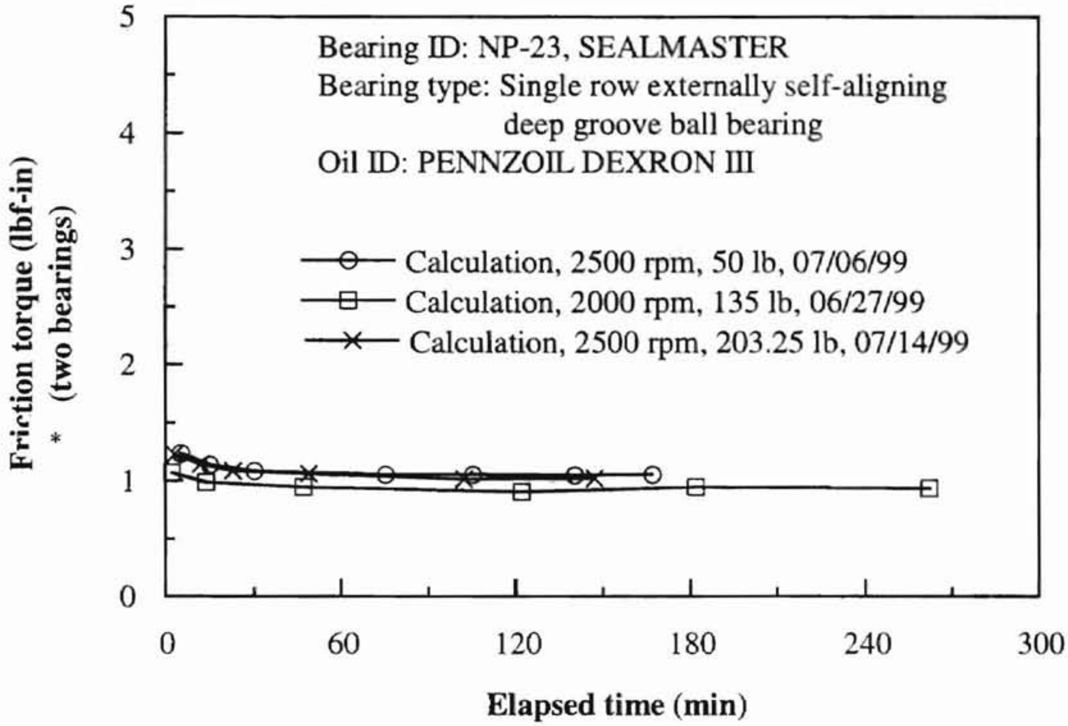

Figure 60. Effect of the elapsed time on bearing friction torque

3.3.2.4 1209K EK TN9/C3 (Double row internally self-aligning ball bearing)

Internally self-aligning ball bearings consist of two rows of balls in two grooves in the inner ring and a spherical outer raceway. These bearings therefore allow misalignment of the shaft with the housing to avoid the occurrence of vibration and high loads. Figure 64 shows that the repeatability was good at 1000 rpm. The effect of oil type, as shown in Figure 85, indicates that the viscosity considerably affects the friction torque. On the other hand, the effect of load, as shown in Figure 83, implies that the load does not substantially affect the friction torque.

Table 33. Effect of elapsed time on bearing friction torque

Loaded weight: 60.8 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
2	1059	24.0	1800	1.928	22.8	2020	2.082	4.010	2.269
9	1082	27.4	1550	1.770	22.8	2020	2.112	3.882	1.925
45	1081	29.0	1400	1.653	24.9	1800	1.955	3.608	1.684
91	1018	31.7	1220	1.449	27.9	1510	1.670	3.119	1.547
139	1020	31.5	1250	1.475	28.9	1400	1.590	3.065	1.478
178	1020	31.7	1220	1.451	28.9	1400	1.590	3.041	1.444
226	1022	32.0	1200	1.437	28.9	1400	1.592	3.029	1.409
296	1024	32.0	1200	1.439	28.9	1400	1.594	3.033	1.409

The first measured distance of the moving mass from the extremity of the wing was 2".
Lubricant: PENNZOIL 20W-50 (Motor oil)
Pitch of bearing: 65mm, Factor f_o: 1.5
Test date: 08/01/99

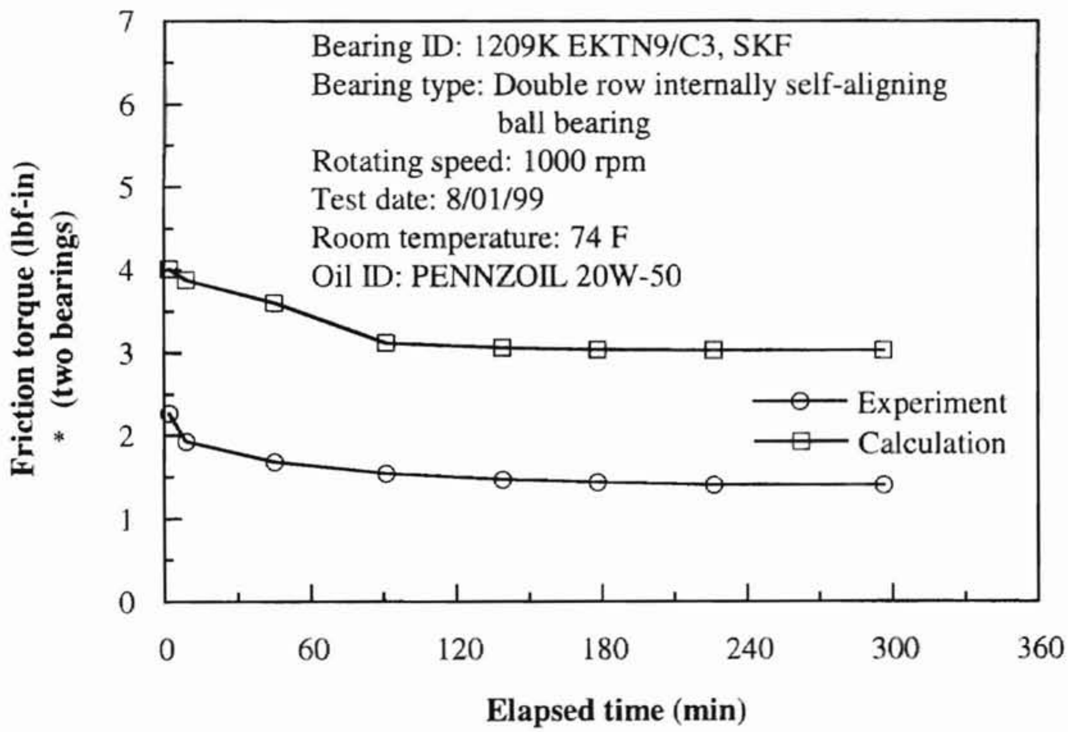

Figure 61. Effect of the elapsed time on bearing friction torque

Table 34. Effect of elapsed time on bearing friction torque

Loaded weight: 60.8 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
3	1085	24.9	1700	1.886	22.8	2000	2.102	3.988	2.716
7	1076	26.0	1670	1.854	23.9	1800	1.949	3.802	2.509
14	1087	27.3	1550	1.776	24.9	1700	1.888	3.664	2.372
26	1079	28.8	1400	1.651	25.9	1650	1.842	3.493	2.166
48	1062	30.6	1300	1.555	27.9	1450	1.672	3.227	1.959
93	1073	32.1	1170	1.459	29.9	1300	1.566	3.025	1.822
140	1084	33.2	1130	1.436	31.0	1250	1.536	2.971	1.753
184	1054	34.2	1100	1.384	32.0	1180	1.450	2.834	1.684
238	1040	34.0	1050	1.330	32.0	1180	1.437	2.767	1.650
308	1040	33.6	1120	1.388	32.0	1180	1.437	2.826	1.650

The first measured distance of the moving mass from the extremity of the wing was 3.81".
Lubricant: PENNZOIL 20W-50 (Motor oil)
Pitch of bearing: 65mm, Factor f_o: 1.5
Test date: 08/14/99

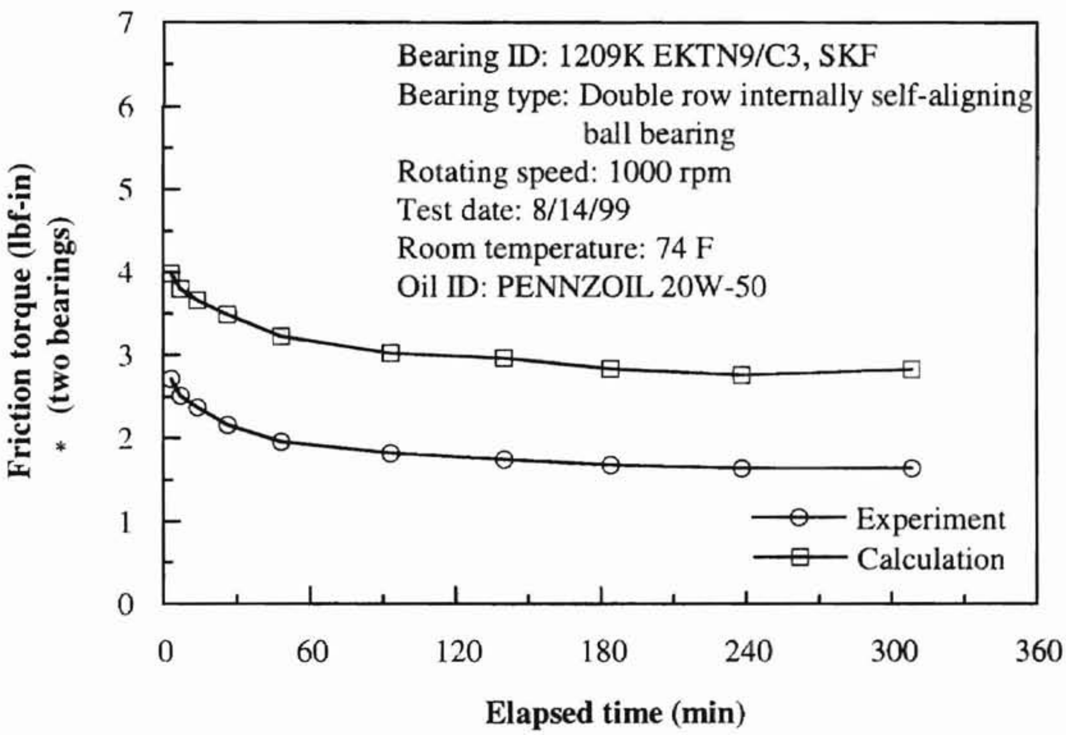

Figure 62. Effect of the elapsed time on bearing friction torque

Table 35. Effect of elapsed time on bearing friction torque

Loaded weight: 60.8 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
3	1058	24.9	1800	1.927	22.8	2000	2.067	3.994	2.578
8	1067	26.1	1620	1.806	23.9	1900	2.009	3.815	2.372
15	1084	27.5	1520	1.749	24.9	1800	1.958	3.708	2.234
25	1078	28.7	1470	1.705	25.9	1650	1.841	3.546	2.063
53	1046	30.3	1280	1.523	27.9	1500	1.693	3.217	1.856
89	1055	31.5	1220	1.484	28.9	1420	1.642	3.126	1.788
133	1064	32.7	1200	1.476	31.0	1270	1.533	3.009	1.719
173	1071	34.2	1100	1.399	32.0	1190	1.474	2.873	1.650
208	1062	34.0	1110	1.399	32.0	1190	1.466	2.865	1.650
241	1064	33.7	1160	1.443	31.0	1270	1.533	2.976	1.650

The first measured distance of the moving mass from the extremity of the wing was 3.875".
Lubricant: PENNZOIL 20W-50 (Motor oil)
Pitch of bearing: 65mm, Factor f_o: 1.5
Test date: 08/17/99

