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Hybrid analytical-experimental method to map power losses of automotive transmissions over their operating range

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ABSTRACT

This work presents a hybrid analytical-experimental method for determining overall power losses of automotive transmissions. The method consists of measuring load-independent losses and calculating load-dependent losses. Measurements and calculations are done at selected combinations of torque and rotational speed. The results are used for computing the coefficients of a quadratic equation that describes a best-fit surface. The equation is used for predicting the transmission power losses over the operating range defining a transmission efficiency map. The method was verified against power loss measurements of a light-duty six-speed automotive transmission showing a strong correlation between predictions and measurements. The proposed method can be used as an engineering tool to help drive improvements in transmission efficiency and in fuel economy.

1. Introduction

Power transmission efficiency is one of the most relevant themes in the automotive industry today. Engineers work tirelessly on every possible source of power loss to increase the overall transmission efficiency. Therefore, it is crucial for the engineer to be able to reliably determine the power losses in a transmission, identify major contributors, and run trade-off studies to optimize the overall transmission system design for high efficiency. The transmission power losses can be categorized into load-dependent losses (or mechanical losses), such as gear sliding losses and bearing frictional losses, and load-independent losses (or spin losses), such as oil churning losses, seal losses, and bearing drag losses (see Fig. 1). The total power loss in a transmission is the sum of these individual power losses [1]. There are well established analytical models available to predict the load-dependent losses with reasonable accuracy [2–5]. Nevertheless, the situation is quite different for the load-independent losses. The models available to determine the load-independent losses are either too simplified and not sufficiently accurate, or too cumbersome, such as computational fluid dynamics (CFD) models [6–8], which may not be of practical use in the product development process.

Industry standards, such as ISO/TR14179-1 [9], recommend determining transmission efficiency by measuring the power losses on a test stand or by calculating the load-dependent power losses and the load-independent losses. The former is the most accurate method to determine transmission efficiency, but it requires a full-scale transmission and a dedicated test stand such as a dynamometer or a back-to-back stand to run the transmission at operating conditions of selected torque, speed, and temperature. Depending on the number of running conditions, the test may take a considerable amount of time to complete. On the other hand, calculating the power losses using analytical and empirical models is faster and less expensive.

The power losses in transmissions are small compared to the transmitted power. It is not uncommon in modern geared transmissions to find power losses less than one or two percent of the total input power. The task of improving transmission efficiency is a matter of finding ways to shave a fraction of a percentage point off the power loss. Inaccuracies of power loss predictions may mislead one into taking actions contrary to the desired outcome. This becomes even more critical when transmission efficiency data is used for vehicle fuel economy simulations, which may support decisions at vehicle system and sub-system levels. The fuel economy simulations are carried out at different duty cycles, road conditions, and driving styles, thereby requiring transmission efficiency information over a broad range of operating conditions. Similar to combustion engine maps of fuel consumption, which show the amount of fuel rate consumed at different speeds and torque levels, an

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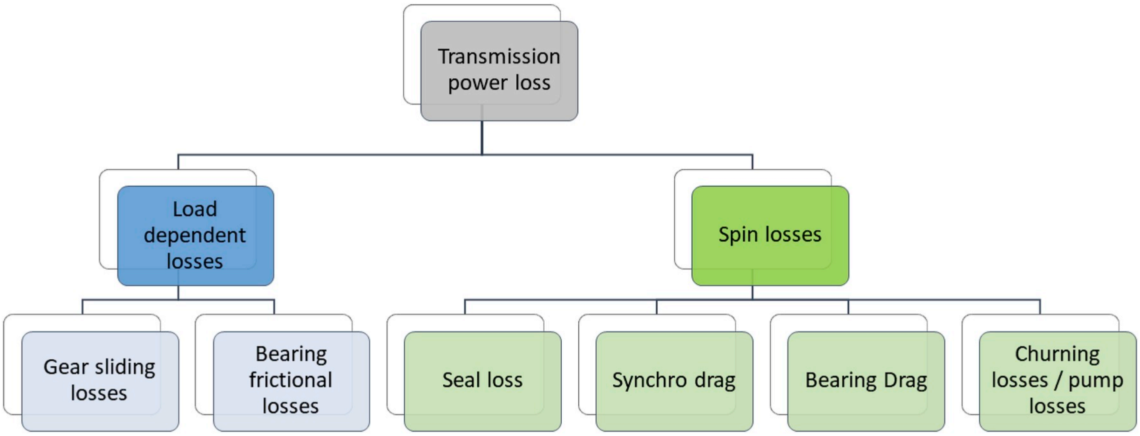

Fig. 1. Breakdown of power losses in a transmission system.

