# CRANFIELD UNIVERSITY

RAJA ISHAK RAJA HAMZAH

## EXPERIMENTAL DETERMINATION OF NON LOAD DEPENDENT LOSSES FOR A DIP LUBRICATED WORM TYPE GEAR UNIT: GEAR CHURNING AND WINDAGE LOSSES

SCHOOL OF ENGINEERING

MSc THESIS

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Supervisor: Dr. David Mba

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# ABSTRACT

Environmental awareness and new legislation in today's market place has encouraged energy reduction activities. In light of this, demand for more efficient machinery has increased. One of the areas that contribute to power losses in most machines is gearbox. Detailed understanding of the reasons and sources of power losses within the gearbox are necessary if any efficiency improvements are to be made.

Power losses within the gearbox can be divided into load dependent and non-load dependent losses. Load dependent losses consist of bearing frictional losses and gear mesh frictional losses. On the other hand, non-load dependent losses consist of the oil seal losses, gear churning losses and bearing churning and windage losses. This research will only concentrate on the non-load dependent losses, particularly for a worm-wheel gearbox.

The purpose of this research is to validate established mathematical models for estimating non-load dependent losses in a worm-wheel gearbox and compare the theoretical estimates to experimental results. A series of experiments were undertaken in a dip lubricated worm-wheel gearbox for this investigation. The experiments are run in a no load condition with 3 different speeds and 10 different oil levels. Data from the experiments are then analyzed and compared with the existing published equations. Finally, conclusion and recommendation are made based on the comparison between the existing published equations and analyzed data.

The work presented is a continuation from research done by Mr. Steven Bray (2001), Mr. David Reynolds (2002) and Mr. Evangelos Tsoudis (2002). An improvement on the test rig and testing methods have been done based on their recommendations, comments and findings in an attempt to get more accurate and reliable result. Additional oil levels also been introduced in order to understand the oil level effects on the power losses.

Due to the time constraints, this research is done in collaboration with Mr. Darren Llyod Evans. The analysis of the non-load dependent losses is divided into gear losses and bearing and oil seal losses. This report will only focus on the gear losses.

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# NOTATION

| Symbol | Term | Units |
|---|---|---|
| $A$ | Arrangement Constant | - |
| $A_g$ | Gear churning arrangement constant | - |
| $b_t$ | Face width | mm |
| $b_o$ | Reference value of tooth width ( 10mm ) | mm |
| $C$ | Centre distance of gears | Inches |
| $D$ | Outside diameter of the element | mm |
| $Dr$ | Root diameter | mm |
| $d_w$ | Operating diameter of gear or pinion | mm |
| $F$ | Total face width | mm |
| $f_g$ | Gear dip factor | - |
| $H$ | Inside height of gear case | mm |
| $h_{e,max}$ | Maximum tip circle immersion depth | mm |
| $h_c$ | Height of point of contact above the lowest point of immersing gear | mm |
| $h_{e,1,2}$ | Tip circle immersion depth | mm |
| $h_{e,0}$ | Reference value of immersion depth ( 10mm ) | mm |
| $L$ | Length element | mm |
| $L$ | Width of gear case | mm |
| $l_h$ | Hydraulic length | mm |
| $m_n$ | Normal module | mm |
| $m_t$ | Transverse module | mm |
| $n$ | Shaft speed | rev/min |
| $R_f$ | Rough surface adjustment factor | - |

| | | |
|---|---|---|
| $T_H$ | Hydraulic torque | N.m |
| $\beta$ | Generated helix angle | Degree |
| $\beta$ | Bubble content | Percent |
| $\lambda$ | Enclosure function | - |
| $\mu$ | Dynamic viscosity | Poise |
| $\mu_b$ | Dynamic viscosity of bubbly oil | Poise |
| $v$ | Kinematic viscosity | mm2/s |
| $v_t$ | Tangential speed | m/s |
| $v_{t0}$ | Reference tangential speed | m/s |
| $\phi$ | Effective density of oil laden atmosphere | - |

# 1. Introduction

## 1.0 General

Gears have been known for centuries as the most efficient medium of transmitting loads. However, due to the environmental awareness and more stringent legislation in the market place, the demands on more efficient gearboxes has increased to comply with the needs. Intensive research has been carried out lately in this area in order to understand the sources of losses and factors that contribute to the power losses in the gearboxes.

