Efficiency measurement campaign on gearboxes

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Abstract

The last decade, new concepts of electrical motors with promising efficiency have entered the market. Such an electric motor is connected to the load machine often by means of a transmission system. Considering the energy efficiency of transmission systems, there is a lack of available information on the market. In contrast to electrical motors and drives, there are very few mandatory regulations imposed on these components. Information on efficiency can be occasionally found in catalogs but accepted test procedures are not available. As a result, the reliability of these efficiency values is low and comparison between brands and technologies is impossible.

Regulation on energy efficiency on the other hand evolves towards a total system approach. The new European fan directive 327/2011 is an example of such an approach where overall efficiency is considered. Information on the efficiency of mechanical transmission components such as gearboxes and belt drives will be required to assess and optimize the overall system efficiency.

Due to the lack of reliable information on energy efficiency of these components, a measurement campaign was set up to test a series of gearboxes. This paper discusses the results of this measurement campaign. Because of the wide variation in types and sizing, the measurements where done on a flexible designed input-output gearbox test bench [1].

Available information on gearbox efficiency

Standards concerning measurement methods and energy efficiency of electrical motors have a long history. In previous research projects at the Ghent University the knowledge of speed regulated motor efficiency was expanded by measurements in the entire working range and made visible by means of iso efficiency maps [2,3]. Nowadays, some innovating manufacturers already make this efficiency information available for some motor types in the form of efficiency maps [4].

In contrast to this, the availability of efficiency information on commercial gearboxes is extremely limited. Information on the mechanical and/or hydraulic losses of a single gear wheel pair is available [5-8], but a complete gearbox consists of several gear pairs and other parts. This means the total losses are a combination of different losses such as bearing losses, seal losses, churning and windage losses as illustrated in figure 1.

Few research projects and therefore few publications pay attention to the total gearbox efficiency. Moreover, the gearbox manufacturers manuals provide few efficiency information. In most catalogs efficiency is generally stated as depended on the number of gear stages. In this way one efficiency value is given for a whole range of gearboxes. For example, gearbox catalogs [9-12] states that a helical and parallel shaft and a helical-bevel gearbox have an efficiency of 97% when they have a 2-stage setup. There is no information on the effect of the ratio, the rated power or the speed and load of the gearbox on the efficiency. Only worm gear units form an exception as their nominal efficiency is given as a function of the power and ratio. However, even for these gearboxes, the effect of the torque and speed on the gearbox efficiency is not mentioned.

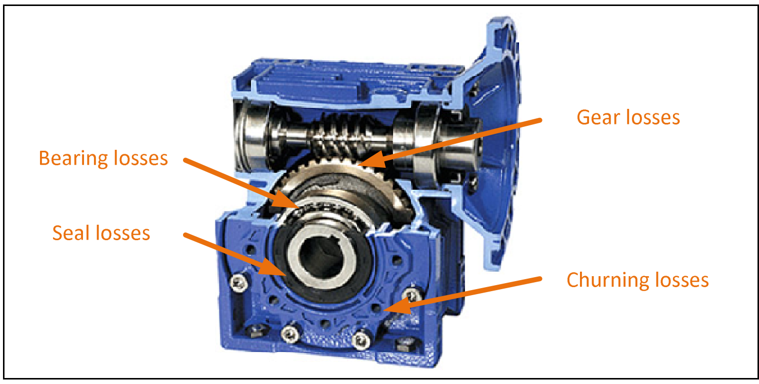

Figure 1: Typical gearbox losses

Another issue about the catalog efficiency is that no efficiency measurement procedure information is given. Some catalogs mention that the nominal efficiency is reached when the gearbox reaches its nominal operating temperature, but a value for this temperature, which is highly dependent on the surrounding ambient temperature, is not given. Various contacts with different manufactures show that the efficiency information is obtained in different ways. Some use measurements while others use mathematical models to determine efficiency values.

The lack of efficiency and measurement information on gearboxes can be partially explained due to the absence of any efficiency standard or measurement standard. In contrast to numerous standards on electrical motor drives no applicable standards can be found for gearboxes.

To optimize the total drive train efficiency, the efficiency values or losses for each part of the drive train need to be known. Because manufacturers use different methods to determine the gearbox efficiency a designer cannot objectively compare different brands. To learn more about the gearbox efficiency in different load points and for different gearbox types a flexible gearbox test bench was designed [1].

Gearbox test bench and measurement flowchart

The purpose of the test bench is to measure gearbox efficiency at different loads and speeds within the allowed working area of the gearbox. A lot of industrial gearboxes are used for conveyors and other applications in the lower power range and they come in various types. With the gearbox test bench it is possible to test a large scope of these types in a power range up to 15kW and a load torque up to 1000Nm.