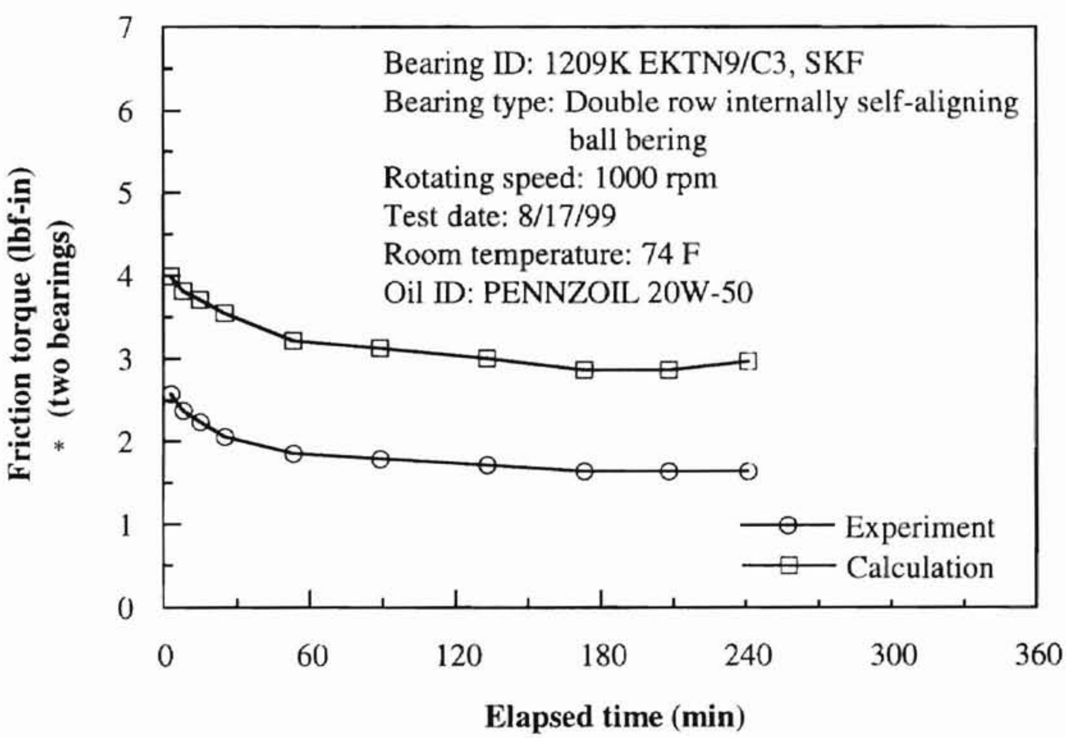

Figure 63. Effect of the elapsed time on bearing friction torque

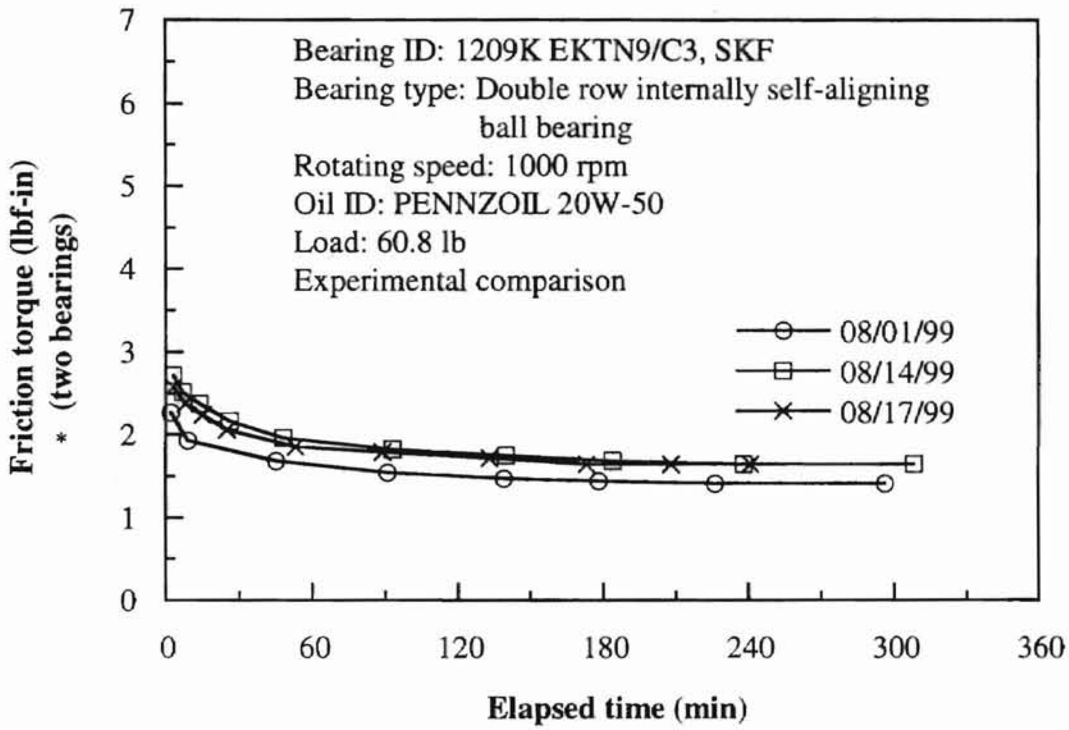

Figure 64. Effect of the elapsed time on bearing friction torque

Table 36. Effect of elapsed time on bearing friction torque

Loaded weight: 60.8 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
7	2448	30.9	1280	2.685	25.9	1700	3.245	5.930	3.403
13	2484	35.4	1000	2.300	28.9	1420	2.906	5.206	3.059
23	2470	38.4	875	2.096	33.0	1100	2.442	4.538	2.681
69	2520	43.8	670	1.778	40.1	800	2.001	3.780	2.200
124	2482	46.3	580	1.599	43.1	700	1.812	3.411	1.994
194	2475	48.8	550	1.540	45.2	625	1.677	3.218	1.856
249	2466	48.7	560	1.555	44.2	650	1.718	3.273	1.856

The first measured distance of the moving mass from the extremity of the wing was 3.84".
Lubricant: PENNZOIL 20W-50 (Motor oil)
Pitch of bearing: 65mm, Factor f_o: 1.5
Test date: 08/21/99

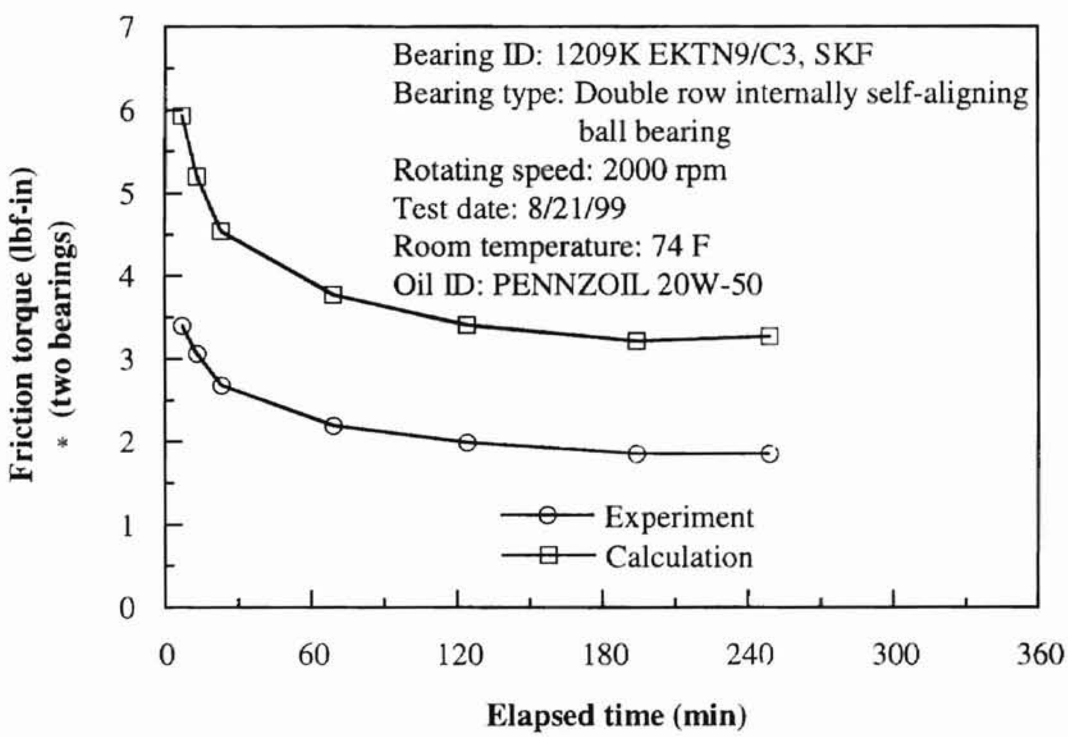

Figure 65. Effect of the elapsed time on bearing friction torque

Table 37. Effect of elapsed time on bearing friction torque

Loaded weight: 60.8 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
5	2873	32.7	1280	2.402	26.9	1700	2.902	5.304	4.056
10	2870	35.9	1000	2.036	31.0	1420	2.572	4.608	3.334
20	2864	39.8	875	1.860	35.0	1100	2.167	4.027	2.853
47	2832	46.8	670	1.545	42.1	800	1.739	3.284	2.372
71	2832	49.1	580	1.404	44.2	700	1.591	2.994	2.200
152	2821	51.3	550	1.351	47.2	625	1.471	2.823	2.063
210	2851	51.7	560	1.377	47.2	650	1.521	2.898	2.063
250	2853	51.9	550	1.361	48.2	620	1.475	2.836	2.028
342	2854	51.8	555	1.370	50.3	600	1.443	2.813	2.028

The first measured distance of the moving mass from the extremity of the wing was 3.84".
Lubricant: PENNZOIL 20W-50 (Motor oil)
Pitch of bearing: 65mm, Factor f_o: 1.5
Test date: 08/22/99