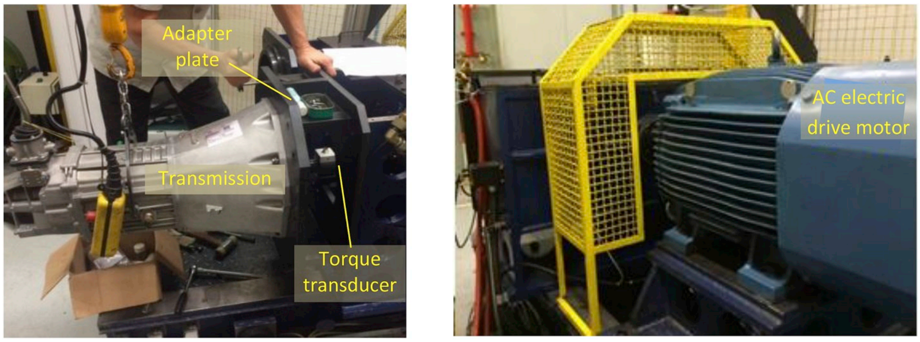

Fig. 2. Variable speed spin test setup.

efficiency characteristic map of the transmission is desired, with which one can determine the overall transmission efficiency, or the total power loss of each gear speed at different rotational speeds and torque levels [1]. This paper presents a hybrid analytical-experimental method for constructing a transmission efficiency map that consists of measuring the load-independent losses at points of interest and calculating the load-dependent losses at certain operating conditions using well-established analytical models. The key results are then combined and used for creating a transmission efficiency map over the transmission operating range. The proposed method is demonstrated step by step through a case study using a selected six-speed transmission. Results obtained with the proposed method are compared to full experimental results. A very strong correlation is shown between predictions and measurements with a correlation coefficient of 0.9916 and a coefficient of determination, R-squared, of 0.9833. An uncertainty analysis was done to estimate the experimental error from the torque meter's accuracy, revealing that all deviations of the predictions from the measured results were within the uncertainty values. The practical application and accuracy of the novel approach of constructing a power loss map that is presented in this paper make it a valuable engineering tool to help increase transmission efficiency and, ultimately, improve fuel economy.

2. Method

The hybrid analytical-experimental method used in this study to determine the overall transmission efficiency (or total power loss, P_V) map consists of three main steps: determination of the load-independent power losses (P_N), determination of the load-dependent power losses (P_L), and data post-processing for defining a mathematical function that fittingly describes the total power losses in a three dimensional space. The load-independent power losses of a representative transmission are measured on a variable-speed spin test rig under no load and at several rotational speeds. The load-dependent power losses of gears and bearings are calculated at selected combinations of torque and rotational speed using well-known analytical models. In the post-processing step, all power losses are added up and a coarse matrix of torque, speed, and total power loss is created. Lastly, the coefficients of a quadratic equation that describes a surface through the matrix points are determined for each transmission speed. The total power loss function can then be used the calculate the power loss or overall transmission efficiency at any relevant operating condition. In the subsequent sections, the steps of the method are explained in detail.

2.1. *Determination of load-independent power losses* (P_N)

Fig. 2 shows the variable-speed spin test setup used for measuring the load-independent losses. The transmission clutch housing was bolted to the test rig adapter plate. The transmission input shaft was connected to an electric motor through a metal-disc coupling of high torsional stiffness and flexible in bending and axial directions. A HBM torque transducer model T22/20Nm was placed on the drive shaft to measure transmission drag torque at different speeds. Rotational speed was measured by an optical sensor, Balluff – BOS15k S-E1, and the transmission speedometer rotor. The torque transducer and the speed sensor were connected to a universal measuring amplifier module, HBM QuantumX MX840A. The signals were recorded using a HBM QuantumX CX22w data recorder. Thermocouples (K type) and a Testo 176T4 data logger were used for monitoring the transmission oil sump temperature. During the test, the torque losses were recorded when the oil sump temperature was within a range of ± 2.5 °C of the test temperature target.