The direct back to back method is used to determine the overall efficiency. This method requires accurate measurement of the mechanical in- and output power. The torque is measured by means of dedicated 'dual range' torque sensors with an accuracy of 0.1% full scale. The speed is measured using incremental encoders. The measurement principle is shown in figure 2.

The aim is to conduct steady state efficiency measurements, i.e. measurements at constant speed and constant load torque. The gearbox under test is driven by means of a speed controlled motor. The loading of the gearbox is realized by means of a reducer gearbox driven by an induction machine which is torque controlled with a regenerative VSD. The flexible design of the test bench allows different shaft heights and dimensions of the test gearbox. The drive side can rotate 90 degrees to test straight and right-angled gearboxes. The testing room is temperature controlled to stabilize the temperature dependent losses. With the gearbox test bench it is possible to drive gearboxes up to 15kW and 3000rpm at input and load the gearbox up to 15kW and 1000Nm at output.

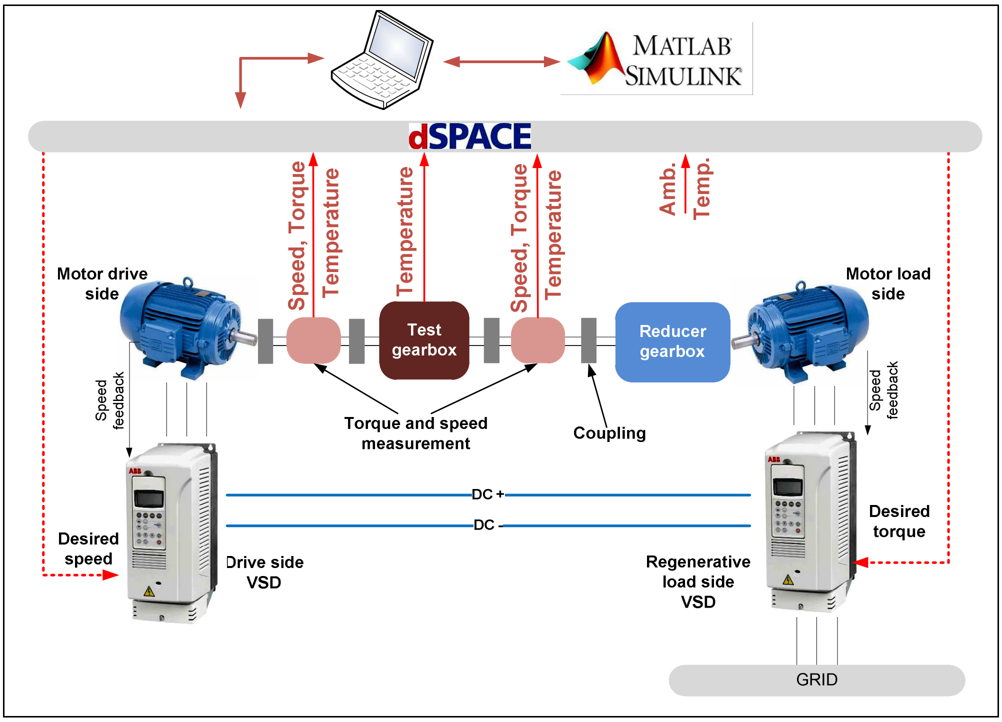

Figure 2: measurement principle gearbox test bench

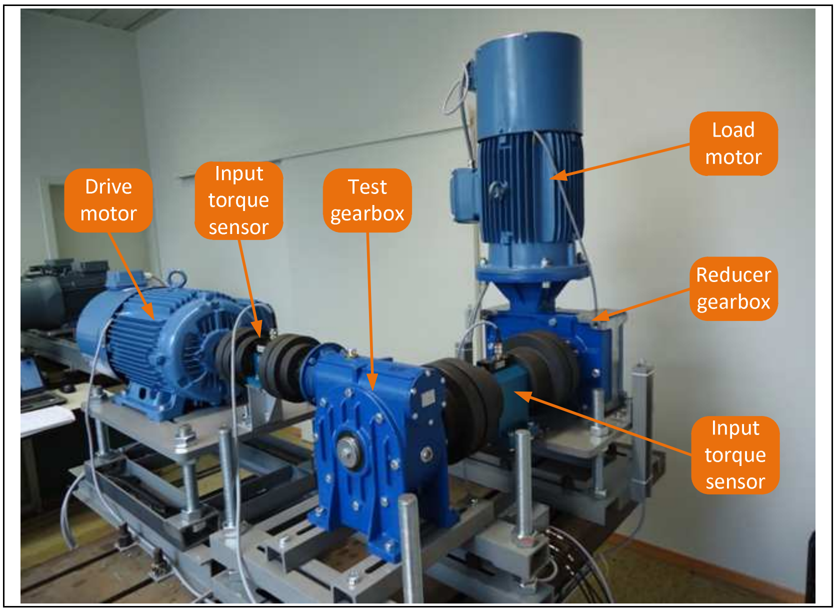

Figure 3: Mechanical design gearbox test bench

