

# Gear Train Mesh Efficiency Study: The Effects of an Anti-Backlash Gear

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## ABSTRACT

In recent years, the focus on engine parasitic losses has increased as a result of the efforts to increase engine efficiency and reduce greenhouse gasses. The engine gear train, used to time the valve system and drive auxiliary loads, contributes to the overall engine parasitic losses. Anti-backlash gears are often used in engine gear trains to reduce gear rattle noise resulting from the torsional excitation of the gear train by the engine output torque. Friction between sliding surfaces at the gear tooth is a major source of power loss in gear trains. The effect of using anti-backlash gears on the gear friction power loss is not well known. As a part of the effort to reduce parasitic losses, the increase in friction power loss in the Cummins ISX 15 gear train due to the anti-backlash gear was quantitatively determined by modifying the methods given in ISO 14179-2 to fit the anti-backlash gear sub-assembly. A test case with a two gear mesh arrangement was designed for the purpose of validating the analysis by rig testing. The torque required to drive the test case as a function of gear rotational speed was measured on the rig. The test plan consisted of two configurations: 1. the anti-backlash gear and a regular spur gear mesh, and 2. the anti-backlash gear replaced by a regular spur gear. An anti-backlash and spur gear from the gear train of the Cummins ISX 15 engine - for the heavy duty market - were used in the rig. Results revealed that the anti-backlash gear-regular spur gear mesh required a mean torque of approximately 5 Nm, whereas the regular spur-regular spur gear mesh only required a mean torque of approximately 0.75 Nm. The power losses for these configurations were found to be in good agreement with the analytical results obtained by using the equation for friction losses according to Mauz. The conclusions of this study will impact engineering decisions that must consider the advantages of an anti-backlash gear (e.g. reduced gear rattle noise) with its disadvantages (e.g. cost and increased friction).

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## INTRODUCTION

The U.S. Environmental Protection Agency (EPA) and the Department of Transportation's National Highway Traffic Safety Administration (NHTSA) have drafted a new program to reduce greenhouse gas (GHG) emissions and improve fuel consumption standards for medium and heavy duty vehicles. By 2017, when the final standards are set to take effect, the carbon dioxide emissions and fuel consumption for heavy-heavy duty (class 8) vehicles must be reduced by up to 10% from their 2010 baseline levels [1]. This is a challenging task and must be faced with creative and innovative engineering and technology. One such method to reduce fuel consumption is to reduce parasitic power losses in the base engine components. Therefore, engine manufacturers are seeking all possible means of minimizing parasitic power losses.

Due to increasing efforts to reduce parasitic losses, gear mesh friction has received significant attention in recent years. Multiple publications discuss the gear mesh efficiency and the parameters affecting the gear mesh efficiency [3, 4, 5, 6, 7, 8, 9]. The effect of lubrication regimes on friction coefficient has been studied for regular gear arrangements [10]. However,

there has not been much study of the effect of gear arrangements such as anti-backlash gear on the gear train efficiency.

Anti-backlash gears are often used in engine gear trains to overcome the issue of gear rattle noise. Among various configurations, one widely used configuration has biased load acting on the gear mesh. The load is high enough to prevent the separation of the gear mesh. The effect of the anti-backlash gear on the gear friction loss in engines is not well known and has not been reported in the literature.

One anti-backlash gear is used in the Cummins ISX 15 engine to reduce the gear rattle. The ISX 15 gear train is shown in Figure 1. The anti-backlash gear meshes with the crank gear and three other gears. As a part of the Department of Energy's project to increase on-highway truck efficiency, gear mesh efficiency analysis was carried out for the ISX 15 gear train. An investigation was conducted to understand the increase in load dependent power loss in an anti-backlash gear mesh as opposed to a regular gear mesh, and subsequently validate the analysis method by experimental results. The objectives of the analysis were:

1. To compare mesh power loss calculations for an anti-backlash gear and regular spur gear arrangement.
2. To calculate mesh power losses for a simplified, two gear mesh arrangement for the verification of the calculation procedure by an experimental setup.