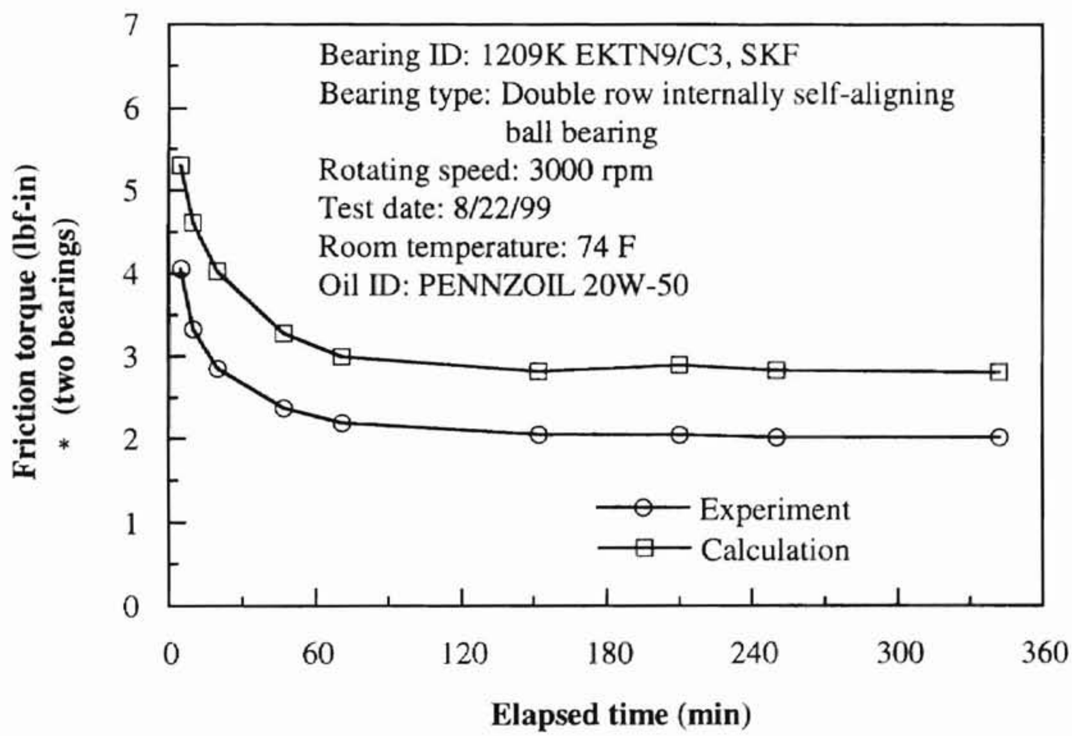

Figure 66. Effect of the elapsed time on bearing friction torque

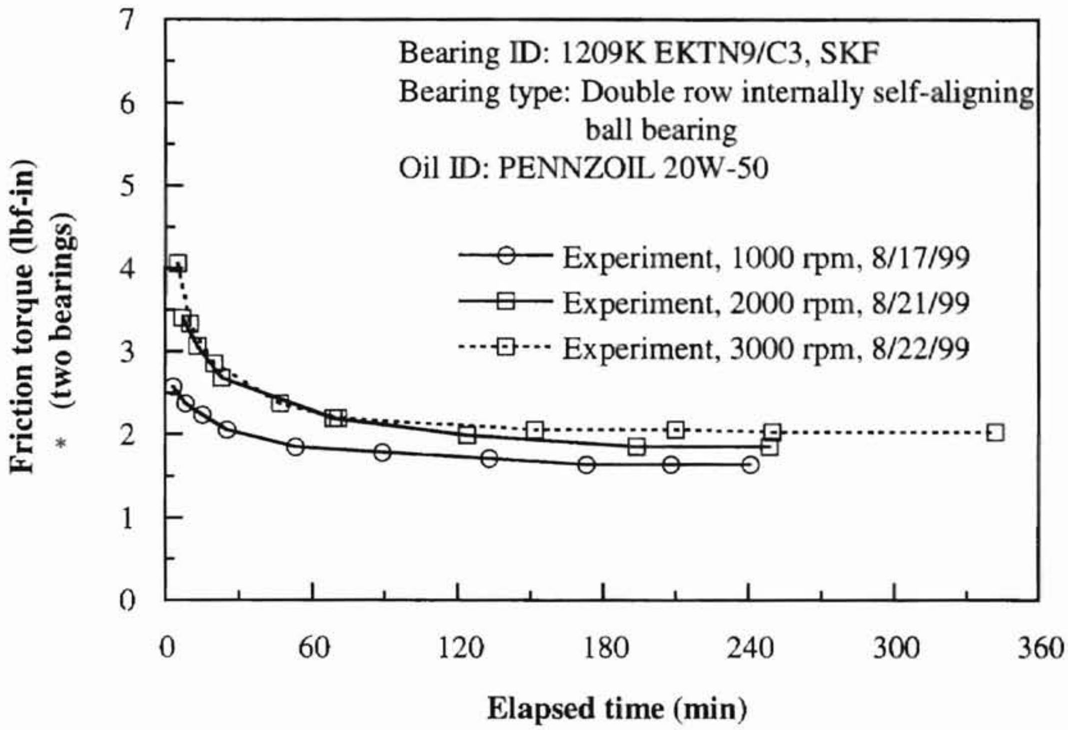

Figure 67. Effect of the elapsed time on bearing friction torque

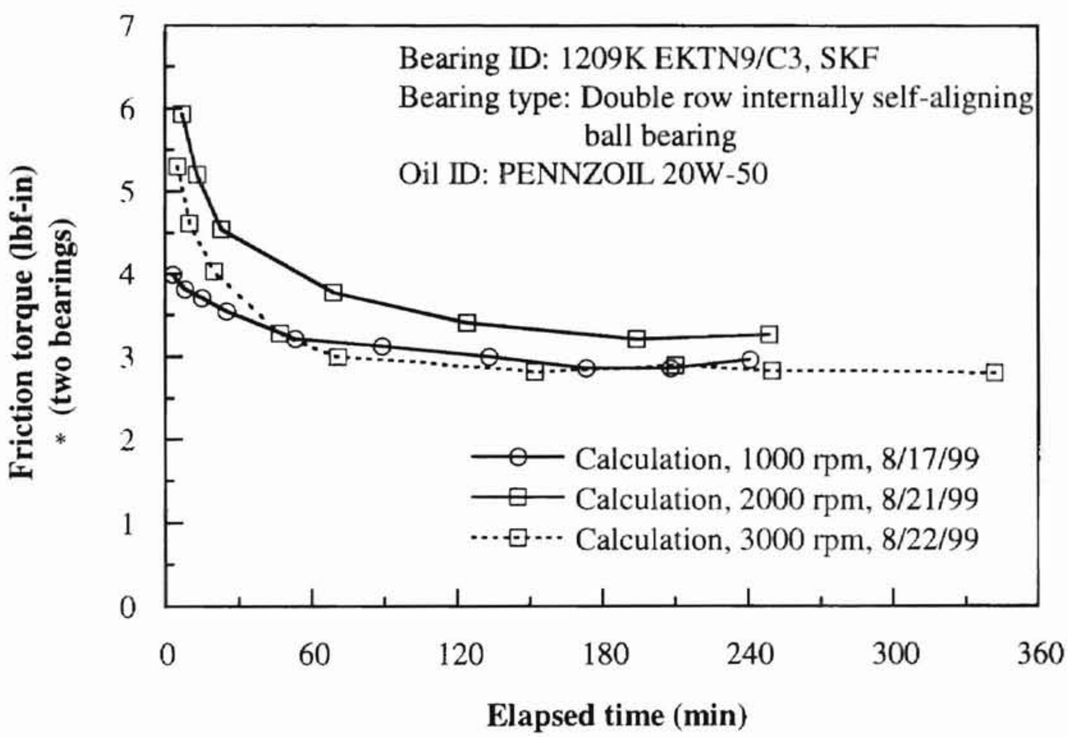

Figure 68. Effect of the elapsed time on bearing friction torque

Table 38. Effect of elapsed time on bearing friction torque

Loaded weight: 60.8 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
2	1116	23.5	345	0.661	22.8	350	0.668	1.329	0.963
23	1105	25.0	310	0.611	23.9	340	0.651	1.262	0.825
45	1111	25.4	308	0.611	23.9	340	0.653	1.264	0.722
101	1106	26.2	302	0.601	24.9	320	0.625	1.226	0.653
176	1108	26.8	298	0.596	24.9	320	0.626	1.222	0.619
296	1110	27.0	295	0.593	25.9	305	0.606	1.199	0.619
354	1111	27.0	295	0.593	25.9	305	0.607	1.200	0.619
392	1110	27.0	295	0.593	25.9	305	0.606	1.199	0.619

The first measured distance of the moving mass from the extremity of the wing was 4".
Lubricant: PENNZOIL DEXRON III (Automatic transmission oil)
Pitch of bearing: 65mm, Factor f_o: 1.5
Test date: 08/30/99

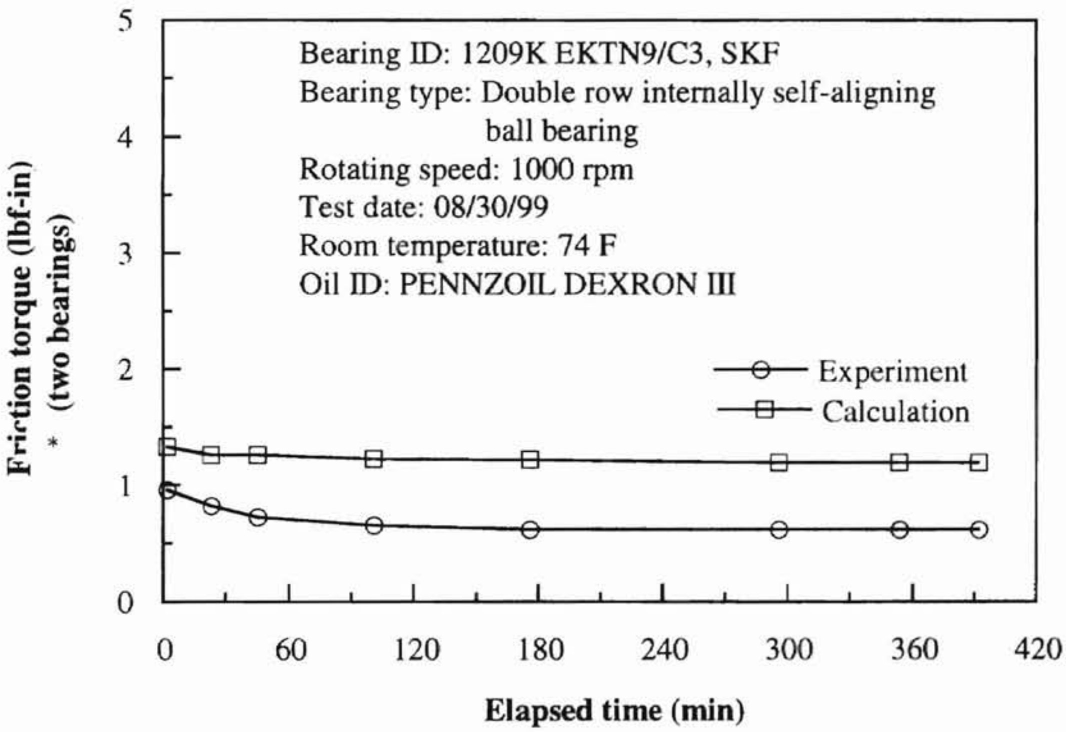

Figure 69. Effect of the elapsed time on bearing friction torque.

Table 39. Effect of elapsed time on bearing friction torque

Loaded weight: 60.8 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
5	2136	24.2	330	0.990	22.8	360	1.049	2.039	0.791
9	2132	24.7	320	0.968	22.8	360	1.048	2.016	0.722
65	2211	28.6	278	0.902	26.9	300	0.949	1.851	0.653
119	2177	29.9	260	0.853	27.9	285	0.908	1.761	0.619
190	2189	30.7	246	0.824	28.9	270	0.878	1.703	0.602
286	2191	31.0	243	0.818	28.9	270	0.879	1.697	0.602
356	2188	31.2	242	0.815	29.9	260	0.856	1.671	0.602
406	2183	31.0	243	0.816	28.9	270	0.877	1.693	0.602

The first measured distance of the moving mass from the extremity of the wing was 3.84".
Lubricant: PENNZOIL DEXRON III (Automatic transmission oil)
Pitch of bearing: 65mm, Factor f_o: 1.5
Test date: 08/31/99