As stated before an efficiency measurement standard does not exist for gearboxes. In order to guarantee reproducibility and obtain accurate measurements, a measurement protocol has been setup. After mechanical installation and alignments, the gearbox is tested in three steps as shown in figure 4.

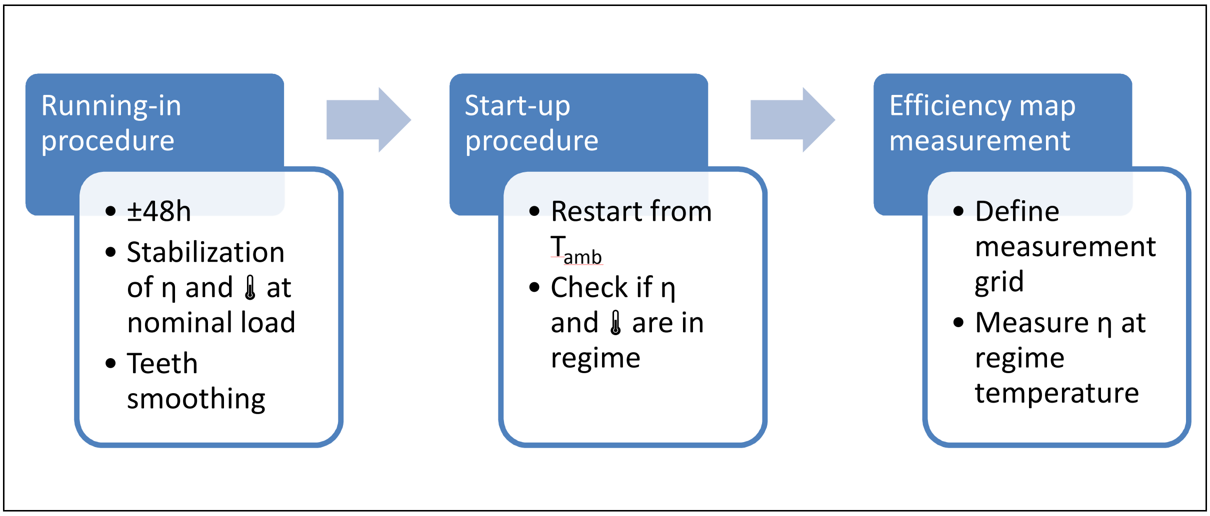

Figure 4: measurement protocol flowchart gearbox test bench

During the initial step the new gearbox is driven and loaded at nominal conditions until it reaches stabilized efficiency and temperature values. By this test, the gear teeth get smoothed. Most gearbox catalogs indicate that a gearbox reaches its nominal efficiency after 24 to 48 hours. Thereafter, the gearbox is stopped and cooled down until ambient temperature before being driven and loaded again at nominal load. If the same stabilized efficiency value is reached during this second test this means the gearbox has run in completely. This step insures the repeatability of the measurements in further steps. In the last step the efficiency is measured in the total working area by means of a predefined measuring grid. The test room temperature is controlled and monitored and during all steps, the device temperature is also monitored because of the high impact of temperature on the losses.

Measurement campaign

Overview

During the research project, 13 gearboxes have been measured resulting in many possible comparisons. The basic properties of each gearbox are summarized in table 1. In this paper the most important results will be discussed.