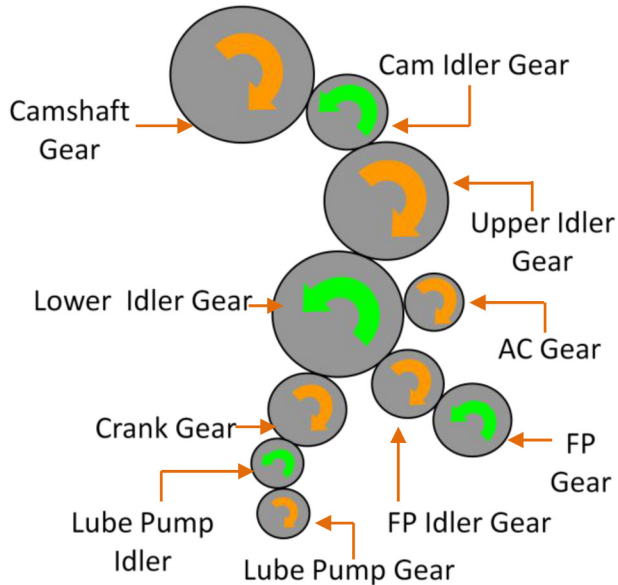


Figure 1. ISX15 engine gear train.

## ANTI-BACKLASH GEAR FRICTION POWER LOSS ANALYSIS

As a first step, a Free Body Diagram analysis was done to understand the loading paths in the anti-backlash gear. The power flow path in the engine is from the crank gear to the anti-backlash gear. The anti-backlash gear has two segments - wide and narrow (Figure 5). The wide gear meshes with the crank gear and two auxiliary gears, and also transfers power to the narrow segment of the anti-backlash gear. The power is transferred by the narrow segment of the anti-backlash gear to the upper idler gear. The two segments of the anti-backlash gear are connected by seven springs.

Three main cases differing in gear arrangements were analyzed using the method described above.

Case I: Gears in mesh with regular spur gears

Arrangement:

The arrangement is seen in Figure 2. It consists of the crank gear meshing with the lower idler gear, which meshes with upper idler gear, and two accessory gears. All gears in this arrangement were regular spur gears.

Case II: Gears in mesh with an anti-backlash gear

Arrangement:

The arrangement is seen in Figure 3. It consists of the crank gear driving the anti-backlash gear, which in turn drives the upper idler gear, and two accessory gears.

Case III: Simplified two gear setup

Arrangement:

It consists of two configurations, as seen in Figure 4-

- a. An anti-backlash gear meshing with the upper idler gear mounted on frictionless bearings.
- b. A regular gear meshing with the upper idler gear mounted on frictionless bearings.

Case III was selected for the ease of construction of a test rig and validation in a laboratory setting. It is used to investigate the loss from a single gear mesh. The torque is transferred from the anti-backlash/ regular gear to the upper idler gear.

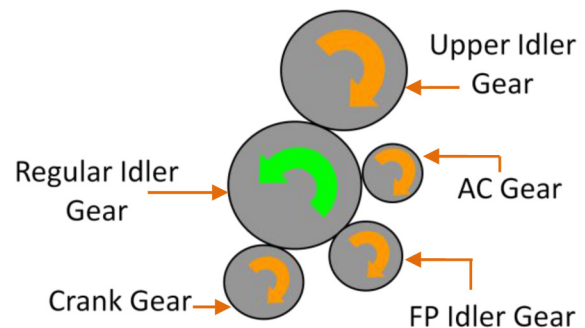


Figure 2. Arrangement for case I.

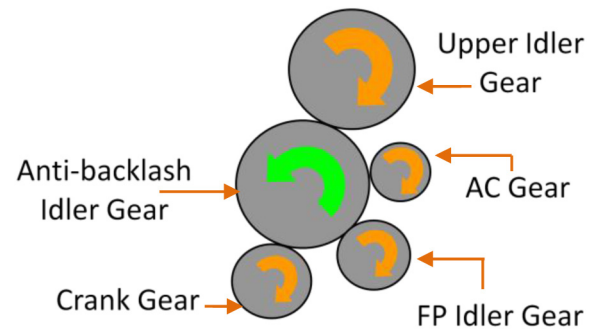


Figure 3. Arrangement for case II.

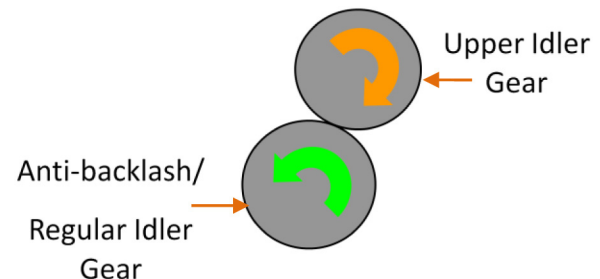


Figure 4. Arrangement for case III.

