An Experimental Study on the Efficiency of Bicycle Transmissions

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Abstract:

The objective of this project is to measure the efficiencies of bicycle drive systems. Previous efficiency studies tested several planetary hubs, belt drives and derailleur chain drives. This study will evaluate the efficiency of Pinion® internally geared transmission models P1.12 and P1.18. A new apparatus provides improved accuracy, reduced measurement noise and increased functionality for testing efficiency over a range of speeds and power levels. Each drivetrain gear is tested for five minutes at fourteen different speed and power combinations, spanning a range of output torques. Efficiency is then modelled as an exponential function of output torque and is fitted to the data with a non-linear regression. Results to date indicate the Pinion® P1.12 transmission is comparable to higher quality hub gears, with efficiencies ranging from 90.41% to 98.82%, depending on the gear. The Pinion® P1.18 transmission will be tested after further repeatability studies are performed on the P1.12 model.

Keywords:

Gearbox, transmission, efficiency, bicycle, Pinion

Introduction:

Bicycles receive input power over finite time intervals, determined by rider strength and endurance limits. They are optimized by minimizing external and internal power losses. Drive losses reduce the amount of input power transferred to the drive wheel. In *Bicycling Science*, Wilson[1] notes that race outcomes could be determined by the bicycle with the highest efficiency transmission. Thus, bicycle drive efficiencies factor into reduced race times, especially for long-distance races.

Bicycle drive efficiency is the ratio of the output power of the driven wheel to the input power from pedaling. Most studies evaluate power as the product of torque and angular velocity measurements, as shown in Equation 1.

Equation 1: Bicycle Drivetrain Efficiency

$$\eta_{bicycle\ drive} = \frac{Power_{driven\ wheel}}{Power_{chain\ ring}} = \frac{\tau_{driven\ wheel}\ \omega_{driven\ wheel}}{\tau_{chain\ ring}\ \omega_{chain\ ring}}$$

Initially, Spicer[2] used motor-generated input power to test a derailleur drive efficiency over five speed-power combinations. Efficiency was plotted against reciprocal chain tension, and a linear model fit the data. In a later study, Casteel and Archibald[3] measured the efficiencies of four planetary hubs, a belt drive and a derailleur using a modified ergometer. In each case, input (motor) and output (flywheel) power was measured over fourteen speed and power variations per gear. Calculated efficiency was plotted against flywheel torque, and an exponential model fit the data. Rohloff® hub efficiency ranged 95.8 to 99.5%, while the derailleur ranged 97.7 to 99.4%. In contrast, Wu et. al.[4] used angular velocities derived from a kinematic analysis and ideal static torques from gear ratios to calculate the efficiency of a 14-speed planetary hub. Their theoretical efficiencies of 96.77 to 100.00% were higher than Casteel and Archibald and Spicer's experimentally-determined efficiencies because losses due to bearing friction were not considered. Casteel and Archibald's experimental method will be applied to two Pinion® gearbox transmissions.

Pinion® gearbox transmissions include a P1.18 model of eighteen spur gears and the P1.12 model of twelve gears. They are incorporated into the cranks, rather than the drive wheel, with two constant gear stages transmitting power. Although Pinion®[5] evaluates each gear's efficiency prior to product shipment, documentation of these tests is not yet publically accessible. Building on efficiency studies of internally-geared hubs and derailleur drives, this study will assess the Pinion® P1.12 and P1.18 gearbox transmission efficiencies, and compare results to hub and derailleur drive efficiencies.

Methods

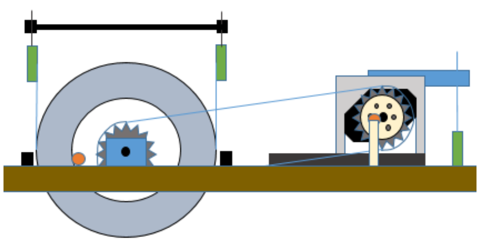

Figure 1: Apparatus Schematic, Front Tabletop View

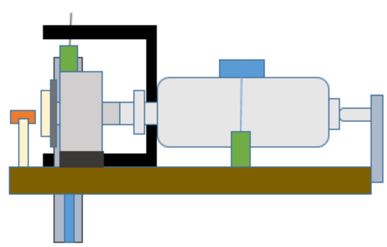

Figure 2: Apparatus Schematic, Right Tabletop View

This study's efficiency apparatus evaluates a complete drivetrain, including transmission, chain, sprockets and hub. The driveshaft of a Baldor® DC geared motor is connected to the input shaft of the Pinion® P1.12 transmission. The motor can freely rotate along its longitudinal axis. A 100 pound load cell, shown in green in Figure 1, measures input force from the motor lever arm with a wire. An Eaton® shielded E57-08GE03-C inductive-proximity sensor measures input velocity six times per revolution. A custom flywheel is housed on a Shimano® Deore FH-M595-L Freehub. An Aeco® unshielded SIV000024 inductive-proximity sensor, orange circle in Figure 1, picks up all thirty-two spokes per revolution to measure the output speed of the flywheel. A friction belt, shown in blue in Figure 1, contacts the bottom of the flywheel, instead of the top, to improve torque control and simplify force transducer calibration. Output force is the difference between readings from a 50 pound load cell, measuring the slack side of the friction belt, and a 200 pound load cell, measuring the tension side.