Table 1: overview gearbox measurements at rated power

	Brand B (I)	Brand A (II)	Brand C (III)	Brand C (IV)	Brand C (V)	Brand D (VI)	Brand D (VII)	Brand E (VIII)	Brand E (IX)	Brand E (X)	Brand F (XI)	Brand F (XII)	Brand F (XIII)
Type	Right angled	Right angled	Right angled	Right angled	Right angled	Right angled	Right angled	Right angled	Right angled	Straight	Right angled	Right angled	Right angled
Techno-logy	Helical bevel	Worm	Helical bevel	Helical worm	Helical spirod	Helical bevel	Helical worm	Helical bevel	Helical worm	helical	Helical worm	Helical worm	Helical worm
Stages	2	1	3	2	2	3	2	3	2	2	2	2	2
Ratio	77.76	80	72,54	71,75	74,98	72,21	77	11,41	11,67	10,93	87,65	68,44	30,26
Torque (Nm)	505	450	186	167	180	190	180	434	373	390	285	270	260
Power (kW)	0,95	0,82	0,37	0,35	0,36	0,39	0,34	5,58	4,7	5,23	0,69	0,82	1,51
Catalog η	95%	62%	96%	62%	±90%	95%	78%	94%	90%	96%	69%	71%	83%
Measured η	84,5%	73%	88%	56,5%	65,5%	87,5%	70,5%	95,5%	91,5%	95,5%	59%	62%	68%

Catalog versus measured efficiency

In figure 5 the catalog efficiency, measured efficiency at rated power and the difference between them are displayed for all the tested gearboxes listed in table1. The depicted efficiency values are measured at nominal speed and torque.

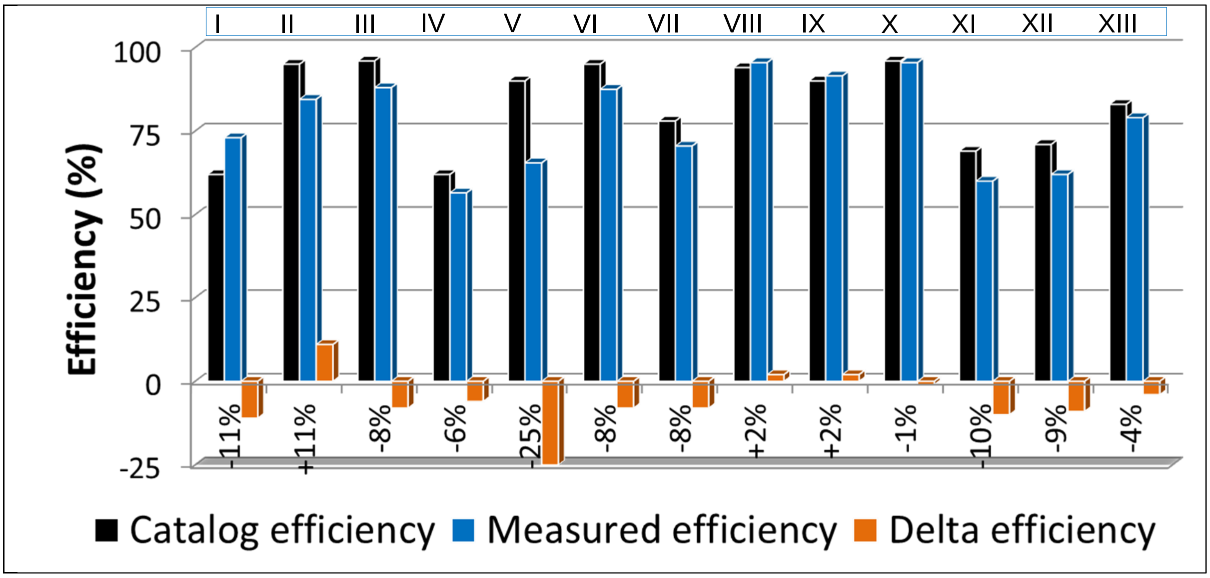

Figure 5: comparison of catalog efficiency versus measured efficiency at rated power for 13 tested gearboxes (points efficiency).

The comparison shows a significant difference between the efficiency mentioned in the catalogue and the measured efficiency for almost all the gearboxes. In most cases the catalogue efficiency is higher than the measured efficiency. It is difficult to determine straightforward conclusions because of the large variety in gearbox parameters. Gearboxes VIII, IX and X show the smallest efficiency difference. These gearboxes have a low ratio and high power compared to the other gearboxes in the measurement set. For higher ratios, such as gearboxes III to VII, the efficiency difference is about 8%. In this comparison the type of gearbox (straight or right-angled) or technology does not seem to have an influence on the difference between catalog and measured efficiency.

The difference between catalog and measured efficiency can be explained by some factors. Since there are no measurement standards, the measurement conditions of different manufactures can vary, which leads to differences. Some manufactures use models to estimate the efficiency, others use measurements and calculations. This means comparing gearboxes from different brands is difficult. To confirm our statements and to learn more about these differences some manufacturers were contacted during the project. In figure 6 the difference between stated catalogue and model based calculated efficiency is shown for a 200Nm and 800Nm gearbox range based on internal manufacturer information.