A considerable amount of research has been carried out in order to correlate gearbox parameters including the lubricant properties to the non-load dependent losses. A number of equations showing the relationship between the gearbox parameters and the losses have also been published. Most of the equations are either empirical or semi-empirical derived through extensive series of experiments. However, due to the complicated geometries and other parameters in the gearbox, the reliability of the equations are still been discussed. Many researchers believe that intensive research is still needed in this area in order to validate the existing equations or explore other parameters that might influence the losses in the gearbox.

The worm gearbox is considered as the least efficient gearbox. The efficiency of worm gearbox is rated to be 96% or less. Higher reduction ratio will give lesser efficiency. 'David Brown Engineering Ltd' reported that the overall efficiency for worm gearbox can fall to below 50% for reduction ratio higher than 50:1. In worm-wheel gearbox, the worm gear is the driving gear while wheel gear is the driven gear. The main advantage of using worm-wheel gearbox is the ability to transmit high torque from high reduction ratio, in addition to having 90 degrees angle between input and output shaft.

Losses in gearbox can be divided into load dependent losses and non-load dependent losses. Load dependent losses consist of gear friction loss and bearing friction loss. On the other hand, non-load dependent losses consist of oil seal loss, gear churning and windage loss and bearing churning and windage loss. This program of research will only concentrate on investigating the non-load dependent losses particularly in a dip lubricated worm-wheel gearbox. Due to time constraint, analysis and findings in this report will only focus on the gear churning and windage losses

Churning loss can be defined as the losses due to the actions of gears moving inside the lubricant and losses due to entrapment of lubricant in the gear mesh. Windage loss, on the other hand is defined as the losses coming from the frictional resistance on the gear due to the surrounding atmosphere of the gearbox. The atmosphere can consist of only air or mixture of air and oil mist. Details on churning and windage losses will be discussed in the later chapter.

The purpose of this research is basically to validate the existing mathematical expressions and verify the suitability of these expressions in determining the non-load dependent losses. This program of research aims to derive a model to predict non-load dependent losses in worm gearboxes. Beside gear parameters, the effect of oil temperature and properties also play an important role in contributing towards the non-load dependent losses in the gearbox. However, due to time constraints, the temperature effects and lubricant properties are kept constant.

