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# Measurements and Predictions of Plastic Gear Transmission Errors with Comparisons to the Measured Noise of Plastic and Steel Gears

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## TECHNICAL PAPER



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[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

## Abstract

In recent years, plastic gears have found their popularity as replacements for metal gears in selected, lightly loaded applications. Many studies have been done in the area of plastic gearing such as plastic material selection, injection molding and load capacity of plastic gears. Several historical papers imply that plastic gears are “quieter” than steel gears. Yet, there have been few studies that focus on studying the transmission errors of plastic gears and relating these errors to the noise that is generated.

This paper focuses on the transmission error and sound pressure level measurements of several plastic gear sets and compares experimental static transmission error measurements to computer predictions. Based on the experimental results, in plastic gears the tooth contact is more susceptible to occurring off the line of action due to excessive tooth deflection. This directly affects the transmission error behavior. A computer program that considers off line of action contact is used to accurately predict static transmission error for the experimental plastic gears.

According to previous studies on metal gears, there is a correlation between mesh harmonics of transmission error and sound pressure level. This study presents results used to check this correlation in plastic gears. The comparison of the ratio of sound level to transmission for the plastic gears and steel gears with similar overall geometry specifications is also presented.

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## Introduction

In recent years, plastic gears have found their popularity as replacements for metal gears in selected, lightly loaded applications. Many studies have been done in the area of plastic gearing such as plastic material selection, injection molding processes, and load capacity of plastic gears. Many historical papers imply that plastic gears are "quieter" than steel gears. Yet, there have been few studies that focus on making the comparison of the transmission error and sound pressure level of plastic and steel gears, as is done in this paper.

## Research Objectives

There are two main objectives of this paper. 1) The first is the measurement of transmission error of two different plastic gear sets and then to compare these measurements with analytical predictions of static transmission error. 2) The second objective is to compare the relationships between measured sound pressure level with transmission error of plastic gears (Nylon and Acetal) and steel gears that have similar overall geometries, loads and speeds.

## Plastic Gear Manufacturing Overview

Plastic gears can be produced by a variety of manufacturing methods. Thermoplastics can be machined from rod stock. Polymer rods are first formed via standard extrusion processes. In some of these rods, a metal insert is included to form a strong hub for the gear. Then a sophisticated cutting machine

is used to slowly cut the tooth profiles. Machine cut plastic gears are usually made for prototyping testing purposes. Since extremely small quantities of the test gears used in this study were produced, they were machined from plastic rod stock. Therefore, the manufacturing errors of these gears are more typical of those observed in metal gears.

Net shape manufacturing processes are more common with plastic gears since these processes are much more economical. Compression molding is used to produce thermosetting polymer gears. The complimentary process for thermoplastics is injection molding. This process allows the cost-effective production of plastic gears in high volume. Furthermore, compound gears can be easily produced in a single mold thus reducing part count. Manufacturing inaccuracies of gears produced with these processes differ greatly from those of machined gears. For instance, gating methods greatly affect part shape and shrinkage is of major concern. It is not the intent of this paper to address these issues, but techniques similar to those that are used in this paper could be applied to net shape manufactured plastic gears.

## Measurement Methodology

### Test Rig

The major part of this experimental study was conducted on the Variable Center Distance Test Rig located at the Ohio State University [1]. The gears were continuously lubricated during the test, however an important variable, operational temperature, was not monitored. In this experiment, eight different

signals were simultaneously recorded while the test rig was running: a) signals from four sound pressure level meters placed 45 inches above the test rig, b) a pulse signal from a tachometer that measured shaft speed, c) the output of a gearbox housing accelerometer. d) the sum of the two angular accelerometers of the pinion and the sum the two angular accelerometers of the gear. The data were recorded so that they could be analyzed further using a spectrum analyzer. More details on these measurements are given below.