With increasing ratio the efficiency difference between catalog and model based efficiency enlarges for both gearbox power ranges. When the torque, which is proportional with the power, increases the efficiency difference drops. When the ratio is low, the catalog and model based efficiency match well. These conclusions also match the test bench results during the measurement campaign in the research project (table 1).

It is remarkable that the efficiency data in catalogs (green line) is not equal to the more correct model based efficiency although it is known by the manufacturer. Because there are no standards the manufactures are not obliged to state how the efficiency is measured or obtained so they can choose themselves. From a commercial point of view, manufacturers are reluctant to indicate lower efficiency values.

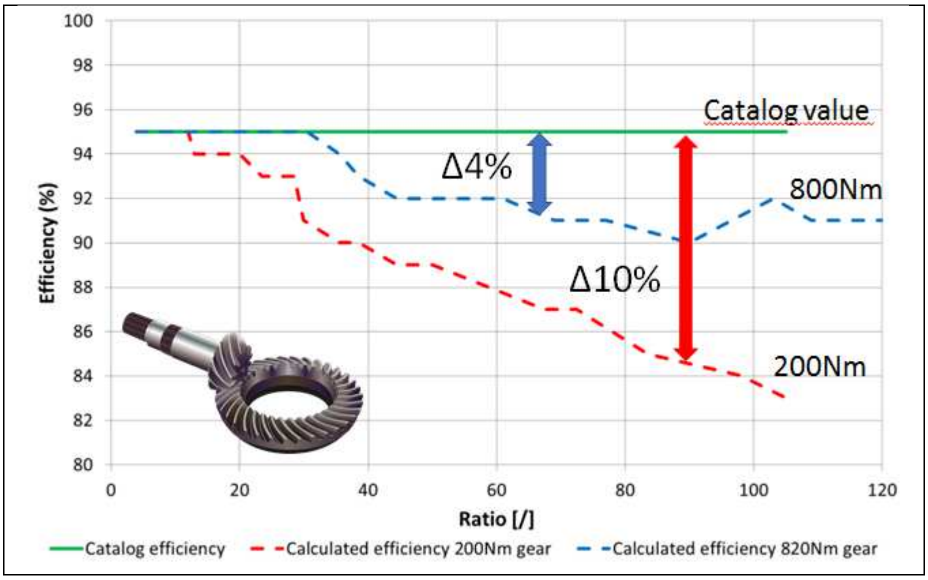

Figure 6: comparison between stated catalog efficiency versus model based calculated efficiency helical bevel gear

Efficiency of gear boxes in part load conditions

In gearbox catalogs, the efficiency value is only stated at nominal conditions. Figure 7, which is an efficiency map of a tested helical bevel gearbox, clearly shows that the efficiency is not equal in the entire working area. Particularly the load torque has an impact on the gearbox efficiency. The highest efficiency is measured at the nominal load torque. When the load decreases the efficiency decreases too. Speed variations have a rather small impact on the gearbox efficiency.