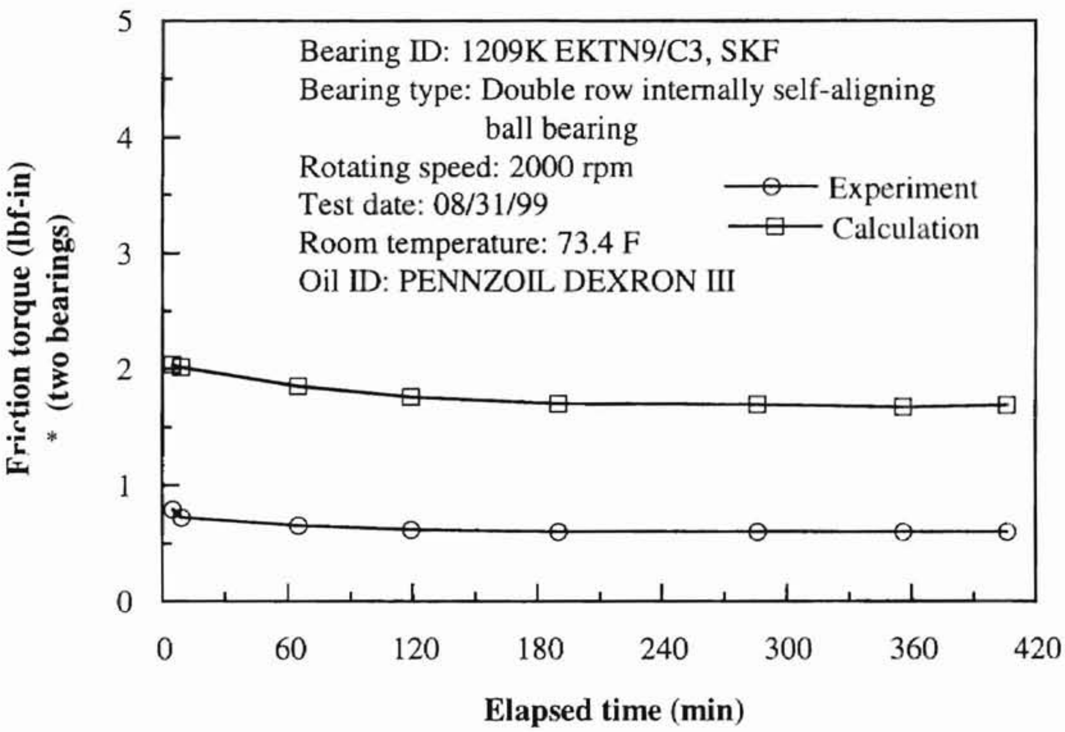

Figure 70. Effect of the elapsed time on bearing friction torque.

Table 40. Effect of elapsed time on bearing friction torque

Loaded weight: 60.8 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
5	3034	24.2	330	1.255	22.8	350	1.305	2.560	1.100
11	3009	24.7	320	1.223	23.9	338	1.268	2.491	1.031
50	2964	28.6	272	1.086	28.9	272	1.086	2.173	0.894
86	2915	29.9	260	1.042	31.0	250	1.016	2.058	0.825
132	2904	30.7	250	1.013	32.0	240	0.986	1.999	0.825
300	2880	31.0	248	1.002	33.0	237	0.972	1.974	0.791
405	2888	31.2	245	0.996	33.0	237	0.974	1.970	0.791

The first measured distance of the moving mass from the extremity of the wing was 5.1".
Lubricant: PENNZOIL DEXRON III (Automatic transmission oil)
Pitch of bearing: 65mm, Factor f_o: 1.5
Test date: 09/01/99

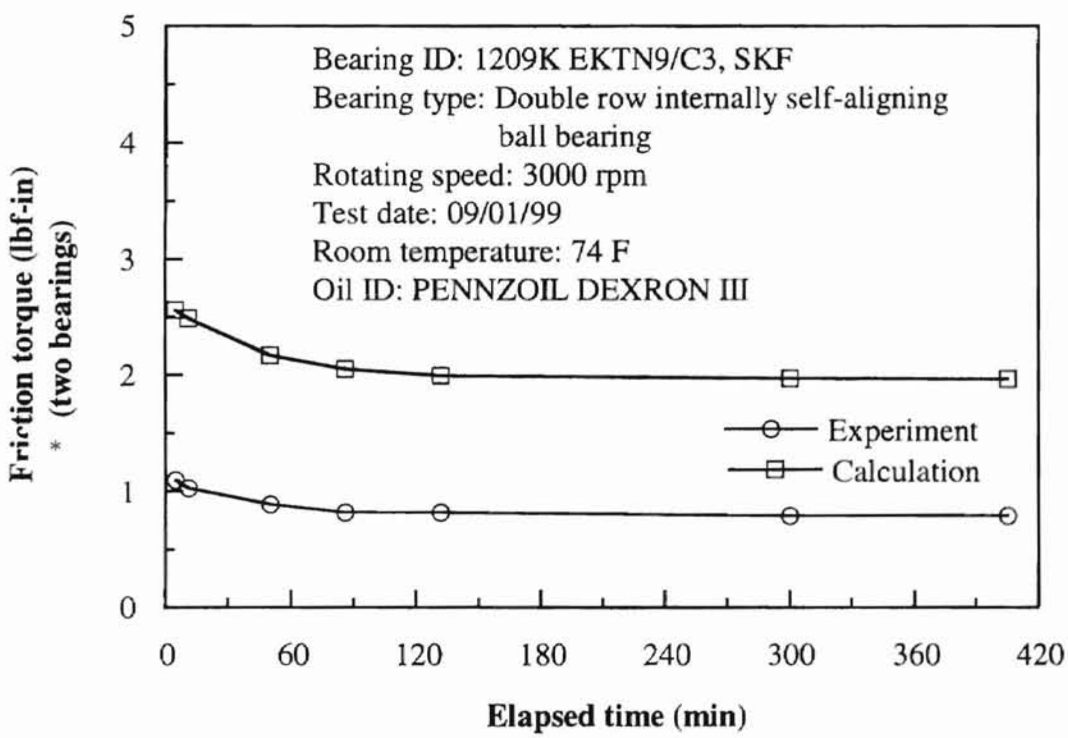

Figure 71. Effect of the elapsed time on bearing friction torque.

Table 41. Effect of elapsed time on bearing friction torque

Loaded weight: 60.8 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
4	2166	23.9	335	1.013	22.8	350	1.043	2.055	0.756
23	2197	26.1	300	0.950	23.9	335	1.022	1.972	0.688
49	2188	27.7	290	0.926	25.9	310	0.968	1.894	0.653
155	2185	30.2	257	0.854	28.9	266	0.873	1.727	0.619
300	2191	31.2	250	0.840	29.9	260	0.862	1.701	0.619
470	2196	30.9	255	0.852	29.9	260	0.863	1.715	0.619

The first measured distance of the moving mass from the extremity of the wing was 5.1".
Lubricant: PENNZOIL DEXRON III (Automatic transmission oil)
Pitch of bearing: 65mm, Factor f_o: 2
Test date: 09/03/99