Each gear ran at 300W output power for 30 minutes before undergoing the same 14 speed and power combinations used for Casteel and Archibald's efficiency tests (Table 1). A Somat® eDAQlite data acquisition unit collected sensor data using corresponding Somat® TCE

3.14.0.353 software. An existing MATLAB script processed the ASCII file to determine the efficiency, according to Equation 2, and calculate the 95% confidence intervals.

Table 1: Efficiency Test Output Power and Input Speed Variations Conducted Per Gear

Trial	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Motor Speed (RPM)	60	70	80	90	100	110	120	120	120	120	120	120	120	120
Average Flywheel Power (W)	180	180	180	180	180	180	180	90	150	210	270	330	390	450

$$Transmission\ Efficiency = \frac{\left(F_{tension} - F_{slack}\right) * r_{flywheel} * \omega_{flywheel}}{F_{motor} * r_{lever\ arm} * \omega_{motor}}$$

Equation 2 Experimentally Determined Efficiency

Plots of calculated efficiencies versus flywheel torque and the 95% confidence intervals were generated. The data was fit, using a non-linear regression, to the exponential model, Equation 3, calculating constants for "A", "B" and "C". Constant "A" is the maximum efficiency.

$$\eta = A + Be^{C*\left(F_{tension-}F_{slack}\right)*r_{flywheel}}$$

Equation 3 Exponential Model used for Linear Regression

Preliminary Results

Maximum P1.12 efficiency measurements, listed in Table 2, range 90.41 to 98.82%. These were determined by plotting efficiency measurements against flywheel torque and fitting the data with an exponential curve, Figure 3. Figure 4 shows the maximum efficiencies of all twelve gears in the P1.12 transmission. Initial test results are plotted in green; second efficiency test results on gears 1, 2, 3, 5, 6, 7, 8, 11 and 12 are red. Gears 4, 9 and 10 have only been tested once.

Table 2: Maximum Efficiencies Results of P1.12 Gears 1-12 for Tests 1 and 2

GEAR	1	2	3	4	5	6	7	8	9	10	11	12
MAXIMUM EFFICIENCY TEST 1	95.86	93.98	90.85	96.73	93.95	93.5	96.37	96.98	93.18	92.28	94.54	90.41
MAXIMUM EFFICIENCY TEST 2	98.82	94.73	95.69	-	94.51	94.5	94.2	93.5	-	-	92.13	91.35

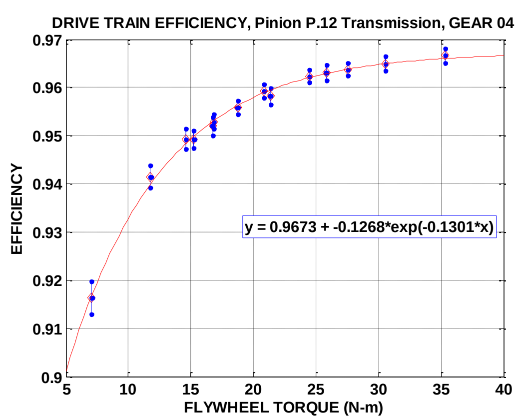

Figure 3: Sample Efficiency vs. Torque with Exponential Fit, Gear 4

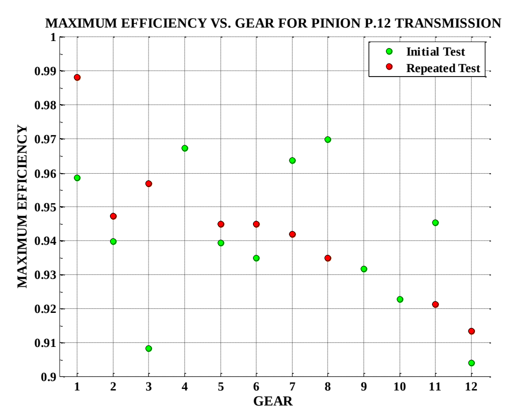

Figure 4 Maximum Efficiency vs. P1.12 Gear

Discussion

In general, the P1.12 transmission has efficiencies comparable to or slightly better than geared hubs but lower than derailleur systems. Measurement repeatability is currently being investigated, and preliminary results indicate there is some cause for concern. Most, but not all, repeated measurements to date show a higher efficiency for the second set of test data. While this could be partially due to wear-in of the gears, some cases have shown quite large differences for which that explanation is unlikely. Further, two cases (gears 7 and 8) showed significant drops in efficiency between the first and second data sets. Twice, during early testing, the apparatus was disassembled for maintenance, and it is also possible that components may have been improperly aligned during reassembly. Additional testing and realignment of the motor will be done in the near future to assess the repeatability questions. An uncertainty analysis is in progress to consider the accuracy of the instrumentation in the experimentally-determined efficiency calculations.

Conclusions

Current results indicate the P1.12 transmission efficiency is comparable to internally geared hubs. Although the relatively poor repeatability of results is a concern to be addressed, the magnitude of the difference between trials is rather small, compared to the range of many hub gears. This provides confidence that efficiencies are comparable to or better than most hub gears.

Recommendations

The repeatability study should be completed for all gears in the P1.12 transmission, and the discrepancy cause identified and corrected, if at all possible. Likewise, the uncertainty analysis should be completed. Then, the next phase of testing the P1.18 transmission efficiency can begin. Procedurally, the efficiency tests are manually operated for nearly two hours per gear, which could be reduced with a fully-automated apparatus.

References

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