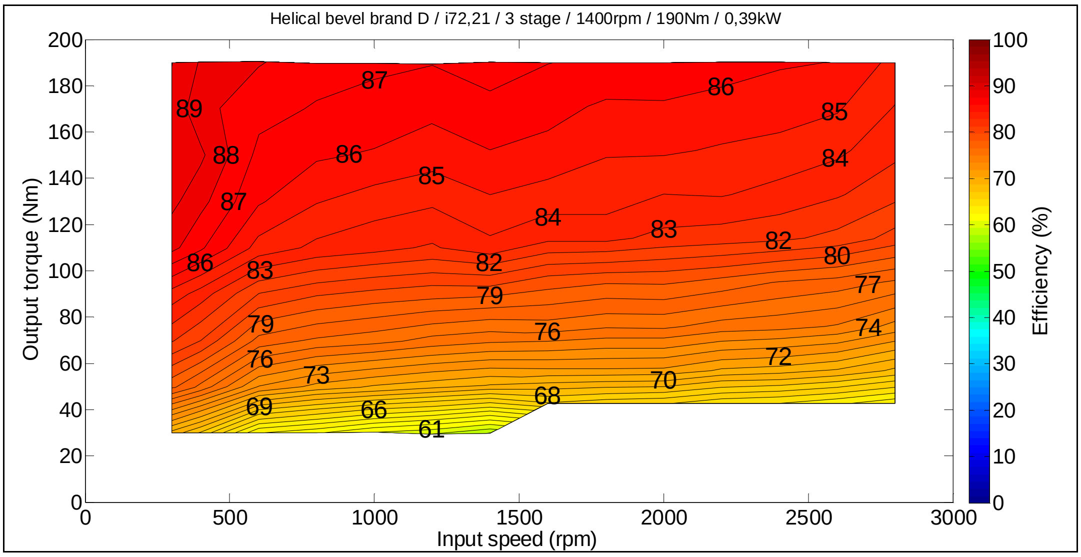

Figure 7: efficiency map of a helical bevel gearbox

Identical conclusions as for this helical bevel gearbox can be found for all gearboxes. All the tested gearboxes show a similar shape of efficiency map. For gearboxes with a high ratio the efficiency decrease is sharper compared to that for gearboxes with lower ratio. This is shown in figure 8 for a helical bevel gearbox with ratio 72. The efficiency drops 8% at 50% of the nominal torque. The efficiency from the gearbox with ratio 11 only drops 1,5% at 50% of its nominal torque. Again, the mainly independent effect of speed variations on the efficiency can be found in these figures.

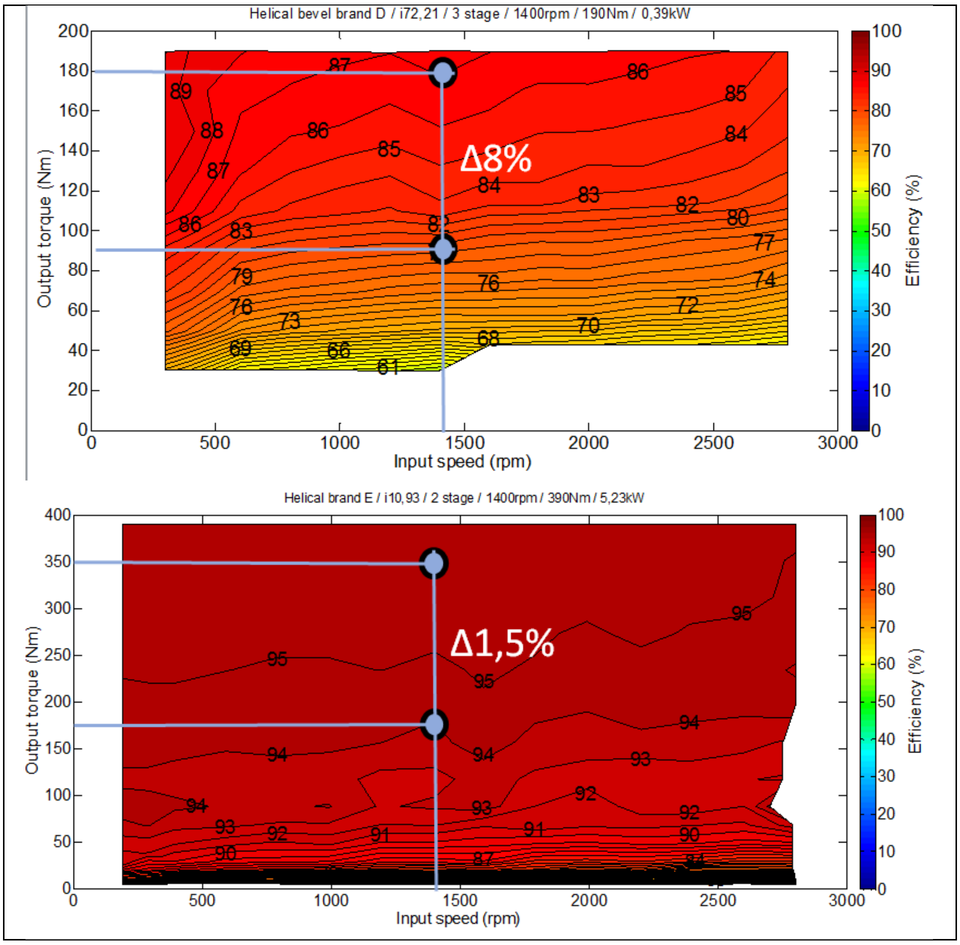

Figure 8: load dependent efficiency variation for different gearbox ratios

Power dependency of gear box efficiency

As with induction motors the efficiency of a gearbox is power dependent. This is confirmed by the measurement campaign. Also in figure 6 it is clear that the 800Nm gearbox power range always has a higher efficiency than the 200Nm range. Although the needed power or torque range is linked and determined by the application, it can be important to keep this in mind when designing a drivetrain.

