Technical Report

Gearbox Lifetime Assessment Experiment: Experiment Design, Operation Guide, and Data Collected

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1. Introduction

In order to test methods for predicting the remaining life of a gearbox, an experiment will be conducted on a gearbox in the Reliability Research Lab. In order to finish the experiment in a reasonable amount of time, we need to determine the load, input shaft speed, sampling frequency, sampling duration, and time interval for sampling. We also need to estimate the lifetime of the system, under various operating conditions.

2. Notation

b_i: Tooth width (face) of the i^{th} gear (mm), See Fig. 1.

d_i: Pitch diameter of the i^{th} gear (mm), $d_i = m \times z_i$,

$F_{t,i}$: Circumferential force of the i^{th} gear (N),

$i_{T1,T2}$: Pulley transmission ratio,

$i_{i,j}$: Transmission ratio between the i^{th} gear and the j^{th} gear,

$K_{a,i}$: Operating condition coefficient of the i^{th} gear,

$K_{v,i}$: Dynamic load coefficient of the i^{th} gear,

$K_{b,i}$: Uneven load coefficient of the i^{th} gear,

$K_{HN,i}$: Lifetime coefficient of the i^{th} gear considering the surface stress,

$K_{FN,i}$: Lifetime coefficient of the i^{th} gear considering the bending stress,

m_i: Modulus of the i^{th} gear (mm),

n_i: The rotation speed of the i^{th} gear or the i^{th} shaft (rpm),

n_{motor}: The rotation speed of the motor (rpm),

P: Power of the motor,

P': Power that we need in this experiment,

r_i: Radius of the i^{th} gear ($d_i = 2r_i$) (mm),
sf: Safety factor of the motor, sf=1.15,
S_i: Safety coefficient of fatigue stress of the i^{th} gear, $S_i = 1$,
t: Gearbox working time (Hour),
T_i: Torque of shaft i (N.m),
V_i: The velocity of the i^{th} gear (m/s),
$Y_{Fa,i}$: Coefficient of the i^{th} gear profile,
$Y_{Sa,i}$: Correction coefficient of the stress of the i^{th} gear,
z_i: Number of teeth on the i^{th} gear,
$Z_{u,i}$: Gear tooth ratio coefficient of the i^{th} gear,
$Z_{E,i}$: Coefficient of elasticity impact of the i^{th} gear,
$\sigma_{H,i}$: Surface contact fatigue stress of the i^{th} gear,
$[\sigma]_{H,i}$: Allowable surface stress of the i^{th} gear,
$\sigma_{H\lim,i}$: Surface contact fatigue limit of the i^{th} gear,
$\sigma_{F\lim,i}$: Root bending fatigue limit of the i^{th} gear,
$\sigma_{F,i}$: Root bending fatigue stress of the i^{th} gear,
$[\sigma]_{F,i}$: Allowable root bending stress of the i^{th} gear,
α_i: Pressure angle of the i^{th} gear,
β_i: Tilt angle of the i^{th} gear.

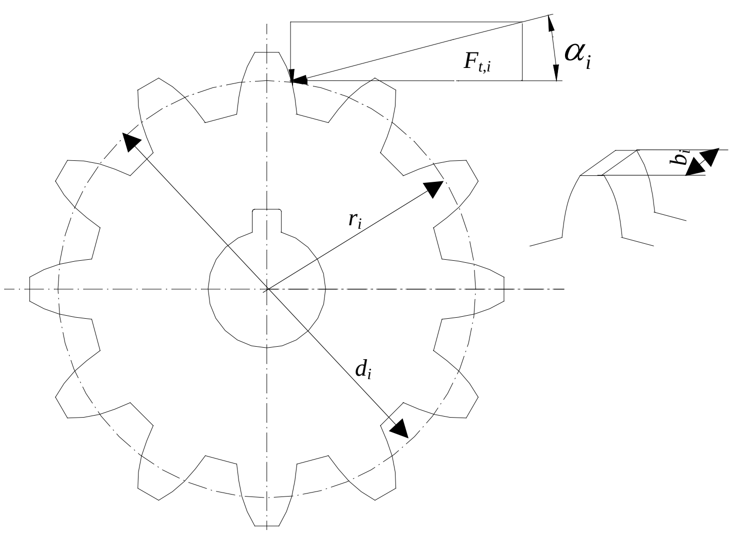


Figure 1. The profile of the gear

3. Experimental system

The experimental system is shown in Fig. 2. The key characteristics of the system are provided below.