### Transmission Error Measurement

Transmission error is defined as the deviation of the position of the driven gear from the position that it would occupy if both driven and driving gear were infinitely stiff and had perfect involute profiles. Transmission error may be expressed in angular units or as a linear displacement along the line of action. The following are the respective equations for linear and angular transmission error acceleration:

$$\ddot{\theta}_{TE} = \ddot{\phi}_P - \frac{N_G}{N_P} \ddot{\phi}_G \quad \text{Eq. 1}$$

$$\ddot{TE} = R_{BP} \ddot{\phi}_P - R_{BG} \ddot{\phi}_G$$

where

- $R_{BP}$  = the base radii of the pinion
- $R_{BG}$  = the base radius of the gear
- $N_G$  = number of teeth on the gear
- $N_P$  = number of teeth on the pinion
- $\phi_P$  = pinion angular acceleration
- $\phi_G$  = gear angular acceleration

By double-integrating both sides of each equation, one can obtain the transmission error in displacement units (effectively by removing the double dots above each term).

The transmission error measurement methods that have been implemented in the past on this rig include the use of torsional accelerometers, optical encoders and tangentially mounted translational accelerometers [2]. In this research, two translational accelerometers are mounted on the arbor where the gear is mounted (shown schematically in Figure 2). The advantage of this arrangement is that the arbor is manufactured as one piece with the mounting surface located adjacent to the test gear, therefore minimizing the possibility of shaft compliances and resonances affecting the measurement. In a previous study, the translational

accelerometers were mounted at the end of the gear and pinion shafts, but resonances caused dynamic measurement errors [3].

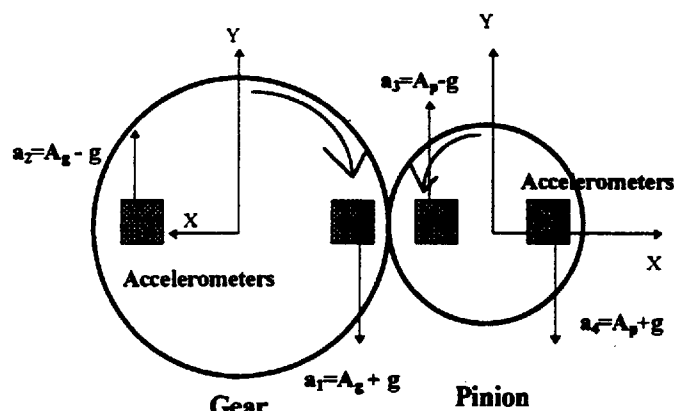


Figure 1. Schematic of Accelerometers Mounted on the Test Gears

To obtain the transmission error displacement, the transmission error acceleration has to be integrated twice. The double integration can be performed in the time domain or in the frequency domain by using a pseudo integration method. In this research, the pseudo integration technique is preferred because it is easy to implement with a spectrum analyzer and does not sacrifice accuracy. The pseudo integration method involves dividing the Fast Fourier Transform spectrum of transmission error acceleration by the square of the corresponding frequency (Eq. 2)

$$TE = \frac{g}{K\omega^2} (TE) \quad \text{Eq. 2}$$

$$TE = \frac{gR_{BP}}{2r_p K\omega^2} ((a_3 + a_4) - \frac{N_G}{N_P} (a_1 + a_2))$$

where

- $g$  = gravitational acceleration (in/sec<sup>2</sup>)
- $K$  = calibration gain (Volt/g)
- $\omega$  = corresponding frequency of each discrete signal (rad/sec)
- $a_1$  = acceleration of accelerometer 1
- $a_2$  = acceleration of accelerometer 2
- $a_3$  = acceleration of accelerometer 3
- $a_4$  = acceleration of accelerometer 4
- $r_p$  = radial distance from the pinion shaft center to the accelerometer neutral axis

The translational accelerometers are calibrated while they are mounted on the gear and the rig is running at low speed. This rotating motion causes the two 180° apart accelerometers to measure  $\pm 1g$