Ratio dependency of gear box efficiency

The ratio of a gearbox has an important impact on the gearbox efficiency. In most worm gearbox catalogs this efficiency variation due to the gear ratio is already stated and the efficiency is given for each different ratio. A decreasing efficiency while ratio increases can be found. These catalog values only apply for nominal speed and load. However figure 9 shows a measured delta or difference efficiency map of two worm gear units with same power but different ratio. The map shows a rather constant efficiency difference in the entire working area.

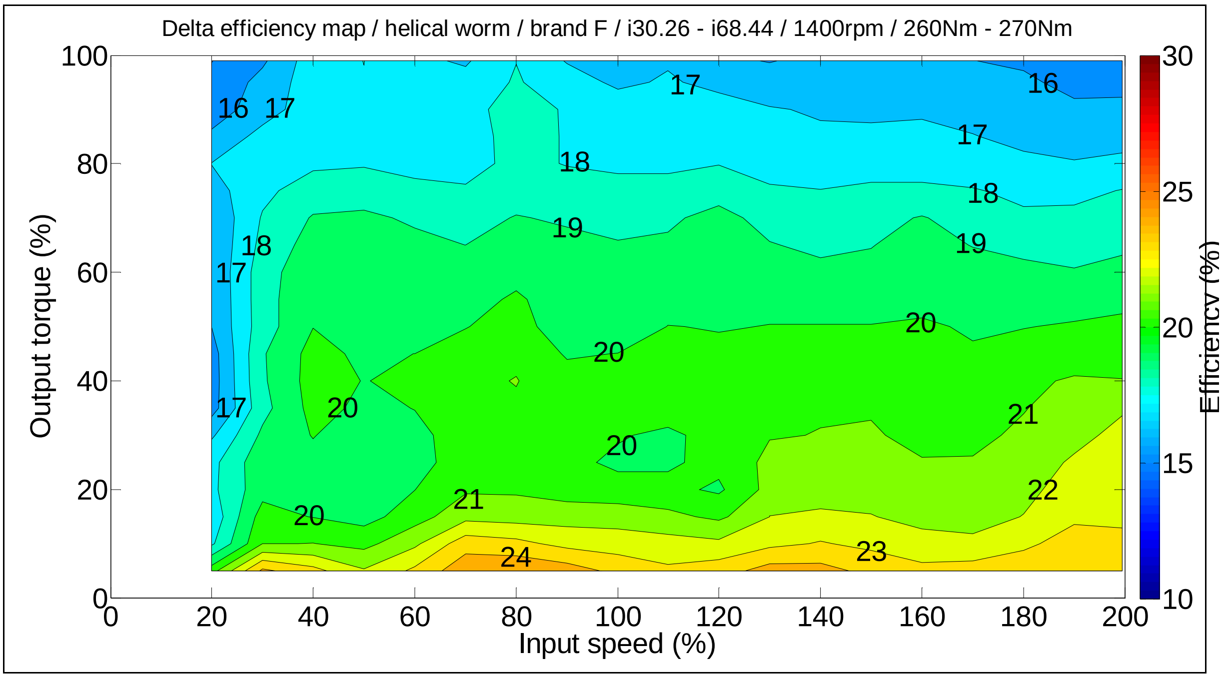

Figure 9: delta efficiency map of two helical worm units with ratio 30 and 68

In the case of helical and helical bevel transmissions the ratio dependency is not clarified in commercial catalogs. These catalogs only describe the effect of the number of gear stages on the nominal efficiency. This effect is also clearly represented in figure 6. When the ratio gets higher, the efficiency drops. This effect enlarges when the power or torque range decreases.

Type dependency (straight vs. right angled) of gear box efficiency

In many industrial cases the space requirements or space limits are an important design factor. Therefore it can be interesting to know whether or not this choice influences the efficiency of the drive line. For example three measured gearboxes during the campaign, two right-angled and one straight, with comparable specifications are considered. The properties are summarized in table 2.

Table 2: straight vs. right angled gearboxes

	Brand E	Brand E	Brand E
Type	Right angled	Right angled	Straight
Technology	Helical bevel	Helical worm	helical
Stages	3	2	2
Ratio	11,41	11,67	10,93
Torque (Nm)	434	373	390
Power (kW)	5,58	4,7	5,23
Measured efficiency (%)	95,5	91,5	95,5
Price (%)	147	98	54

The nominal efficiency of gearbox number 1 (right-angled) and 3 (straight) is comparable. However, the efficiency of number 2 (right-angled) versus number 1 and 3 (straight-angled) drops about 4% at nominal conditions. This difference is mainly technology dependent (helical bevel vs. helical worm). On the other hand, a much larger difference can be noticed at the gearbox price. The straight gearbox only costs half of the price of the helical worm gearbox and merely one third of the price of the right-angled helical bevel gearbox. If the installation space allows for a straight gearbox, this could reduce the costs of a drive train solution while maintaining or even raising the overall efficiency of the drive train.