- The gearbox is driven by a 3HP (P=2.2371KW[1]) motor
- The safety factor (sf) of the motor is 1.15[1].
- The rated current of the motor is 7.6A[1]. In fact, the maximum allowed current is about 5.2A according to our test with load 40Nm. If the current is stronger than 5.2A, the temperature of the motor will rise and the motor will stop.
- Range of motor's speed: 0 to 4000rpm[2]. In fact: 1800~3450rpm[3]. Our test proved that the motor's rotating speed should be higher than 2400rpm. If the speed is too low, the temperature of the motor will be too high to keep the motor working.
- Magnetic Brake: It is electrically adjustable from 0 to 36ft-lbs (48.816Nm[2]). Transmission ratio of the pulley:

$$i_{T1,T2} = 84/20 = 4.2 \,. \tag{1}$$

Transmission ratio of the gearbox:

$$i_{1,6} = i_{1,2} \cdot i_{5,6} = \frac{Z_2}{Z_1} \cdot \frac{Z_6}{Z_5} = \frac{48}{16} \cdot \frac{160}{96} = 3 \times 1.67 = 5.01, \tag{2}$$

where 3 is the 1st stage transmission ratio, and 1.67 is the 2nd stage transmission ratio.

- All the gears are spur gears. The pressure angles, α_i, are 14.5°. Tilt angles β_i of all the gears are equal to 0°.

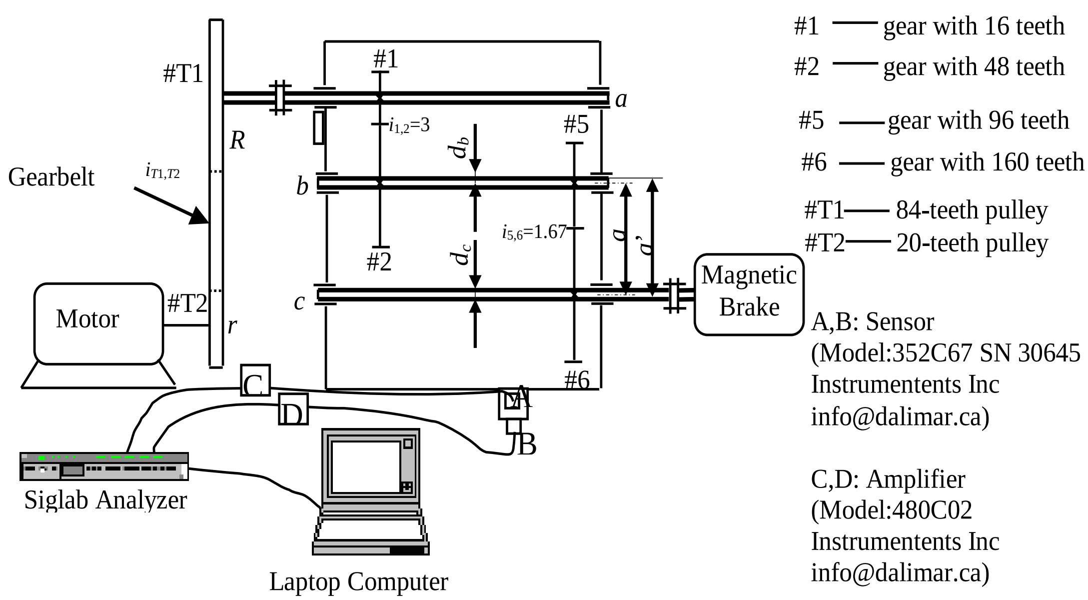


Figure 2. The diagram of the modified experimental system

The stress on gears depends heavily on the material and modulus of the gears. In this gearbox, there is a two-stage speed reduction. The first stage is between gears 1 and 2, the second stage is between gears 5 and 6. Which gear will break or wear out first? Gears 1 and 2 have a larger modulus and are made of softer material; gears 5 and 6 have a smaller modulus and are made of harder material. Under these conditions, we are not sure which gear could break or wear out first. We need to check both pairs.