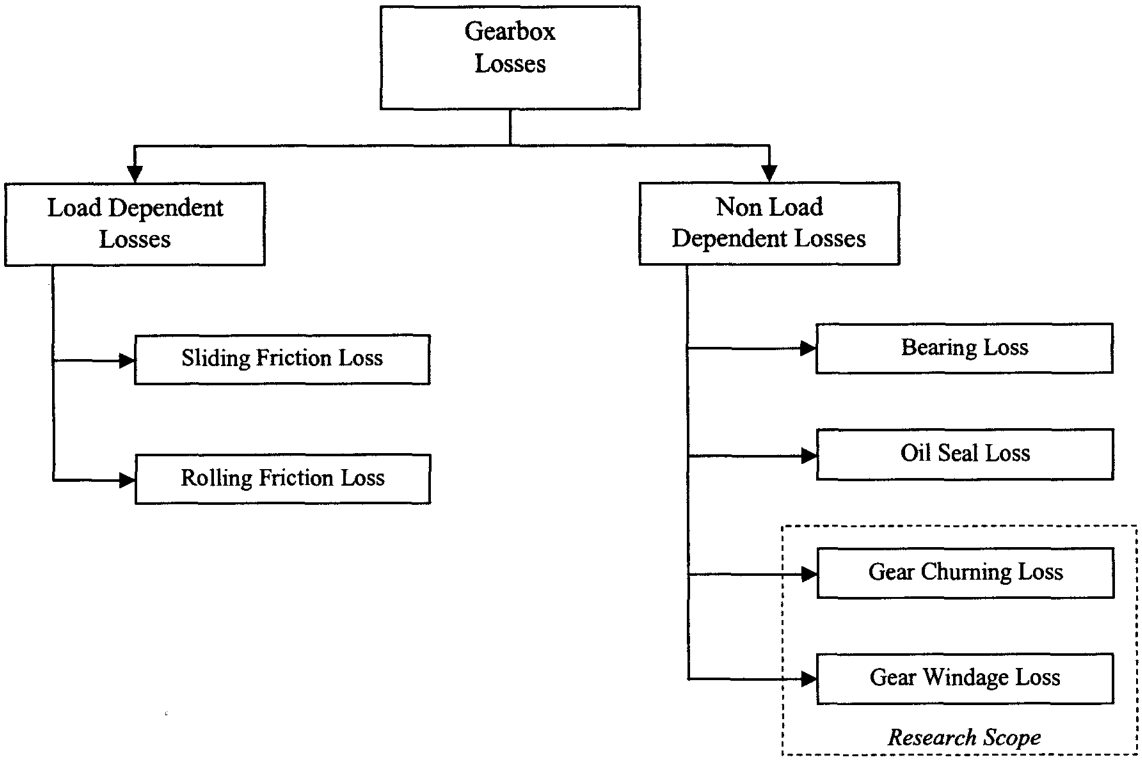


*Figure 1.1 : Power Losses In Gearbox ( Research Scope Shown In Dotted Box )*

## 1.1 Background

This research is the continuation of research done by Mr. Steven Bray[6], Mr. David Reynolds[29] and Mr. Evengelos Tsoudis[36], former students of the MSc in Design of Rotating Machines. The specifications of this project are mostly based on their recommendations, comments and discoveries. Mr Steven Bray[6] in his thesis, 'A Report On The Churning Losses For A Dip-Lubricated Enclosed Worm Gear Unit' has revealed that most published gear churning equations cannot accurately model the losses within the enclosed worm gearbox. However, the most interesting discovery found by Mr Steven Bray[6] was the similarities between his results and equations from ISO/TR14179-1:2001[30]. This shows the potentiality of this equation to be used in finding the non-load dependent losses in the enclosed worm gearbox.

Mr. David Reynolds[29] and Mr Evengelos Tsoudis[36] built of Steven Bray's project in their efforts to validate the potentiality of some equations to be used in finding non-load dependent losses in the enclosed worm gearbox. In their thesis, 'Experimental Determination of Non Load Dependent Losses for A Dip Lubricated Worm Type Gear Unit', they have introduced a very interesting method of finding every single non-load dependent loss in the enclosed worm gearbox. The used of shaft with insignificant diameter in their tests has made the calculation of every single non-dependent loss in the enclosed worm gear unit possible. However, since not all of the requirements in their project specification have been utilized, they recommended that the test to be repeated with some modifications on the test rig and test procedures.

Based on their recommendations, comments and findings, the author of this thesis in collaboration with Mr. Darren Llyod Evans have further investigate the possibilities of any published equations to be used in finding the non-load dependent losses in the enclosed worm gearbox.

## 1.2 Project Specification

As mentioned earlier, most of the project specifications are made based on the recommendations, comments and findings from previous thesis. The recommendations implemented included:

- Reducing vibration on the worm step down shaft due to looseness that affect the accuracy of the results.
- Manufacture of special torque bar need to be designed to ensure that the torque arm is accurately calibrated.
- Calibration should be done using both DAQ system and manual meter to give better results.
- Wheel gear should be tested with speed according to the reduction ratio 30:1.
- Rapid increase in oil temperature around the bearing during the test must be avoided.

In this research, improvements have been done particularly in the area of calibrating the equipment, test rig accuracy and test procedure. The detail specifications on the research are shown as below:

- Modify the test rig to reduce vibration on the worm step down shaft. Use lock screw to reduce looseness during testing with worm step down shaft.
- Use specially designed lever arm to get better accuracy during calibration. This lever arm produces more accurate torque on the calibrated torque arm. The slipping effect between torque arm and the lever arm is believed to be eliminated. Previously, C-clamp was used to attached lever arm and the torque arm.
- Use both DAQ system and manual meter during calibration process in order to get better calibration results.
- Use new set of test configuration to get the correct representation of all the elements in the worm wheel gearbox during operation. This configuration eliminates testing with wheel gear only. Losses on the wheel gear and bearings will be found through calculation. Problem associated with exact running speeds according to the reduction ratio on the wheel gear is believed to be eliminated.
- Run the tests with additional oil levels in order to get better understanding on how the oil levels influences the losses.
- Run the tests with different oil temperature to see the temperature effects on non-load dependent losses in the worm wheel gearbox.

Due to the accuracy of the equipment used in this test, the measured values are actually the combination of both churning and windage losses. Since the windage losses is considered to be small compared to the churning losses, the windage losses is assumed to be negligible. So, all the measured and calculated gear losses values in this research will be assumed coming from the churning effect.

Sliding friction loss is also assumed to be negligible in this experiment since the tests are run under no load condition and the gears are adequately lubricated. All the measurements and calculations in this research are made based on all those specifications and assumptions.

