

Experimental study of electric vehicle gearbox efficiency

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Abstract. This paper presents an experimental analysis of the overall efficiency of the gearbox for an electric vehicle with a Dual Motor Drive System (DMDS) propulsion system. The efficiency was measured in the powertrain testbed where the gearbox was placed between two dynamometers. The main aim of the experiment was to get relevant values of an overall efficiency as a function of input speed and torque. All these measured values of the gearbox efficiency are included in graphs and efficiency maps. Tests were run with two different amounts of oil charge. The experiment confirmed the expected high values of the overall mechanical gearbox efficiency. The results can be used further for advanced simulations and other electric vehicle experiments.

1 Introduction

Nowadays, researchers and automobile producers come together in search of a way to increase the efficiency of vehicles by perfecting or changing the technology and concepts incorporating the idea of modern transportation [1]. The whole world has been focused in recent years on vehicles with alternative vehicle propulsion such as electric (EV) and hybrid (HEV) vehicles because of emission restrictions and fuel consumption of vehicles related to global warming and limited energy resources. Research and development are focused on new drive concepts and systems that allow for greater availability of known technologies in terms of affordability and reliability of these drives [2]. The main topics in the field of EV are drive range extension per one charge, performance increase and drive efficiency [3].

The overall efficiency of the EV propulsion system is shown in Fig. 1 and described in formula (1). The overall efficiency η_{EV} includes battery efficiency η_1 , power converter and electric motor efficiency η_2 and gearbox efficiency η_3 [4]. P_1 is input power, P_2 is output power. P_{LOSS1} are losses in battery, P_{LOSS2} are losses in power converter and electric motor, P_{LOSS3} are losses in gearbox. If we want to focus on improving the overall efficiency we need to deal with all of these individual components. This article focuses on the last mentioned component – the gearbox efficiency.

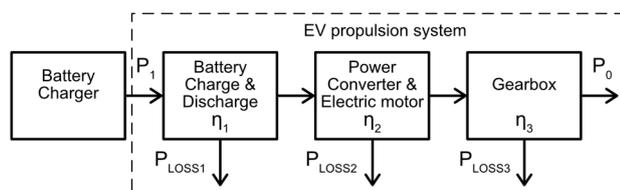


Fig. 1. The individual components of the efficiency of the EV propulsion system [4].

$$\eta_{EV} = \frac{P_0}{P_1} = \frac{P_0}{P_0 + \sum_{i=1}^3 P_{LOSSi}} = \eta_1 \eta_2 \eta_3 \quad (1)$$

Overall gearbox efficiency is determined by individual components loss or equivalently the power losses of the individual components of the powertrain: gearing losses, bearing losses, sealing losses, synchronizing losses, clutch losses, torque converter losses, auxiliary units [5]. Gear power losses are strongly related to lubrication. Load dependent losses are caused by the frictional effects in the lubricant film and load independent losses are from squeezing, churning and windage effects [6]. These hydraulic losses are well analysed in [6].

In scientific publications certain values of gearbox efficiency are often assumed. These values are often based on calculations and simulations and then they are used for other calculations. For example, in book [4] on page 12 are listed values 95-98 %. The authors of paper [7] work with values 86-94 % during the load values 5 Nm. Tehrani in his thesis [8] works with gearbox efficiency values above 98% in some areas of speed and load.

At the Technical University of Liberec current development is focused on a Dual Motor Drive System (DMDS) electric propulsion system shown in Fig. 2. DMDS consists of two electric motors and one single-speed gearbox with a mechanical differential. Current research shows that this system can provide high drive efficiency under all loads, without limiting the driving dynamics [9]. All components of the propulsion system we test in our lightweight battery electric vehicle for educational purposes, which has a completely open frame from aluminium profiles. This solution gives an excellent access to all parts of the vehicle and allows easy modification [10].

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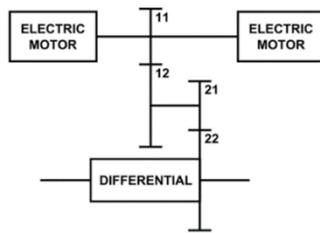


Fig. 2. Dual Motor Drive System components arrangement.

For our next steps in the research, we need to consider the exact values of each component of the overall efficiency. The main aim of our experiment was to measure the efficiency of an EV gearbox in our powertrain testbed.