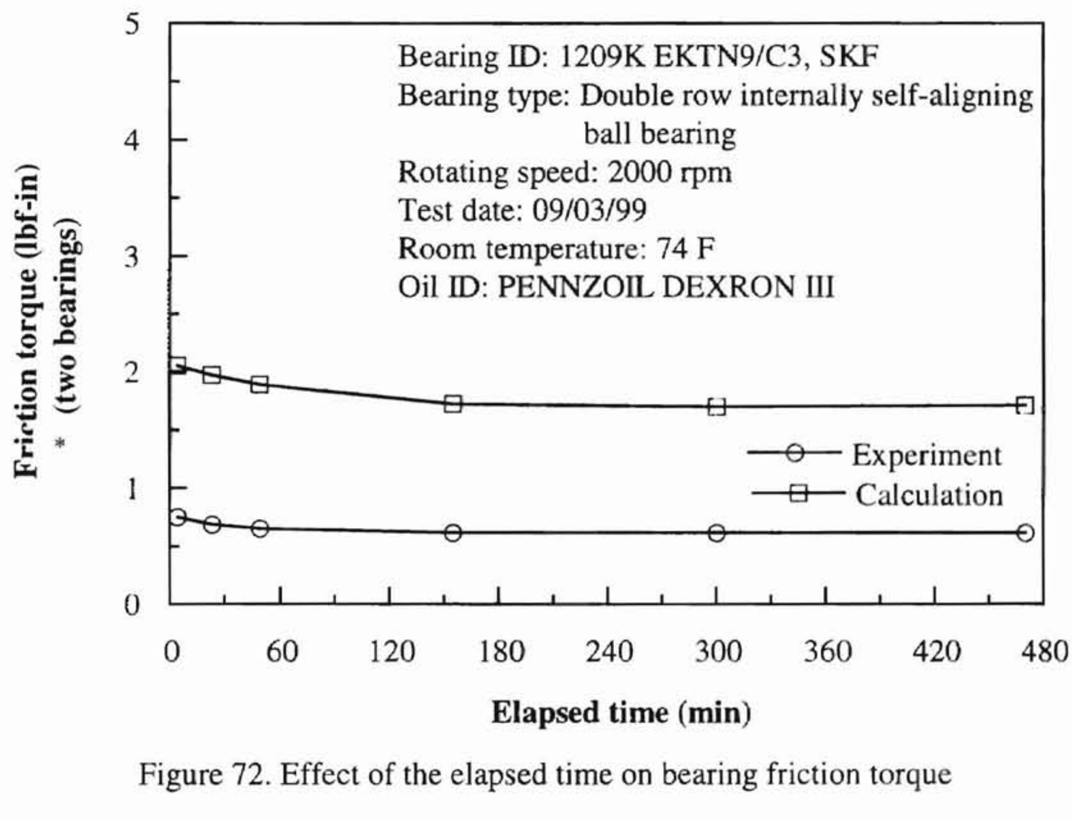

Figure 72. Effect of the elapsed time on bearing friction torque

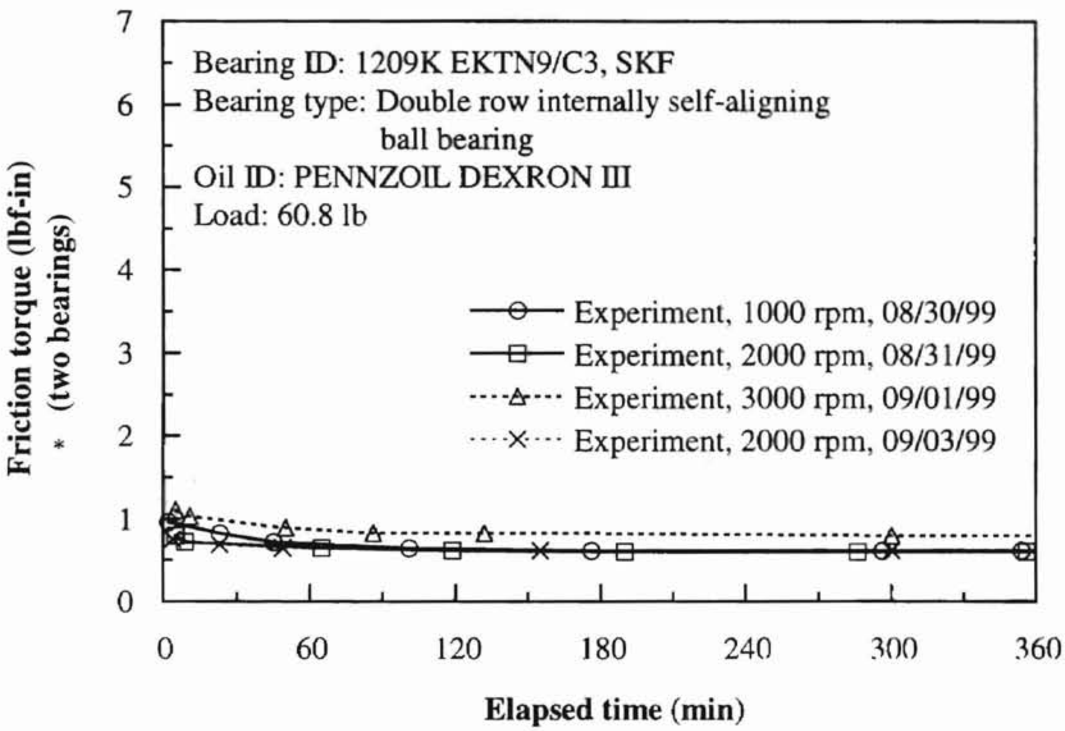

Figure 73. Effect of the elapsed time on bearing friction torque

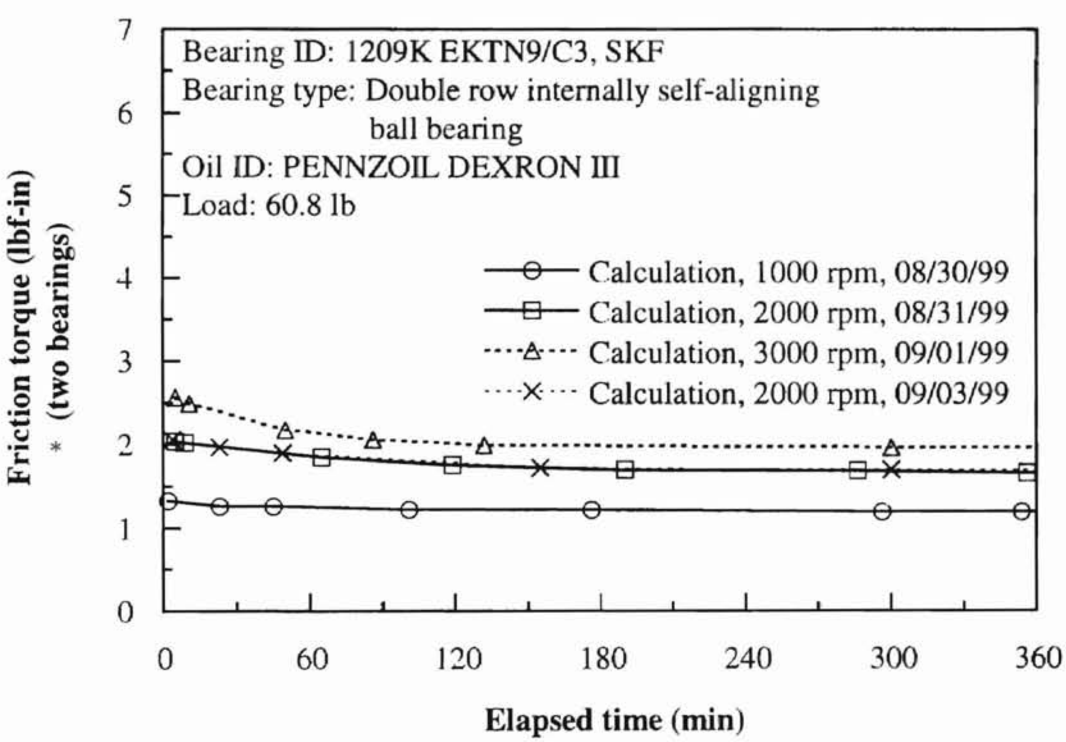

Figure 74. Effect of the elapsed time on bearing friction torque

Table 42. Effect of elapsed time on bearing friction torque

Loaded weight: 132.5 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
3	1037	23.5	340	0.624	22.8	350	0.636	1.260	0.653
8	1012	23.8	338	0.611	22.8	350	0.626	1.237	0.619
27	994	24.6	330	0.594	23.9	337	0.603	1.197	0.602
68	1009	25.6	310	0.575	24.9	320	0.588	1.163	0.584
128	1002	26.3	300	0.560	25.9	301	0.561	1.122	0.567
233	998	27.4	290	0.546	26.9	298	0.556	1.102	0.550
303	1002	27.3	291	0.549	25.9	301	0.561	1.110	0.550

The first measured distance of the moving mass from the extremity of the wing was 4.6".
Lubricant: PENNZOIL DEXRON III (Automatic transmission oil)
Pitch of bearing: 65mm, Factor f_o: 1.5
Test date: 09/08/99

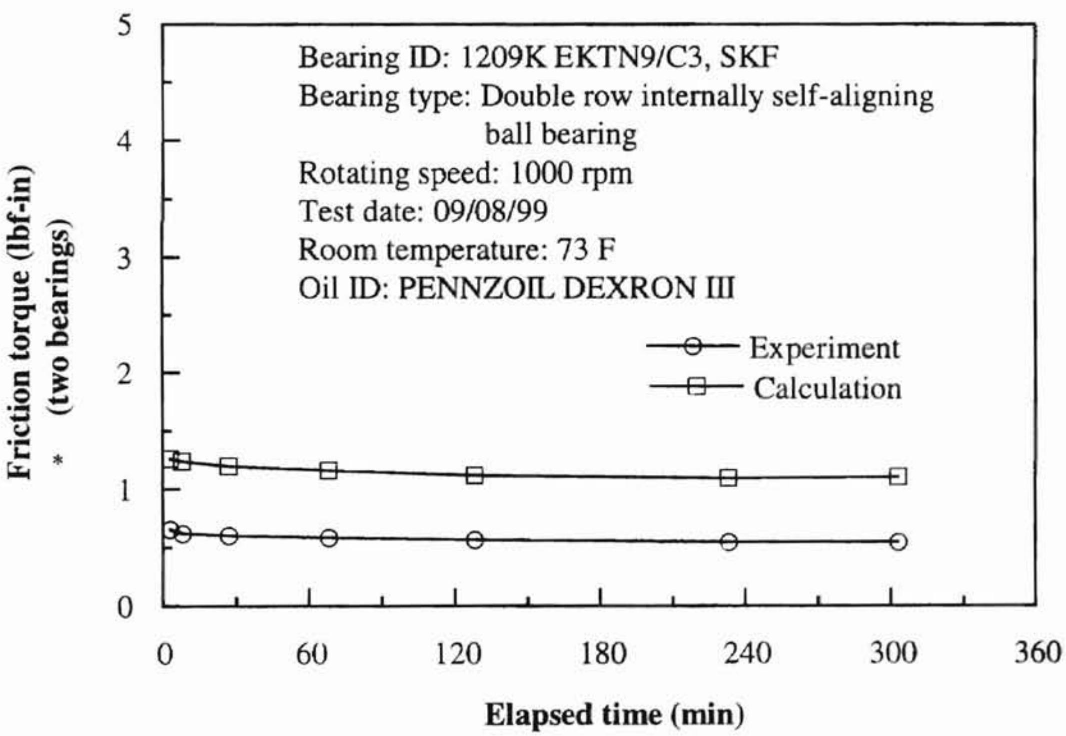

Figure 75. Effect of the elapsed time on bearing friction torque

Table 43. Effect of elapsed time on bearing friction torque

Loaded weight: 132.5 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
1	2000	23.6	340	0.967	22.8	357	0.999	1.965	0.825
7	2004	24.5	330	0.949	22.8	357	1.000	1.949	0.791
39	2015	27.3	290	0.872	25.9	305	0.903	1.775	0.756
109	1995	29.6	265	0.815	27.9	283	0.852	1.668	0.653
204	1999	30.6	250	0.785	28.9	273	0.833	1.618	0.653
272	2004	31.0	245	0.775	29.9	260	0.807	1.583	0.619
374	2011	31.0	245	0.777	29.9	260	0.809	1.586	0.619

The first measured distance of the moving mass from the extremity of the wing was 4.5".
Lubricant: PENNZOIL DEXRON III (Automatic transmission oil)
Pitch of bearing: 65mm, Factor f_o: 1.5
Test date: 09/09/99

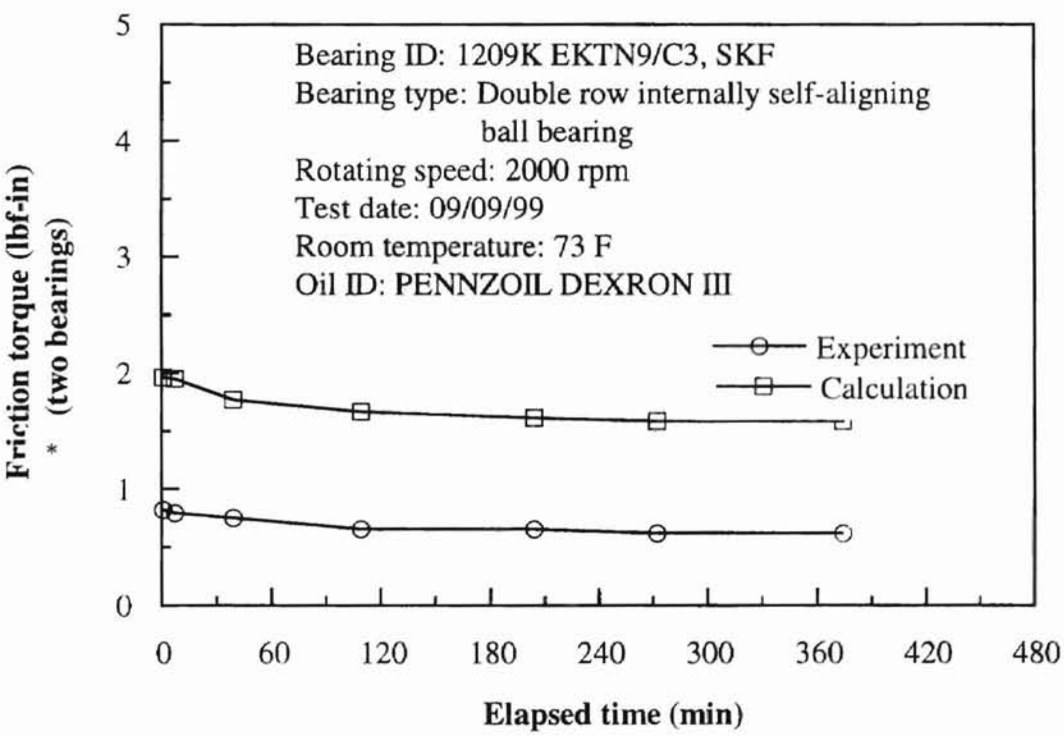

Figure 76. Effect of the elapsed time on bearing friction torque

Table 44. Effect of elapsed time on bearing friction torque

Loaded weight: 132.5 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
2	3002	24.4	330	1.246	22.8	350	1.292	2.538	1.203
5	3000	25.8	305	1.182	22.8	350	1.291	2.473	1.100
44	3084	33.2	233	1.006	28.9	275	1.118	2.124	1.031
74	3042	35.0	215	0.945	32.0	240	1.010	1.955	0.963
114	3068	36.3	205	0.921	33.0	225	0.972	1.892	0.928
182	3001	37.5	195	0.877	35.0	215	0.928	1.806	0.928
252	3006	37.5	195	0.878	35.0	215	0.929	1.808	0.928
341	2992	37.5	195	0.876	35.0	215	0.926	1.802	0.928

The first measured distance of the moving mass from the extremity of the wing was 4.6".
Lubricant: PENNZOIL DEXRON III (Automatic transmission oil)
Pitch of bearing: 65mm, Factor f_o: 1.5
Test date: 09/12/99