## 1.3 Objectives

Since most of the published equations are experimentally derived from the spur or helical gear test rig, it is become one of the research objectives to find any possibility of using those equations in calculating the gear losses in the worm-wheel gearbox. All the non-load dependent gear losses will be compared to the existing published equations in order to find any similarity between them.

Other objectives of the research are as follows:

- Verify the suitability of mathematical expressions in the public domain in measuring non-load dependent gear losses.
- Compare theoretical predicts to the experimental results from a worm gearbox.
- Quantify non-load dependent losses within the enclosed worm-wheel gearbox.
- Study and investigate the cause of result variation between the existing published equations.
- Get better understanding on the effect of all the parameters used in the existing published equations.
- Introduce new parameter that affects the losses if possible.

## 1.4 Test Plan

Gantt chart on figure 1.2 illustrates the planning in order to complete the whole test within the specified time scale.

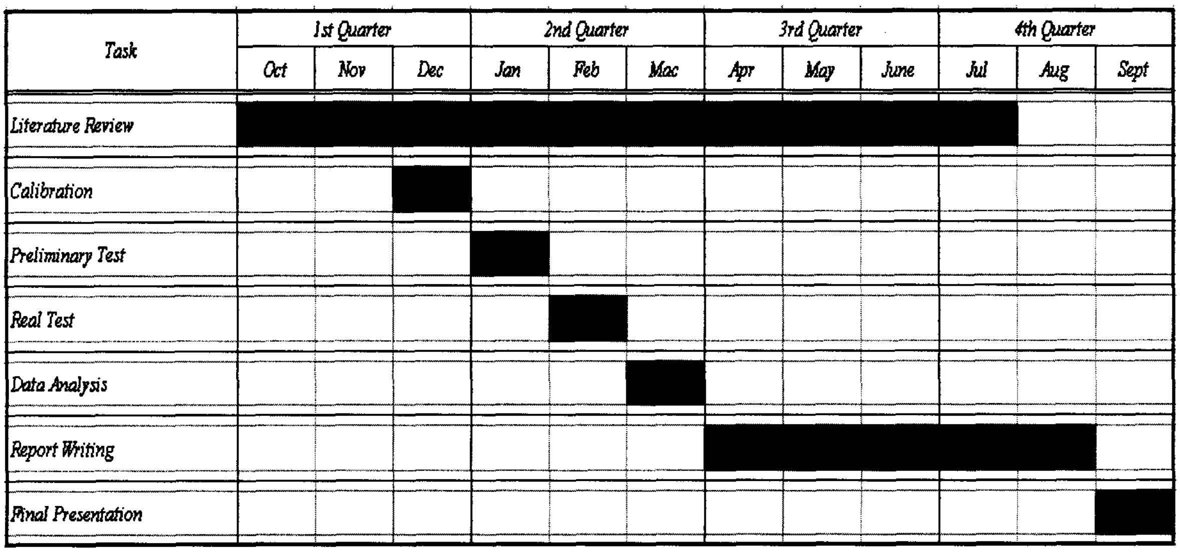


*Figure 1.2: Gantt Chart*

# 2. Literature Review

## 2.0 General

This chapter covers all the literature surveys that have been done for this program of research. In this chapter, basic principle of worm gearbox, gear churning and windage losses are described briefly. Besides, gear lubrication properties effects on the non load dependent losses are also explained. In addition, this chapter focus mostly on various mathematical models for non load dependent losses published by different researchers. Most of the mathematical models presented here were derived from experiments with spur gears.

## 2.1 Worm Wheel Gearbox

Worm gearboxes are usually chosen when large reduction ratios are needed. According to Howstuffworks[18], this type gearbox can provide a reduction ratio up to 300:1 or greater. Worm-wheel gearbox works according to the screw and nut principle. The meshing action is quite similar to helical gear on parallel shaft. However, the sliding velocity at the pitch circle is much higher in worm gears compared to the helical gears. In worm gearbox, the worm is usually the driving gear while the wheel is the driven gear. The input and output shaft is perpendicular to each other. One of the interesting properties that worm gearbox has is; only the worm can turn the wheel. This enables the gearbox to work as a locking mechanism particularly for the conveyor systems.

The losses in worm-wheel gearbox considered as the highest compared to other type of gearboxes. These losses increase as the reduction ratio increase. 'David Brown Ltd' reported that the losses can go up to 50% for reduction ratio more than 50/1. Walker[40], considered the efficiency of worm gearbox to be varied roughly between 85 to 96 percent. The tooth efficiency of the worm gearing may be expressed by the following equation,

$$E = \frac{\tan \lambda}{\tan(\lambda + \phi)}$$

$$\tan \phi = \mu / \cos \psi_n$$

where, $E$ = *Effeciency*

$\lambda$ = *Lead angle of the worm thread*

$\mu$ = *Coefficient of friction*

$\psi_n$ = *normal pressure angle*

Tooth efficiency refers to the efficiency of the gears associated with tooth contact during the engagement.