After some careful calculations, we have designed the experiment so that :

- The rotating speed of the motor is **2400rpm.** Input shaft rotating is $n_a = 571.43$rpm,
- Load is **40Nm .**
- Predicted life of the gears is **70.028h.**
- Two sensors are used to collect the vertical and horizontal signals.
- To determine the sampling frequency, we note that:
  1st meshing frequency is $(16n_a)/60=0.267\ n_a= 152.38$Hz,
  2nd meshing frequency is $(\frac{16n_a}{48}\cdot 96)/60 = 0.533n_a = 114.29$Hz.

According to experience and sampling theory, we chose 5.12KHz as the sampling frequency that can satisfy the sampling principle. In addition, because the lowest frequency component is 571.43/(5.01*60)=1.9Hz, in order to let the lowest frequency signal present more than once in the time domain in a sample set, the sampling time is set at 8192/5120=1.6 seconds. According to the Siglab's ability, we have a maximum of 8192 for each data frame.

4. Main parameters of data collection

In order to catch the break time of the gears, a reasonable interval should be maintained between each collection of data. The main parameters of the data collection are shown in Table 2. The size of all the data file is $(280\times 30\times 7\times 10)/1024 = 574.2$ MB. Here, 280KB is the size of each data file. The value, 30, is the number of times data is collected in an hour. The value, 7, is the work time in a day given in hours. The value, 10, is the number of days in gearbox's lifetime. The disk space of a laptop is 2.2GB which is what is being used at present. It's enough for our experiment.

The main frequency contents of the test rig are summarized in Table 3.

Table 2. Main parameters of this experiment

Speed of motor	Load	Data length of each collection	Time-interval between Every two collections	Work time
2400rpm (40Hz)	40Nm (81.9% of the max load)	8192/(5120)=1.6 Seconds	2minutes	70.028Hours Let the gearbox work for 7 Hours per day.

(Note: In practice, we found that the data collected from a gearbox which works for 7 hours per day cannot reflect the gearbox's pattern of deterioration exactly. We suggest collecting data from the gearbox without pausing in future experiments).

Table 3. Frequency contents of this experiment (Hz)

motor	Shaft a	Shaft b	Shaft c	1^{st} stage meshing and its harmonicas	2^{nd} stage meshing its harmonicas
40	9.52	3.17	1.9	152.32 304.64 456.96 Sidebands: 9.52 or 3.17	304 608 912 Sidebands: 3.17 or 1.9

The RMS, shown below, will be employed as a parameter to denote the vibration level of the gearbox[4].

$$R(x) = \sqrt{\frac{\sum_{i=1}^{n} x_i^2}{n}}\ , \tag{3}$$

where $R(x)$ is the RMS(Root Mean Square), n is the length of data, x_i is the i^{th} data. In this experiment, n=8192.

Kurtosis is another index used in this experiment to detect the state of the gearbox.

$$k = \frac{1}{\sigma^4}\int_{-\infty}^{\infty} (x-\bar{x})^4 f(x)dx \ ^{[5]}, \tag{4}$$

where $f(x)$ is the probability density function of the instantaneous amplitude, $x(t)$ is the observation at time t, $\bar{x}$ is the mean value, x at time t and σ is the standard deviation of $x(t)$. The kurtosis.m file in matlab will be used.

The data will be analyzed the same day it is collected. When the RMS is greater than before, the interval between samplings will be decreased.

Since the computer plots two graphs of RMS changes, the data on these changes can be collected on line if it exceeds its usually value. If we collect data continuously, the maximum number of the frames of data that the Siglab allows is 969. This means that we can collect data continuously for only $1.6 \times 969 = 1550.4\text{seconds} = 0.4307\text{hours}$. The collection process will stop automatically each time. We then have to manually start the continuous data collection process again for another 0.4307hours each time. The size of each data file is $0.28 \times 969 = 271.32$ MB.