2 Methods and Materials

2.1 Prototype DMDS gearbox

The subject of measurement was our prototype DMDS gearbox (shown in Fig. 3) which we designed and made for the purposes of our DMDS research. This prototype gearbox allows for the connection of any two electric motors with a standardized flange NEMA C-face with the limitations of overall maximum input torque at 200 Nm and maximum input speed of 7000 rpm. The overall ratio is 5,857.



Fig. 3. Prototype DMDS gearbox used for the experiment.

Each of the motors is placed on one side of the gearbox and the torque of both motors is brought to the first shaft of the gearbox. First gear set and the final drive with differential are all used from the third gear of Skoda MQ200 02T gearbox. All bearings are also used from this gearbox. Internal components are placed in our designed gearbox housing. The material of the housing is aluminium alloy EN AW 7021 [AlZn5,5Mg1,5].

The main aim of the experiment was to get relevant values of the overall efficiency as a function of input speed and torque for our gearbox. We plan to continue to use these values for subsequent simulations and other experiments.

2.2 Powertrain testbed

We decided to use a special testing mode of our powertrain testbed (shown in Fig. 4) for this gearbox efficiency experiment. This testbed is mainly designed for

complete powertrain testing. It means the assembly of the engine-clutch-gearbox-drive shafts.



Fig. 4. Powertrain testbed room.

The testbed consists of four asynchronous dynamometers. One pair of dynamometers is composed of Siemens 136 ADG 288WP (each one 120 kW / 2600 min⁻¹ / 440 Nm; max. speed 3000 min⁻¹). The second pair is composed of Siemens 111 ADG 286WP (each one 80 kW / 2600 min⁻¹ / 294 Nm; max. speed 3000 min⁻¹). This solution provides testing of 2wheel drive and also 4wheel drive and hybrid powertrain where one axis can be power driven by the combustion engine and the second one by the electric motor shown in Fig. 5. Manual shifting is provided by a shifting robot, which can control the shift lever of manual gearboxes. The testing room is further equipped with the advanced control system, air condition, and extraction of exhaust gases. As fuels, it is possible to use petrol, diesel, LPG, CNG, and hydrogen. We use this testbed mainly for gearbox testing, efficiency measuring and for long-term tests of complete powertrains. During these tests, we normally use combustion engines as propulsion of the testing assembly and the braking torque is generated by a different number of dynamometers as required.

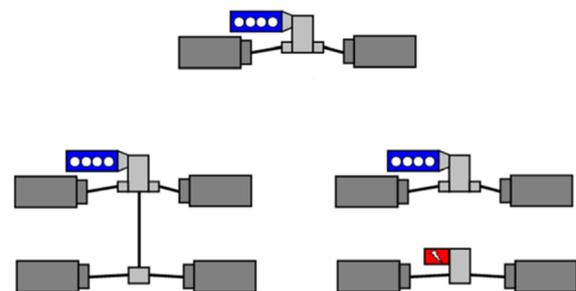


Fig. 5. Powertrain testbed layout possibilities.

2.3 Experimental setup

The special mode mentioned in the previous subsection makes it possible to use one dynamometer as a motor and the second one on the other side as a dynamometer as shown in Fig. 6. Each dynamometer is equipped with very precise measurement of speed and torque. Specifically, the torque is measured by torque flange HBP T40B with accuracy class 0,05. The torque flange is combined with the integrated speed measuring system.

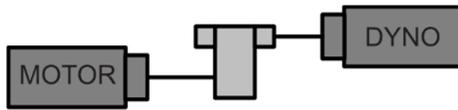


Fig. 6. Powertrain testbed layout for the gearbox efficiency measurement.

The gearbox was placed between two dynamometers on the experimental frame from aluminium profiles at the powertrain testbed shown in Fig. 7. Mounting points were retained as they are used in the vehicle. The gearbox input shaft was connected to the dynamometer which was used in a motor mode. The output shaft was connected to the opposite dynamometer. To evaluate gearbox efficiency we measured and logged values of input speed and torque and the same variables for the output. During testing, we controlled input speed and output torque by the testbed control system.



Fig. 7. Experimental setup of the gearbox efficiency measurement.

For the purpose of this experiment, we had to lock the differential, because we could use only one output shaft of the gearbox. Locking was made by using a special element which was put instead of the differential gear (shown in Fig. 8).



Fig. 8. A special element used to lock the differential

The oil temperature was measured by thermocouple OMEGA Engineering TJC200-CAIN-M025U-150 placed at the inner bottom of the gearbox housing.