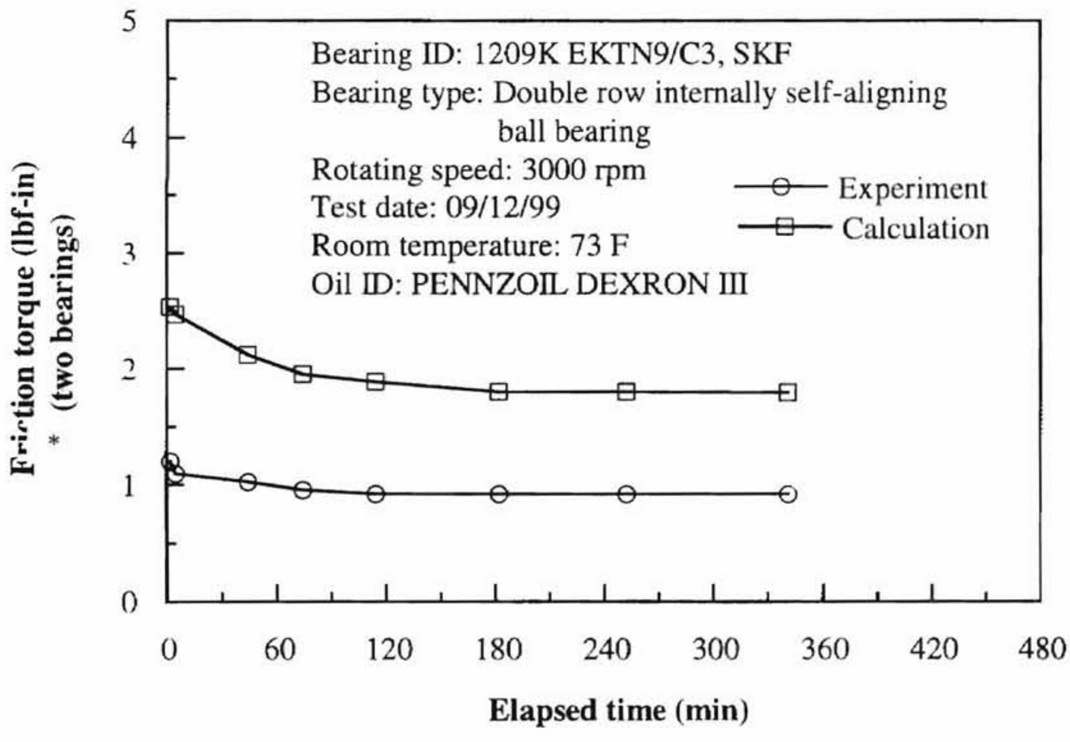

Figure 77. Effect of the elapsed time on bearing friction torque

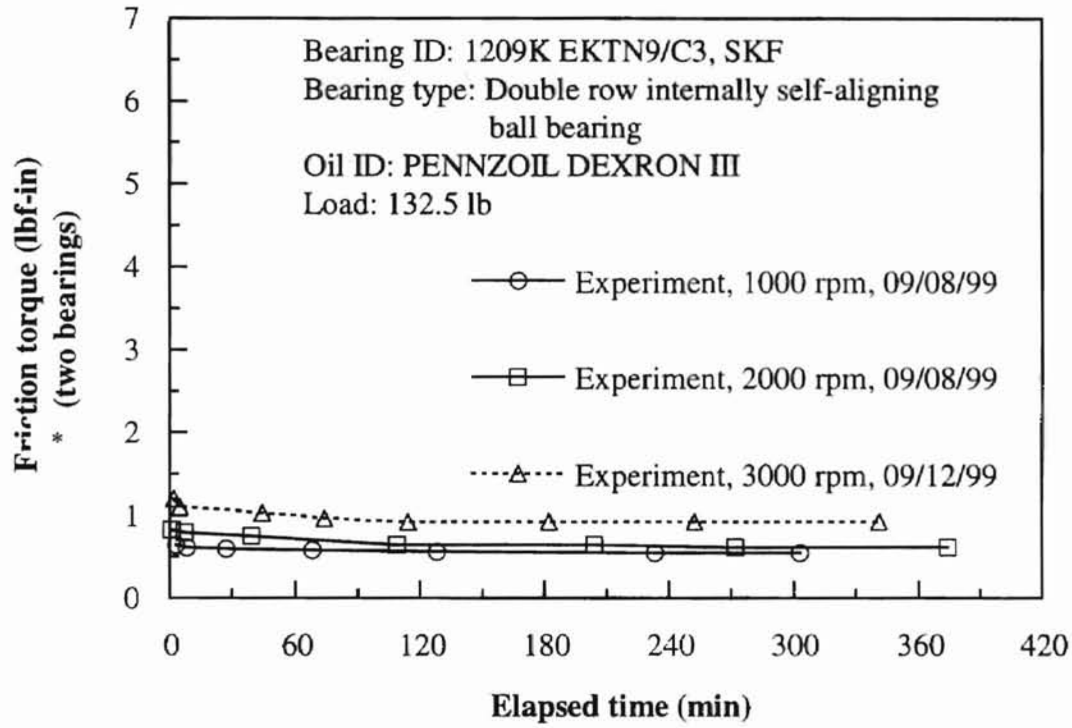

Figure 78. Effect of the elapsed time on bearing friction torque

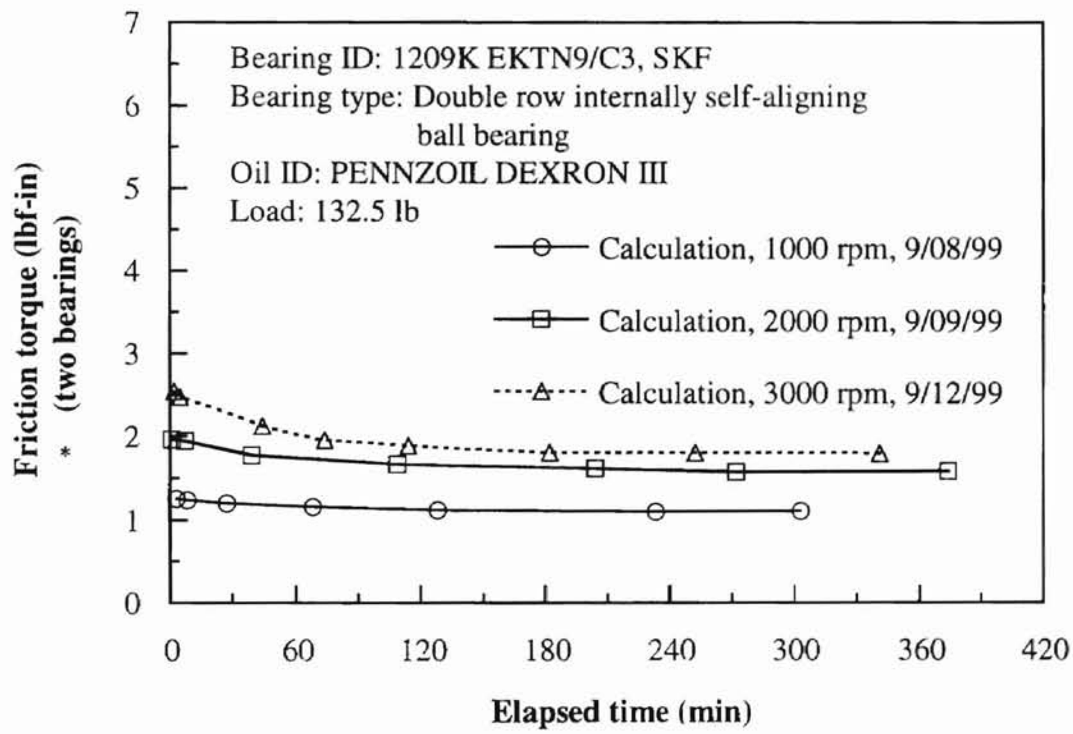

Figure 79. Effect of the elapsed time on bearing friction torque

The load dependent frictional component M_{load} should be considered because the load of 178 *lb* was not negligible. When determining the frictional moment of a ball bearing loaded with considerable weight, the load dependent frictional moment should be added to M_t. Consequently, total calculated torque is simply obtained by adding the load independent torque and the load dependent torque: $M_{Total} = M_{load} + M_t$. A sample calculation is shown in Appendix II.

Table 45. Effect of elapsed time on bearing friction torque

Loaded weight: 178 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
2	994	23.6	338	0.604	22.8	350	0.618	1.271	0.636
7	1001	23.9	335	0.603	22.8	350	0.621	1.273	0.619
38	997	25.0	320	0.583	23.9	333	0.599	1.231	0.584
106	1016	26.4	300	0.566	24.9	320	0.591	1.205	0.550
216	994	27.0	291	0.546	25.9	307	0.566	1.160	0.550
336	992	27.0	291	0.545	25.9	307	0.565	1.159	0.550

The first measured distance of the moving mass from the extremity of the wing was 3.5".
Lubricant: PENNZOIL DEXRON III (Automatic transmission oil)
Pitch of bearing: 65mm, Factor f_o: 1.5
Test date: 09/14/99

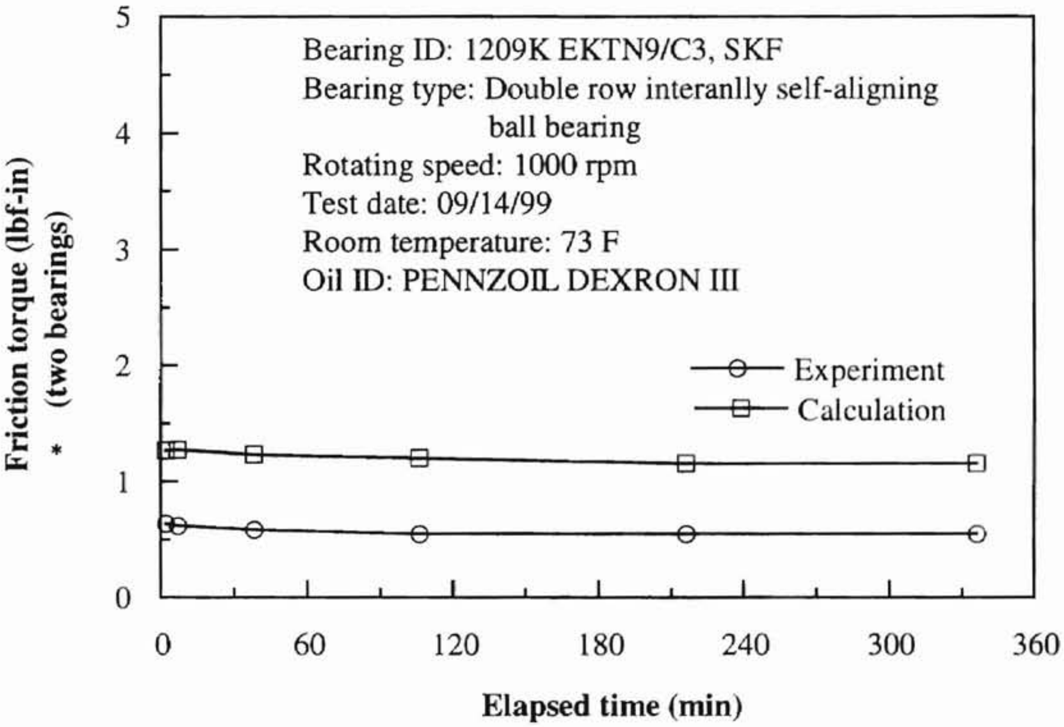

Figure 80. Effect of the elapsed time on bearing friction torque.