In this experiment, fault model of the gearbox is that gear 5 is expected to experience a tooth break first.

4 Operational procedures

The operational procedures are shown below:

(1) Turn on the power through switch labeled **27/29** on the electrical panel in the wall of our lab. Make sure all the equipment has power.

(2) Turn on the signal amplifiers, Siglab data collector, and laptop. Be sure that the signal amplifiers has enough power.

(3) Turn on the gearbox and increase the speed of it slowly. Let the gearbox work at 2400RPM(40Hz). Then, let the workload be gradually increased to 81.9% of the maximum load.

(4) Run the program from the computer.

(4.1) To start, click on the Siglab icon on the desk of the laptop as show, in Fig. 4.

(4.2) After you click on the icon of Siglab icon, the main interface of the data collection will appear, as shown in Fig. 5. Then, click on the menu 'VNA' shown in Fig. 5.

(4.3) After step (4.2), the interface of parameters and data collection will appear as shown in Fig. 6.

(4.4) Click as the guide as shown in Fig. 6. The interface 'Export' will appear, as shown in Fig. 7. Choose "Time Series" in Fig. 7. **(Note:** In order to assure the First data file does not miss any data, please click on the 'Saveas to Text' button at the $(2*n+1)^{th}$ Minute at the beginning.**)**

(4.5) After Step (4.4), the plots of data collection will appear and renew automatically, as shown in Fig. 8.