2.4 Experiment details

As we mentioned in the previous subsection we controlled the values of input speed and output torque. The measurements were performed at the points with the required values shown in Table 1. It was measured for each speed at all loads.

Table 1. Required values for the experiment.

Controlled		Calculated
Input speed	Output torque	Input torque
rpm	Nm	Nm
500	117,1	20,0
1000	234,3	40,0
1500	351,4	60,0
2000	468,6	80,0
2500	500	85,4
3000	-	-

Note: We couldn't measure in the full range of gearbox input torque (max. 200 Nm) because we used only one input point of the gearbox which is designed for max. input torque 100 Nm. The control system of the powertrain testbed allowed us to use max. output torque 500 Nm. That is the reason why the last required value of output torque is 500 Nm and not 585,7 Nm, which would correspond to the max. usable input torque 100 Nm for only one input point.

The amount of oil charge was determined on the basis of a 3D model during the development process of the experimental gearbox. We decided to run two complete efficiency measurements with two different amounts of oil charge to determine the effect of the oil charge on the efficiency. For the first experiment, we filled the gearbox with 500 g of oil. With this amount of oil charge the oil level reached the bottom part of the final drive gear. For the second experiment, we used 820 g of oil. In this case the oil level reached the bottom of the gear on the input shaft. The type of used gear oil was Mogul Syntrans 75W-90 with the specification API GL-4+ for both measurements. This type of oil is normally used in conventional Skoda MQ200 vehicle gearbox. We used this type of oil mainly because almost all internal components come from this gearbox as we described in subsection 2.1.

Each measured point was measured for 30 s with the recording frequency of 100 Hz. During the experiment, we logged the following values of input speed ω_{in} and torque M_{in} , output speed ω_{out} and torque M_{out} and oil temperature. From the logged values were calculated the mean values for each measured point by Matlab. Then we calculated the input power P_{in} and output power P_{out} on the basis of the obtained mean values and calculated the overall gearbox efficiency $\eta_{gearbox}$ according to the equation (2).

$$\eta_{gearbox} = \frac{P_{out}}{P_{in}} = \frac{\omega_{out} M_{out}}{\omega_{in} M_{in}} \quad (2)$$

3 Results

The calculated overall gearbox efficiency from the measurement with 500 g oil charge is shown in Fig. 9 and with 820 g oil charge in Fig. 10. Each symbol corresponds to a different input speed of the gearbox. For each input speed can be found a point close to the input torque values 20 Nm, 40 Nm, 60 Nm, 80 Nm and 85,4 Nm.

The resulting values of the overall gearbox efficiency for 820 g oil charge in Fig. 10 are lower at every point than the other results for 500 g oil charge.

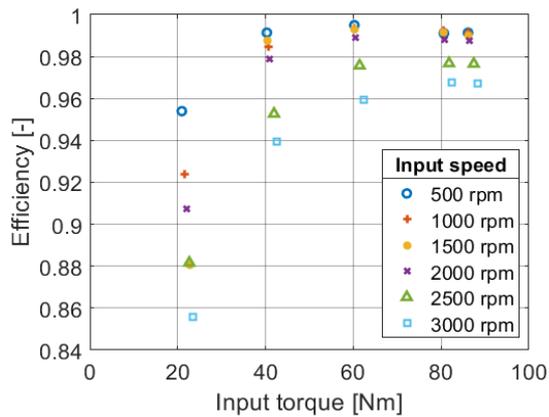


Fig. 9. Results of the overall gearbox efficiency for 500 g oil charge.

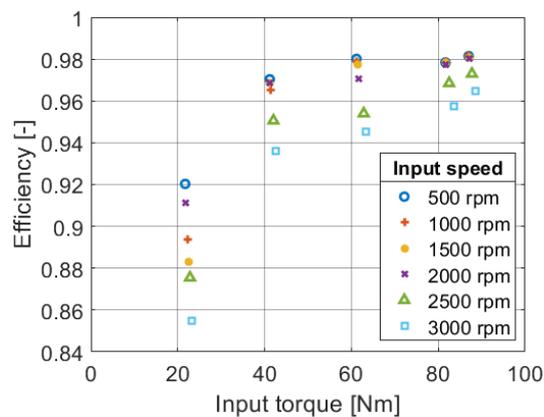


Fig. 10. Results of the overall gearbox efficiency for 820 g oil charge.