Table 46. Effect of elapsed time on bearing friction torque

Loaded weight: 178 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
2	1997	23.8	338	0.962	22.8	350	0.984	1.995	0.825
9	2004	24.7	325	0.939	23.9	337	0.962	1.949	0.791
25	2014	26.2	305	0.902	24.9	320	0.932	1.883	0.756
87	2032	28.9	272	0.840	27.9	283	0.863	1.751	0.722
164	2010	30.2	258	0.805	28.9	272	0.834	1.687	0.688
217	2016	30.7	250	0.789	29.9	260	0.810	1.648	0.688
265	2014	30.8	247	0.782	29.9	260	0.810	1.641	0.688
315	1998	30.8	247	0.778	29.9	260	0.806	1.632	0.688

The first measured distance of the moving mass from the extremity of the wing was 3.4".
Lubricant: PENNZOIL DEXRON III (Automatic transmission oil)
Pitch of bearing: 65mm, Factor f_o: 1.5
Test date: 09/19/99

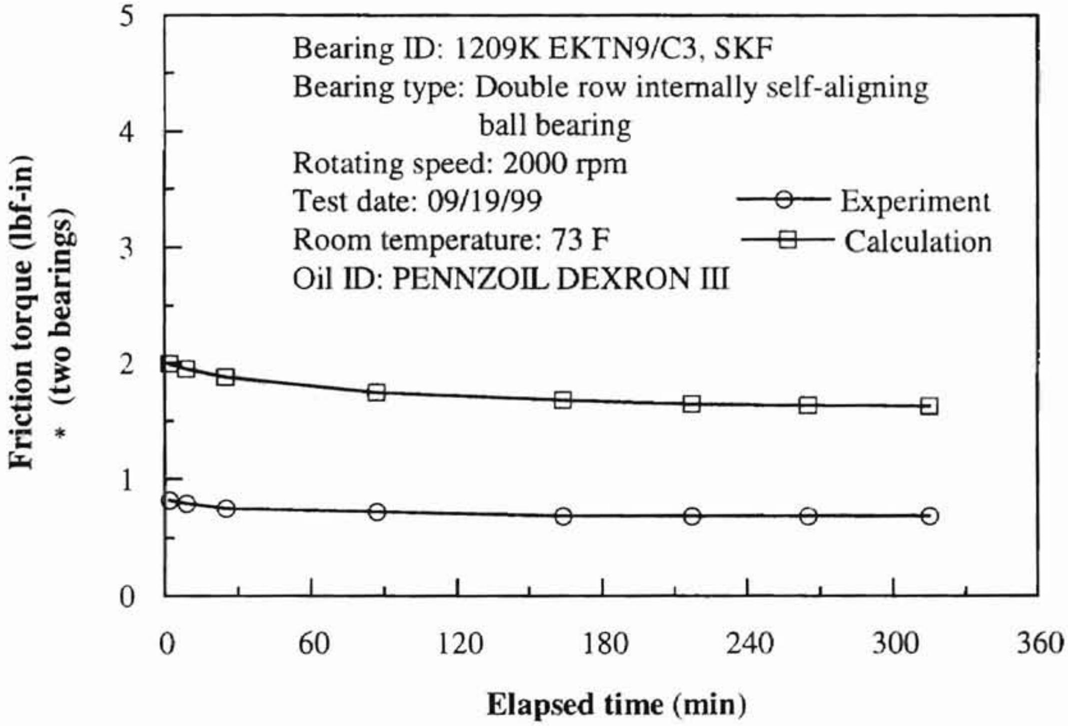

Figure 81. Effect of the elapsed time on bearing friction torque

Table 47. Effect of elapsed time on bearing friction torque

Loaded weight: 178 lb		Bearing I			Bearing II			Total torque (lbf*in)	
Time elapsed (min)	Spindle speed (rpm)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Temp (C)	Viscosity (SSU)	Calculated Torque (lbf*in)	Total Calculated Torque (lbf*in)	Measured Torque (lbf*in)
2	3000	24.4	330	1.245	22.8	350	1.291	2.584	1.134
6	2993	26.0	304	1.177	23.9	338	1.259	2.484	1.031
18	3041	29.1	272	1.104	25.9	304	1.185	2.337	0.928
44	3040	32.6	237	1.006	28.9	275	1.107	2.162	0.859
83	3053	35.1	216	0.948	32.0	240	1.012	2.009	0.842
144	3022	36.9	195	0.880	34.0	225	0.962	1.890	0.825
242	2992	37.3	193	0.868	35.0	216	0.929	1.845	0.791
352	2994	37.5	192	0.865	35.0	216	0.930	1.843	0.791
424	2996	37.5	192	0.866	35.0	216	0.930	1.844	0.791

The first measured distance of the moving mass from the extremity of the wing was 3.5".
Lubricant: PENNZOIL DEXRON III (Automatic transmission oil)
Pitch of bearing: 65mm, Factor f_o: 1.5
Test date: 09/17/99