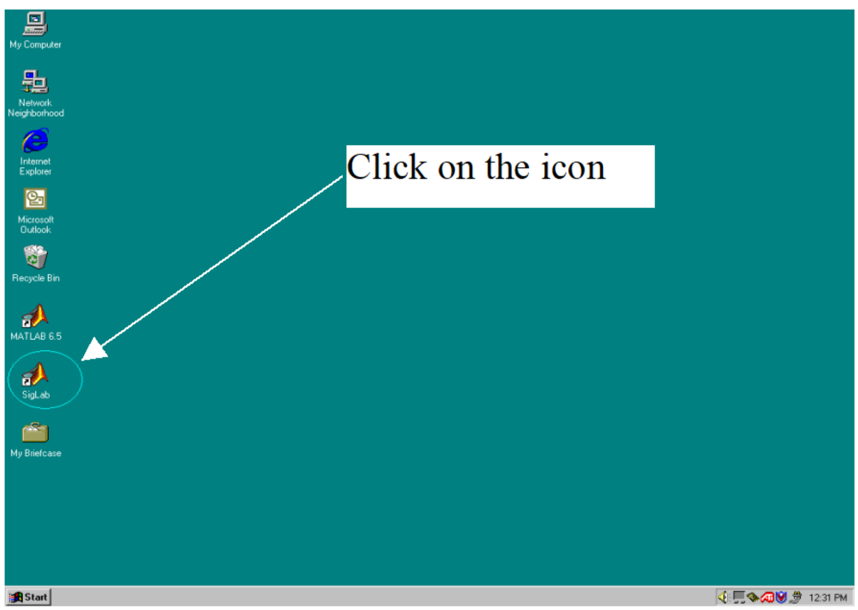


Figure 4. Click on the icon of Siglab to start the experiment's program

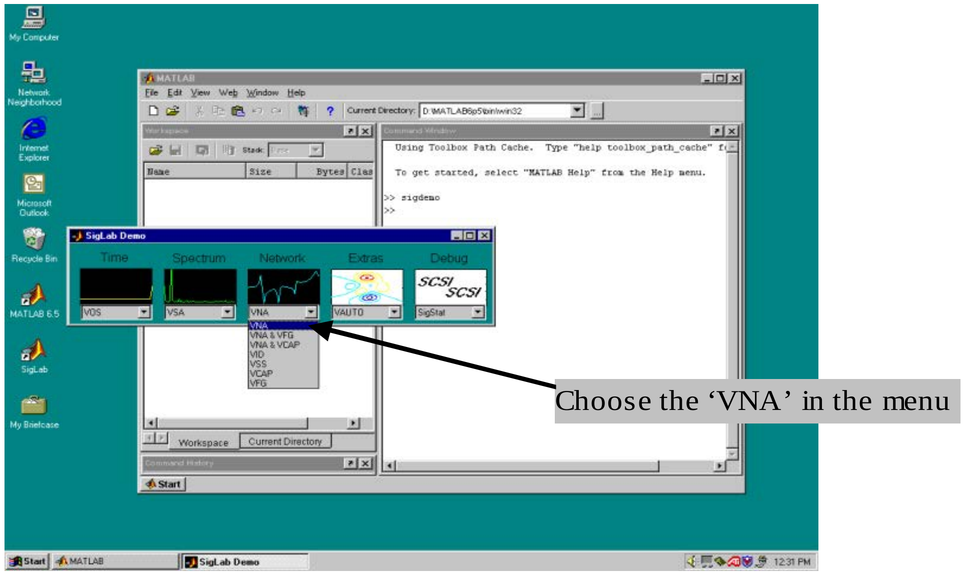
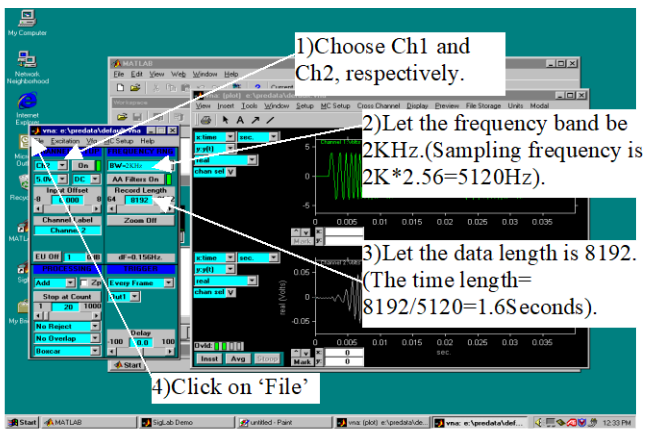
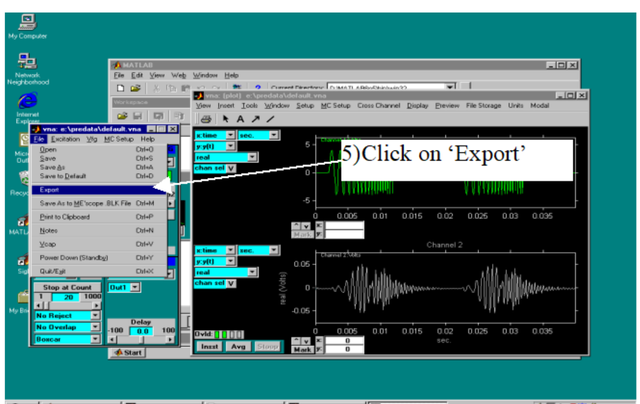


Figure 5. The main interface of the data collection program



a)



b)

Figure 6. The interface of parameters and data collection

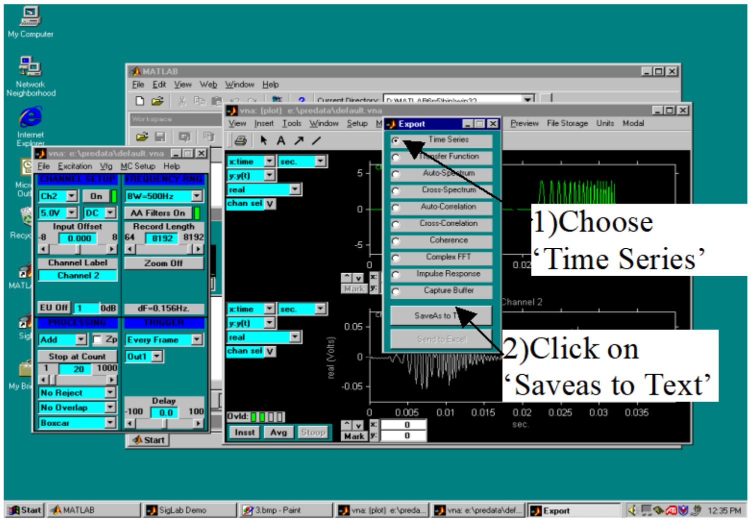


Figure 7. The interface of Step (4.4)