Losses due to drag are not included in this equation. They need to be computed separately in determining the overall efficiency since losses factors are entirely different. In practice, worm gearboxes are usually limited in capacity by temperature rise than by any other factor since the heat generated is proportional to the power loss. So, it has become of prime importance to study the contributing factors leading to the power losses in worm gearboxes.

Losses in gearboxes can be divided into load dependent and non-load dependent loss. Load dependent losses consist of sliding and rolling friction losses. On the other hand, Non load dependent losses consists of gear churning and windage losses, bearing churning and windage losses and oil seal losses. Factors such as gear geometries, speed, lubrication properties and method of lubrication are all contribute towards the losses in worm gearboxes. Townsend[35], stated that many gearboxes could operate at better efficiencies with improved lubrication and cooling methods. He also mentioned that the tooth friction loss is probably the lowest loss when the gears are adequately lubricated.

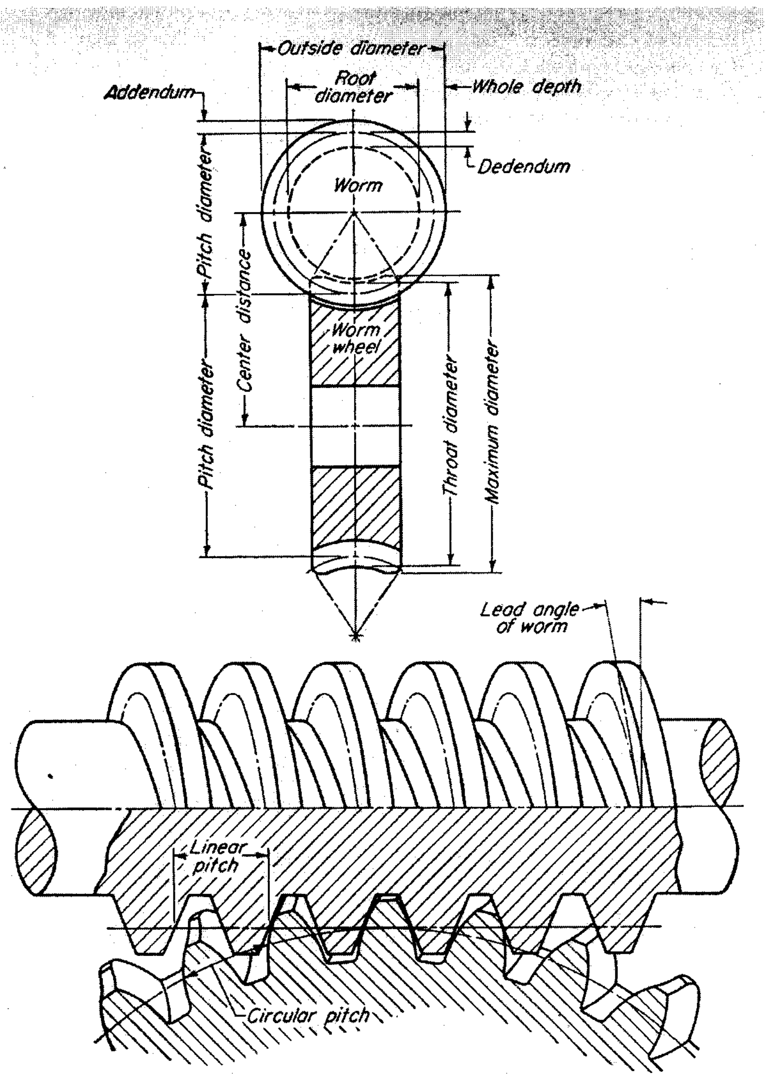


*Figure 2.1: Gear Terminology – Dudley*[13]

## 2.2 Churning Loss

Churning loss is defined by Townsend[35] as the losses due to oil drag and entrapment of lubricant in the gear mesh. Lubricant will be trapped, squeezed and blend as the gear teeth come to the meshing zone. Squeezed lubrications are then splashed out from the meshing zone. Besides, the lubricant will also cause the resistance as the gears move into it. All of these contribute to the churning power loss.