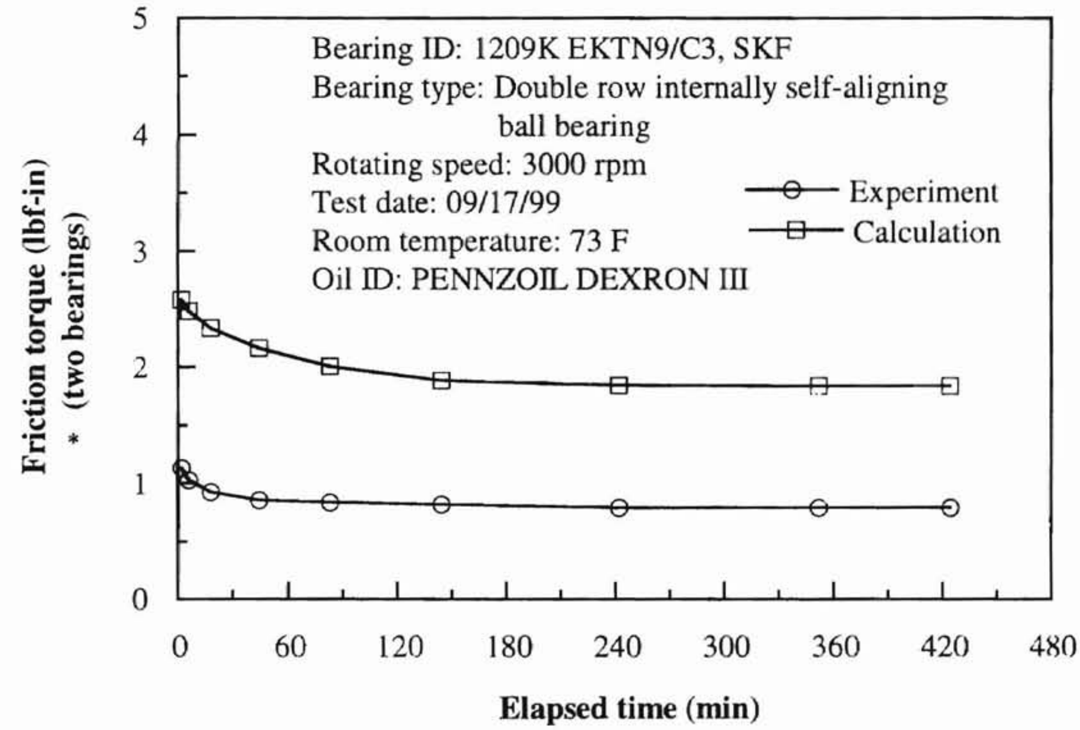

Figure 82. Effect of the elapsed time on bearing friction torque

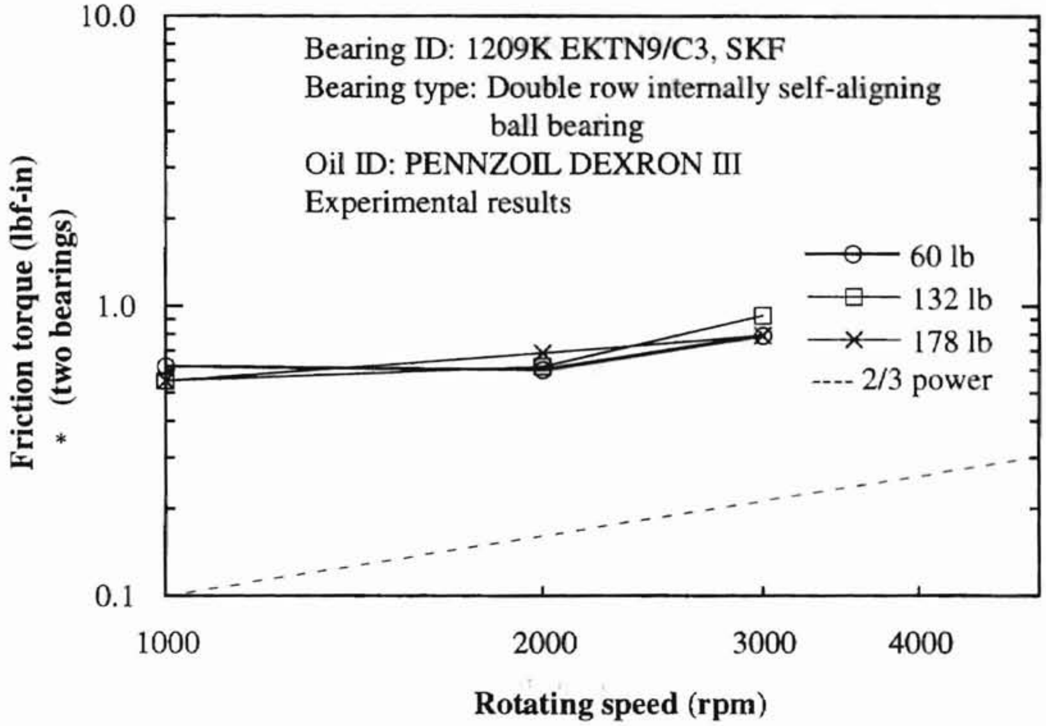

Figure 83. Effect of the rotating speed on bearing friction torque

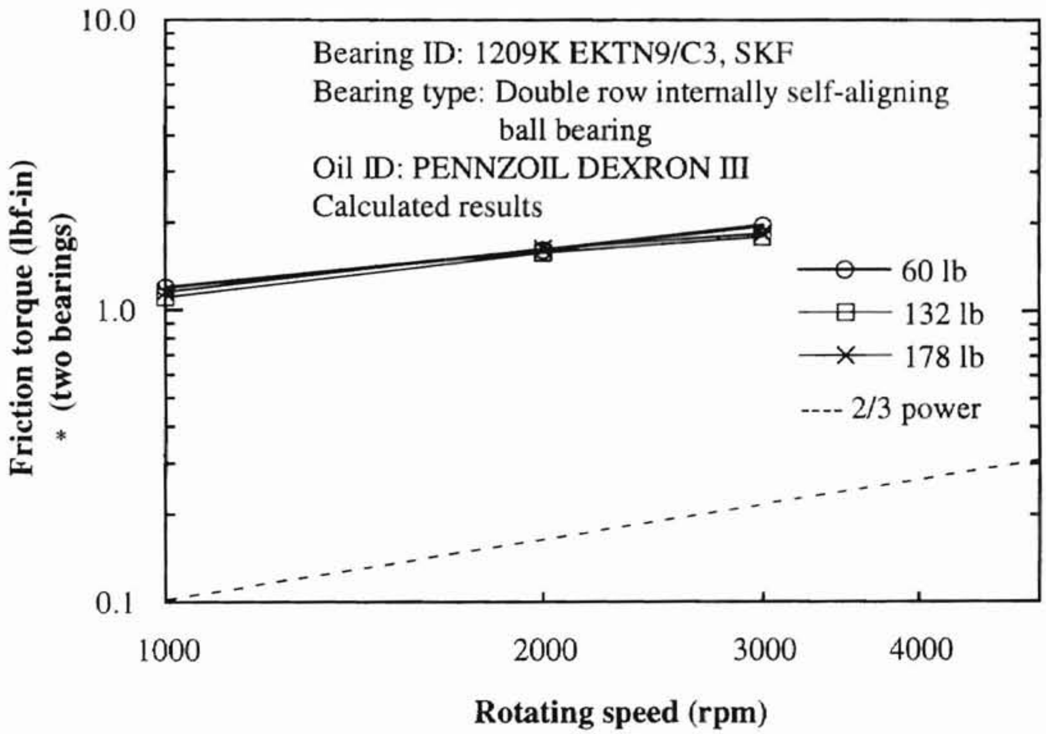

Figure 84. Effect of the rotating speed on bearing friction torque

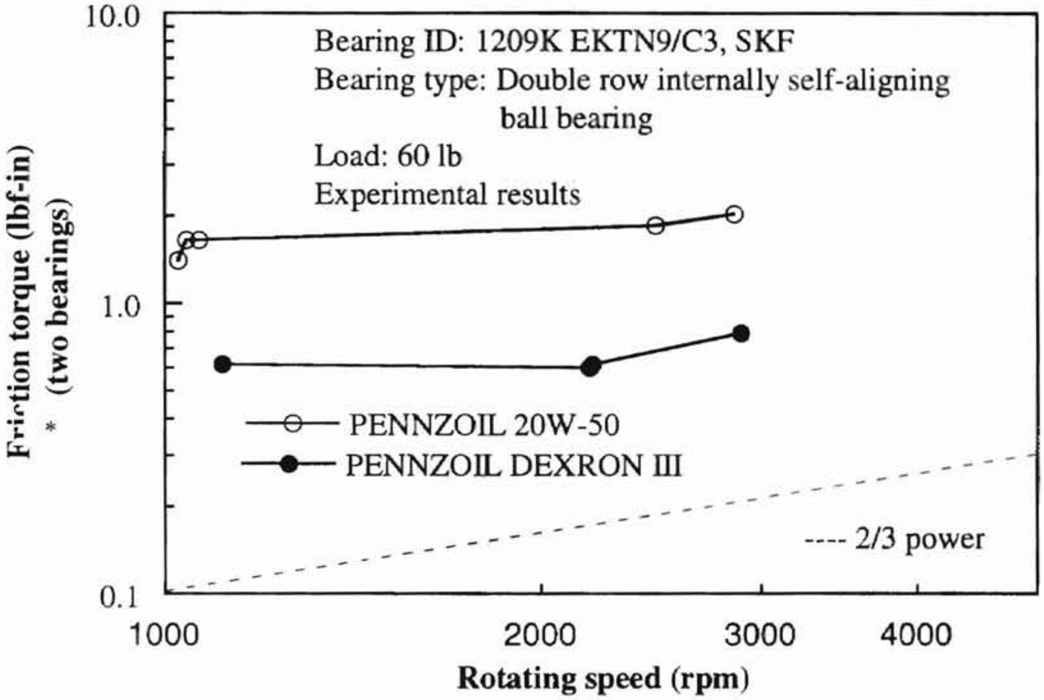

Figure 85. Effect of the rotating speed on bearing friction torque

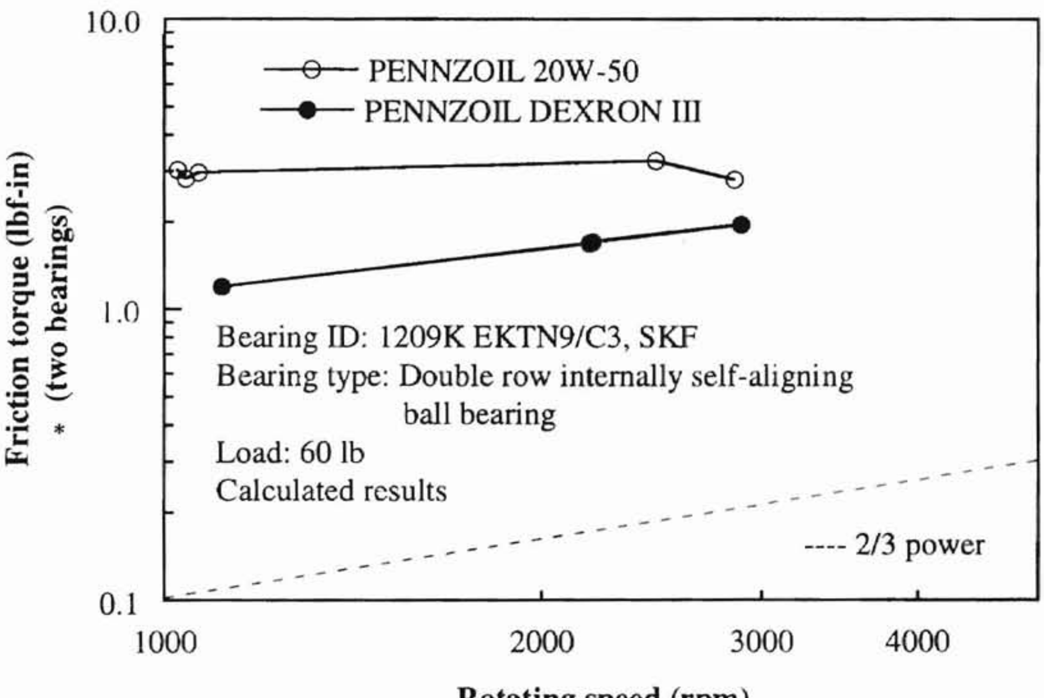

Figure 86. Effect of the rotating speed on bearing friction torque

CHAPTER IV

SUMMARY AND CONCLUSIONS

The mechanism of friction torque for rolling element bearings at low loading conditions was studied by comparing the experimentally determined friction torque with the Palmgren formula. These two methods agree in general trends, but differ in magnitude.

1. Rotating speed does not greatly affect the friction torque, especially for oil lubricated bearings such as double row internally self-aligning ball bearings.
2. Friction torque tests at lightly loaded conditions show that the effect of load is relatively small.
3. In the case of low viscosity lubricant, the friction torque varies little with time for oil lubricated bearings with loads ranging from 60 *lb* to 135 *lb*.
4. In the case of high viscosity lubricant, the friction torque decreases dramatically for the first 30 to 60 minutes.
5. The friction torque for single row deep groove ball bearings at speeds ranging from 1000 rpm to 3000 rpm is higher than that for double row internally self-aligning ball bearings.

CHAPTER V

RECOMMENDATIONS FOR FUTURE STUDY

The turning torque was studied experimentally with commercially available grease lubricated bearings and oil lubricated bearings. The experimental results were compared to the Palmgren formula (1954). A large discrepancy between experimental results and calculated results was observed in most cases. Another problem which was not explained was the fluctuations of turning torque in the grease lubricated bearing tests. The following recommendations are proposed to re-evaluate the Palmgren formula and the test setup for the grease lubricated bearings.

1. Search for different equations, perhaps involving dimensionless groups of variables, to compare to the experimental results.
2. Modify the test setup for grease lubricated bearings to find the effect of rotating speed and the load on friction torque and hence avoid the fluctuation which caused much scattering of data.

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[8] Wikström, V. and Höglund, E., "Starting and Steady-State Friction Torque of Grease Lubricated Rolling Element Bearings at Low Temperatures-Part II: Correlation with Less-Complex Test Methods," STLE/ASME Tribology Conference Preprint No. 95-TC-2D-2, 1995.

APPENDIX I

SAMPLE CALCULATION FOR LOAD-INDEPENDENT FRICTION TORQUE

All calculations were performed with the Palmgren formula for an unloaded bearing.

$M_0 = f_0 \times p \times d_m^{\ 3} \times (\eta \times \omega / p)^{2/3}$ $[kgf \cdot mm]$

where,

$f_0 = 1.5$ (self-aligning ball bearing)

$p = 1.033 \times 10^{-2}$ $[kgf / mm^2]$

$d_m = {(85+45)}/{2} = 65$ $[mm]$

$\eta =$ the dynamic viscosity of the lubricant at the operating temperature $[kgf \cdot \sec / mm^2]$

$\omega =$ the angular velocity of the bearing rings in relation to each other $[rad / \sec]$

For instance, when a double row internally self-aligning ball bearing with a light load of 60.8 *lb* was tested (referring to Table 33 and Figure 60), the above equation would be evaluated as follows:

From the A.S.T.M. Standard Viscosity–Temperature Chart for Petroleum Products (D 341-43), $\eta = 1200$ [SSU] converted to 0.0234 $[kgf \cdot \sec/m^2]$ and $\omega = 1024$ $[rev/\min]$ at 89.6 F^{o}. The friction torque for bearing I is

$$M_I = 1.5 \cdot 1.033 \cdot 10^{-2}[kgf/mm^2] \cdot (65mm)^3 \cdot \left(\frac{0.0234[kgf \cdot \sec/m^2] \cdot 1024 \cdot 2\pi[rad/\sec]}{10^6[mm^2/m^2] \cdot 60[\sec/\min] \cdot 1.03332 \cdot 10^{-2}[kgf/mm^2]} \right)$$

$= 16.576$ $[kgf \cdot mm]$

$= 1.439$ $[lbf \cdot in]$ and the friction torque for bearing II is

$M_{II} = 1.594$ $[lbf \cdot in]$

Therefore the total torque from the two bearings is

$M_t = M_I + M_{II} = 3.033$ $[lbf \cdot in]$

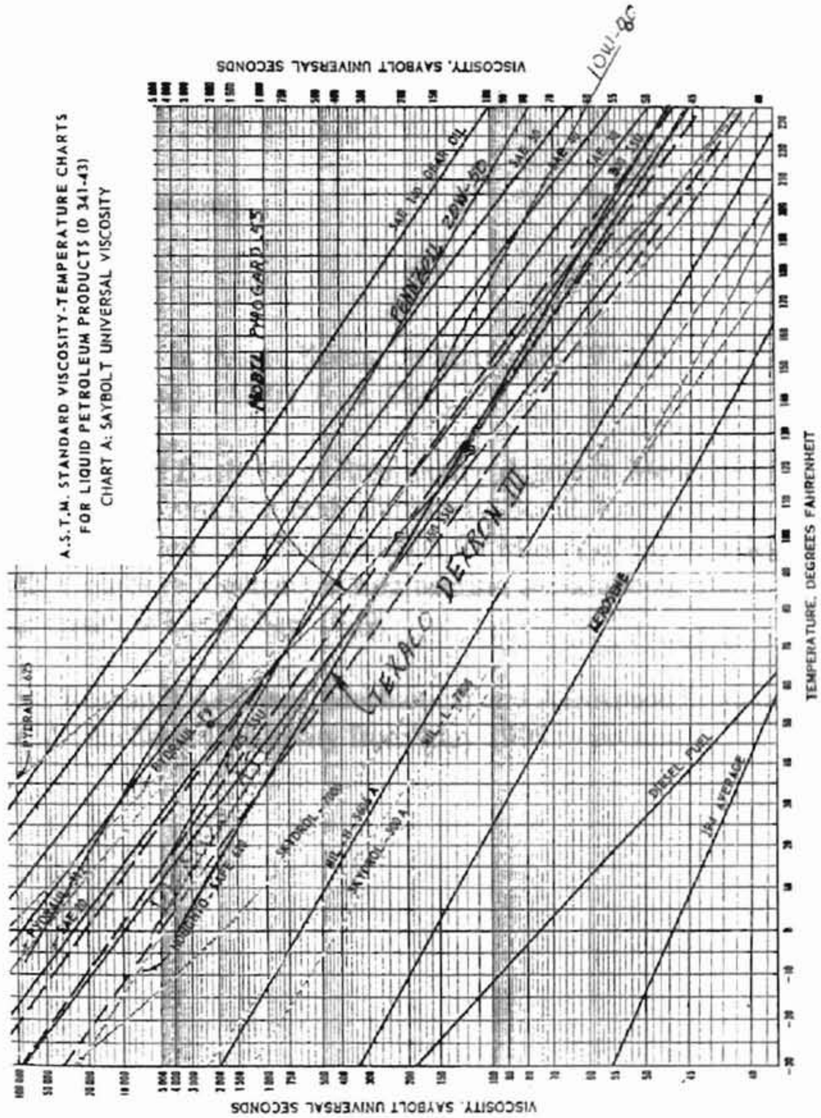
Comparing with the experimental result,

$M_{\exp} = 1.409[lbf \cdot in]$

The experimental result is approximately 115% greater than the calculated result.

$$
\begin{aligned}
M_1 &= 0.000107 \times 178 \times 2.56 \\
&= 0.048758(lb \cdot in)
\end{aligned}
$$

APPENDIX III



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VITA

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