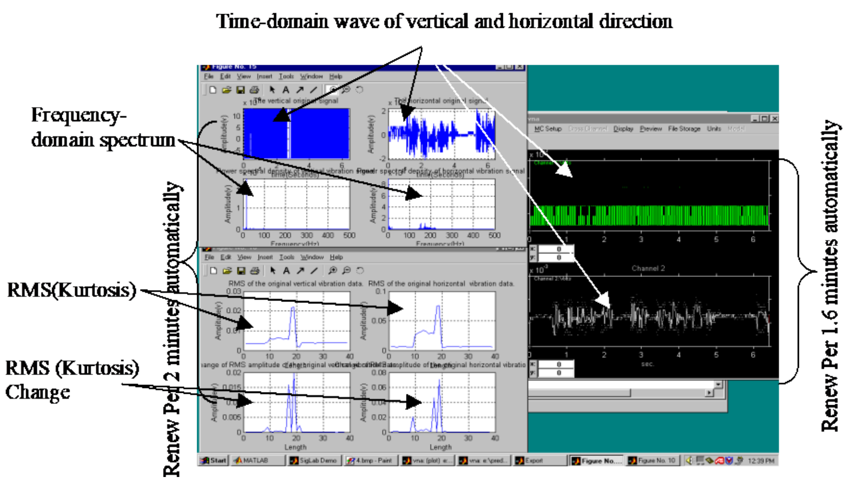


Figure 8. The interface of plots

(5) Stop the program for the experiment.
If we want to stop the experiment, there are two choices.
(5.1) Click on 'Stoop'(Shown in Fig. 9) and close all the windows. At that point, the program will stop collecting data. **(Note:** In order to assure the last data file does not miss any data, please click on the 'Stoop' button at the $(2*n+1)^{th}$ Minute when you want to stop the program.)
(5.2) The second choice for stopping the program is to let it stop automatically and notify us, as shown in Fig.10, to stop the gearbox. The program will, if not stopped manually, stop automatically at 10:13pm. We can change this if we want to change the experiment.

(6) Stop the experiment
After the program stops, we should stop the gearbox at once. Be careful to decrease the load and speed gradually. Then, close all the windows of the laptop. Turn off Siglab and signal amplifiers. Shut down the laptop. Turn off all the power.

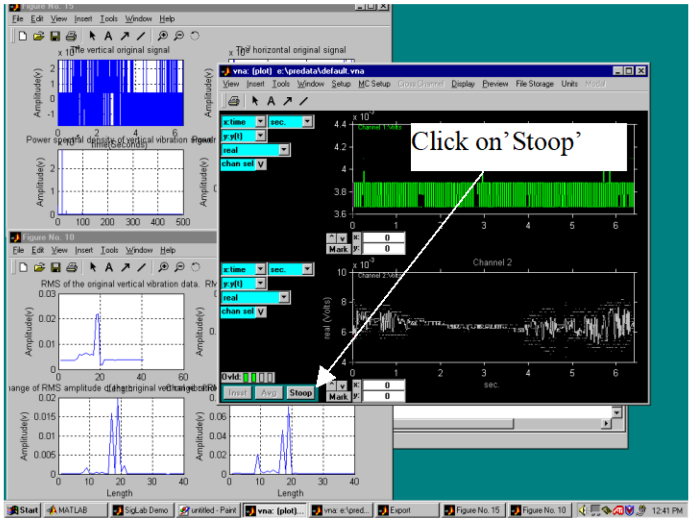


Figure 9 Operation of stop the data collection

Figure 10. Notifies that the data collection is over for the day.