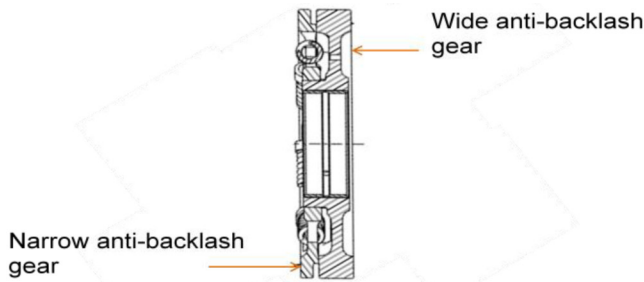


Figure 5. Cross section of the anti-backlash gear.

As the next step, gear mesh power loss calculation method was chosen. Multiple methods are available for the calculation of friction power loss in gears. ISO 14179-2 was selected for the friction power loss analysis.

Dynamic analysis for the engine gear train was carried out and the fluctuation of gear mesh forces with time was obtained as an output of the analysis. The output from the dynamic analysis was used to calculate the average mesh force for each pair of contacting flanks. The value of the coefficient of friction is directly proportional to the fifth root of the mesh force according to the ISO 14179-2 method; thus the impact of variation in mesh force on the power loss, which is directly proportional to the coefficient of friction, is low, if the mean mesh force does not change. The average mesh force was used to calculate torque and power at 600 RPM. The frictional power loss was calculated, taking into account the effect of coefficient of friction and sliding according to the ISO method. A comparison of the above method was done with the power loss calculation using instantaneous gear mesh values and was found to be in good agreement.

The analysis was carried out for each mesh using the Mauz equation, shown in Eq. (1), for load dependent gear power loss in cylindrical gears. The average coefficient of friction, calculated according to ISO 14179-2, was used for the analysis. The total power loss for the anti-backlash gear was calculated by adding the power loss for the individual mesh.

Gear mesh load and oil film thickness analysis of the gear mesh was done using the LDP software [2] to obtain the minimum  $\lambda$  value for both arrangements of case III.  $\lambda$  is calculated as a ratio of minimum film thickness and composite radial surface roughness as seen in Eq. (3). The gears were measured for surface roughness. The measured surface roughness before the start of the test can be seen in Figure 6. The gear surface roughness was re-measured after the completion of the test. The composite surface roughness was calculated by the equation seen in Eq. (2). The composite surface roughness after the test completion was  $0.55 R_a$ .

$$P_{vZP} = P_A \mu_{mZ} H_v,$$

$$P_{vZP} - \text{Load - dependent gear power loss,}$$

$$P_A - \text{Input power,}$$

$$\mu_{mZ} - \text{Friction coefficient,}$$

$$H_v - \text{Tooth loss factor}$$

(1)

$$R_a = \sqrt{R_{a1}^2 + R_{a2}^2}$$

$$R_a - \text{Composite surface roughness}$$

(2)

$$\lambda = \frac{h_{min}}{R_a},$$

$$h_{min} - \text{Minimum film thickness}$$

(3)

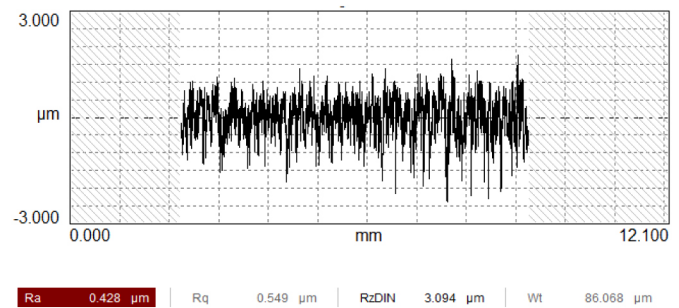


Figure 6. Surface roughness profile of the narrow section anti-backlash gear.

The analysis procedure, described in this section, was used for the estimation of load dependent gear mesh power loss in case I, II, and III. The analysis results for case III were sought to be validated by experimental testing to estimate the accuracy of the approach.

The analysis was done using the following assumptions:

1. The effect of gear inaccuracies on mesh efficiency is negligible
2. Kinematic viscosity of oil at  $100^\circ\text{C} = 15 \text{ mm}^2/\text{s}$
3. Density of oil =  $865 \text{ kg/m}^3$
4. Gear face width centerlines are aligned
5. Effect of gear train inertia on friction power loss is negligible

## EXPERIMENTAL METHODS

### Test Rig Apparatus

The test rig was designed to accommodate the lower idler gear (anti-backlash gear) and the upper idler gear (regular spur gear) on the Cummins ISX 15 gear train. The test rig setup displayed in Figures 7 and 8. A 40 HP electric motor with a