We used the obtained resulting values from both previous graphs to build efficiency maps in Matlab shown in Fig. 11 and Fig. 12. Mesh grids for both maps were created by the linearization with 30 evenly spaced points between the minimal values and maximal values of the input speeds and input torques.

The oil temperature values measured at the inner bottom of the gearbox housing were during the measurement with 820 g oil charge in the range 40,3-51,2 °C with average value of 44,5 °C and with 500 g oil charge in the range 38,1-51,2 °C with average value of 44,0 °C.

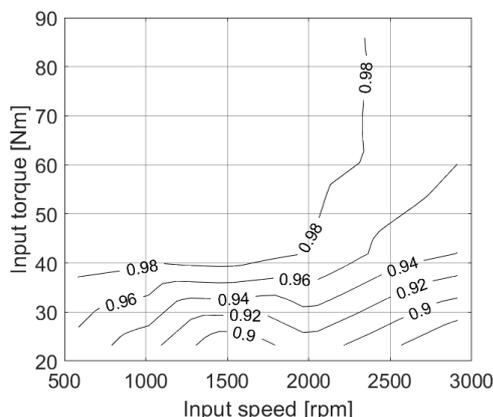


Fig. 11. Overall gearbox efficiency map for 500 g oil charge.

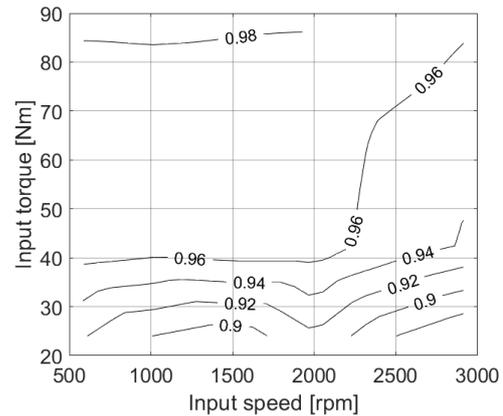


Fig. 12. Overall gearbox efficiency map for 820 g oil charge.

4 Discussion

The results of the experiment provided detailed data on the efficiency of our prototype DMDS gearbox depending on the input speed and the input torque in the range of input speed of 500-3000 rpm and in the range of input torque of 20-85,4 Nm.

In the introduction section of the paper, we mentioned some efficiency values stated in books and other scientific articles. There we can find values of gearbox efficiency around 86% to more than 98%. A lot of them are based on calculations and simulations. The resulting values of our experiment with our prototype DMDS gearbox are almost in the same range. Values for 500 g oil charge at input speeds of 500 rpm, 1000 rpm and 1500 rpm in some areas of input torque of 40 Nm, 60 Nm, 80 Nm, 86 Nm are even higher than 99%. On the other hand, in the areas of the whole measured input speeds of 500-3000 rpm and at a low load of around 20 Nm, the values are significantly lower – in the range of 85,6-95,4%.

A lot of the inside components of the gearbox come from Skoda MQ200 02T gearbox commonly used in today's vehicles. The results of our experiment may also indicate efficiency values in some conventional vehicle transmissions.

The experiment was performed with two different amounts of oil charge. The results show that the amount of charge in the measured gearbox has a relatively significant effect on its overall efficiency. The resulting values are on average by 1,2% lower with the oil filling 820 g than with 500 g. The maximum difference is 3,4% at the point 500 rpm of input speed and 21 Nm of input torque. We plan to investigate more precisely the choice of oil type and its right amount in the next steps to improve the efficiency of our prototype DMDS gearbox.

In our opinion, the results from our experimental analysis of the overall efficiency of our prototype DMDS gearbox in the powertrain testbed confirmed the quality design and the technological process of its production. The resulting overall gearbox efficiency maps can be used for detailed advanced simulations of new EV propulsion systems because they are built from efficiency values measured in specific values of input speed and input torque.

For further work on analyzing the efficiency of this gearbox it would be appropriate to analyze the efficiency in the rest of input torque range 100 Nm to 200 Nm and in the rest of input speed range 3000 rpm to 7000 rpm. For such measurement it would be necessary to use another special testbed with required parameters. Using the resulting efficiency values it certainly would be interesting to measure the efficiency in the smaller intervals of input speed and input torque in the areas of lower input torque than 40 Nm. This would allow us to build more accurate efficiency maps in these areas where there are significant changes in efficiency values. Also it would be appropriate to select such controlled output torque values so that the input torque values would be closer to decimal values. Further work could also be done on efficiency analysis at higher oil temperature values.

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