5 Attachments

- Data files obtained have been stored in the path D:\predata\, as shown in Fig. 11.

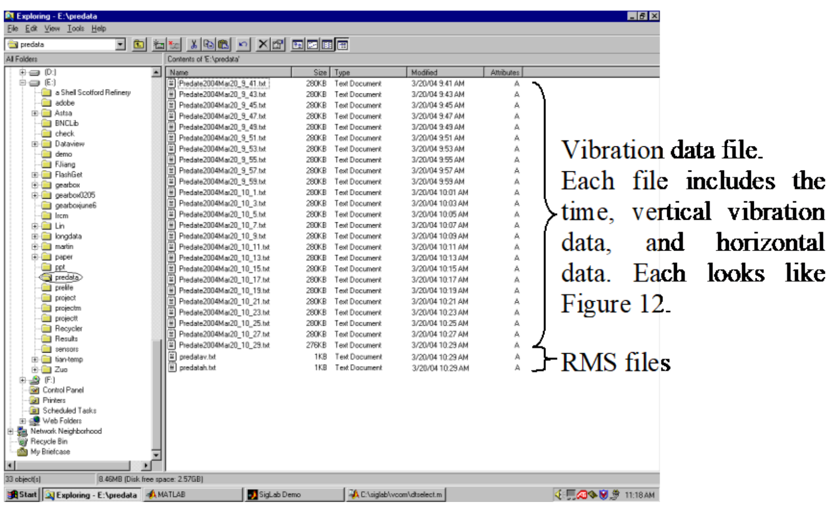


Figure 11. Vibration data collected and RMS files

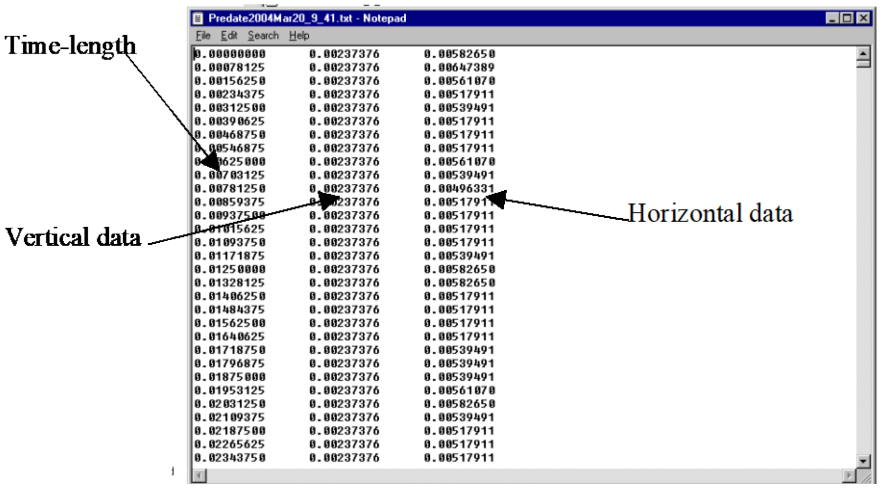


Figure 12. Format of the data collected

- ➢ The total work time of a gearbox is 2*(the number of data files) minutes if we collect the data only every 2 minutes. Otherwise, the total work time of the gearbox should contain the time of collection data on line assuming we collect the data on line.

6 Data Collected

The run-to-failure experiment was conducted in April 2004 using the gearbox dynamic simulator in the Reliability Research Lab at the University of Alberta. The gearbox lifetime experiment started at 6:30pm on April 19, 2004, and finished at 4:40pm on April 23, 2004. The total work duration was approximately 35 Hours. There were several interruptions during the first two days of the experiment. The details of the experiment in each day are shown in Table 4. In the experiment, vibration signals were collected every two minutes. The sampling frequency of each collection is 5120 Hz. The length of each sample is 1.6 seconds with 8192 data points. In total, 1053 data sets were collected.

Table 4: Work time of the gearbox during the experiment

Apr 19, 2004	Apr 20, 2004	Apr 21, 2004	Apr 21–22, 2004
18:35–22:13 (3.67Hrs)	13:47–22:13 (8.47Hrs)	8:57–10:02 (1.1Hrs)	18:49–16:39 (21.87 Hrs)

In the afternoon of April 22, the output shaft of the gearbox stopped running. We stopped the experiment and opened the gearbox. The following phenomena, shown in Fig. 13, were observed:

- Gears 5 and 6 were not meshing any more. Gear 6 shifted along shaft c from its initial position.
- Both gears 5 and 6 were seriously damaged. There were broken teeth and bent teeth. The failure of gear 5 was more serious.

We suspect that gear 6 became loose on shaft c during the experiment. As gear 6 moved to the left, only a fraction of the width of a tooth was meshing and carrying the load. This caused teeth to bend and break. We also noticed that the total running time of the experiment was shorter than the predicted. There are two main reasons for this. One reason was that the experiment design and calculation results were not accurate enough. The second reason was that we had always selected conservative coefficients during the design process.

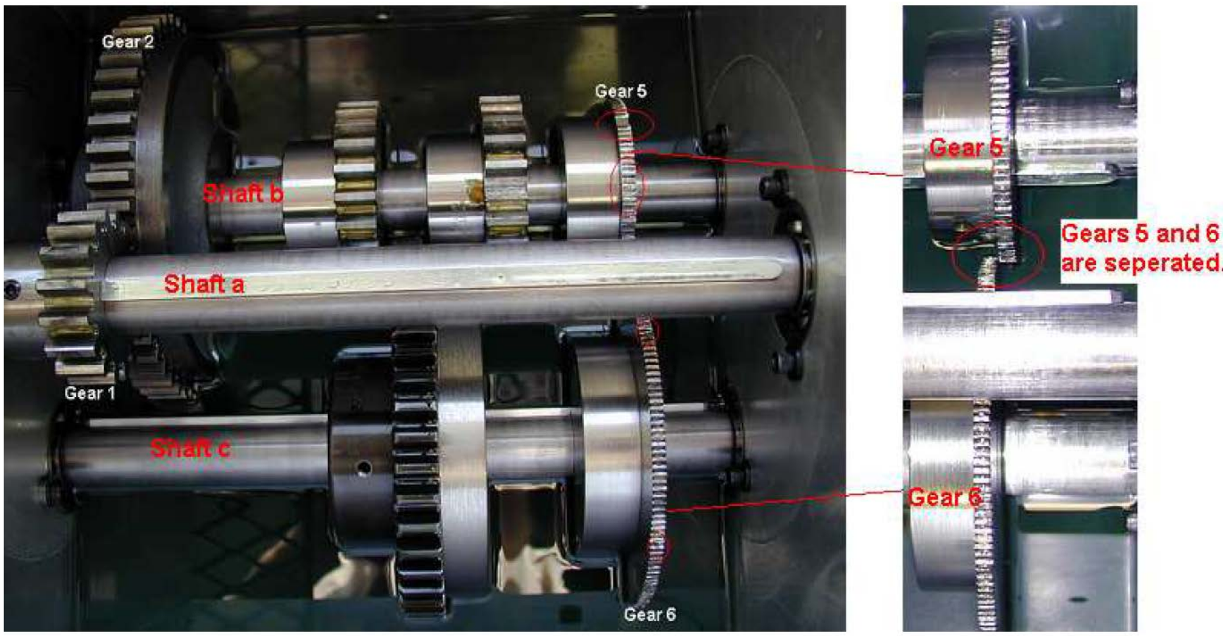


Figure 13. Gear status at the end of the experiment

7 References

[1] Label of the motor that we use in this experiment.

[2] *User Operating Manual for Gearbox Dynamics SimulatorTM v3.0.* Spectra Quest, INC.

[3] Manual for the motor, Alberta Rewind & Pump Services LTD, 8435 McIntyre Road, Edmonton, Alberta.

[4] http://mathworld.wolfram.com/Root-Mean-Square.html

[5] Singiresu S. Rao. Mechanical vibrations. (Fourth Edition). Prentice Hall; March 31, 2003, pp:789.