Technology dependency

It is commonly known that a traditional worm gear unit has a lower efficiency compared to a bevel gear unit. In a lot of low power drive systems where the operating hours are rather low this worm gear proves its usefulness. Also where self-locking is required worm gears show their advantage. Moreover, this paper shows that the bevel gears do not always reach the stated catalog efficiency. One could wonder if the efficiency difference compared to a worm gear is still worth mentioning. Additionally manufactures use new design solutions to optimize the worm gear efficiency. For instance, to enhance the overall gearbox efficiency, an extra gear stage with helical gears is introduced in the worm gear in order to reduce the ratio of the worm-worm wheel itself.

A second consideration can be found in figure 7. Here it was concluded that the efficiency of helical gear units drops with decreasing load. A comparison with a helical worm gearbox can reveal if the efficiency difference between a helical worm and helical bevel gearbox is constant in the entire working area. The specifications of the two gearboxes are listed in table 3. In figure 10 the delta efficiency map is created by subtracting the worm gear efficiency map from the bevel gear efficiency map.

Table 3: specifications of a helical bevel and a helical worm gearbox

	Brand D	Brand D
Type	Right angled	Right angled
Technology	Helical bevel	Helical worm
Stages	3	2
Ratio	72,21	77
Torque (Nm)	190	180
Power (kW)	0,39	0,34
Catalog efficiency	95%	78%

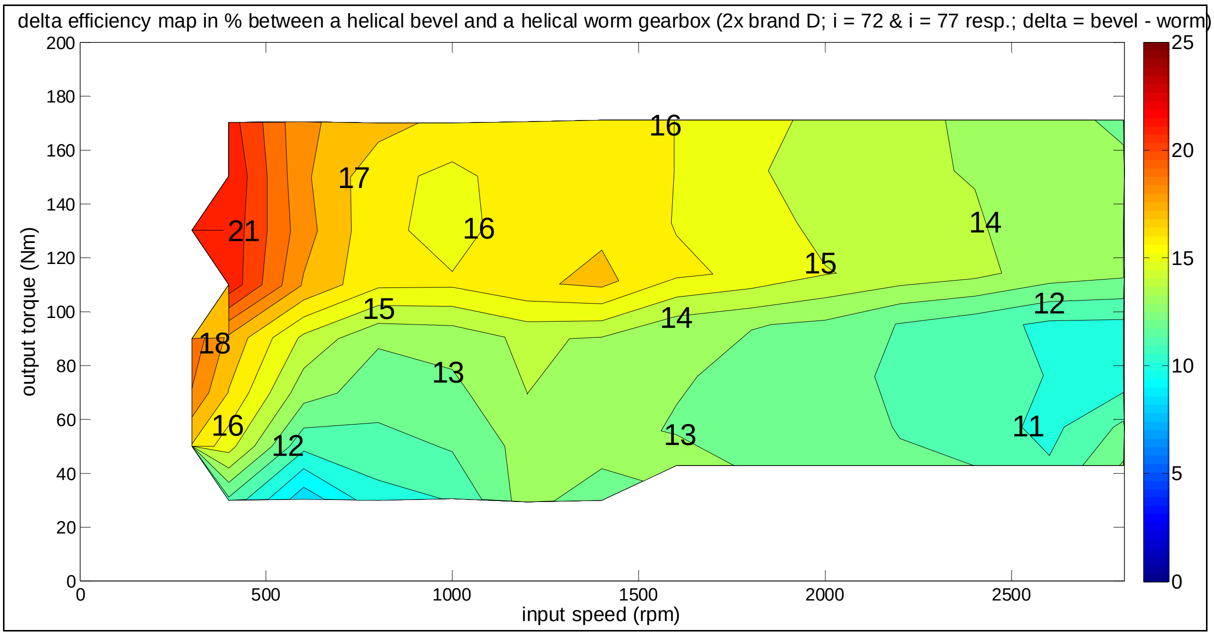

Figure 10: delta efficiency map in points efficiency of a helical bevel and a helical worm gearbox

The delta contour map shows that the efficiency of the helical bevel gear unit is higher in the entire working area. At nominal speed and load the difference is about 16%. This efficiency difference gets higher with increasing ratio.

On this topic, the common knowledge is still correct. Worm gearboxes have a lower efficiency than similar gearboxes. Although gearbox manufacturers optimize the right-angled worm gearbox efficiency the difference with a helical bevel gearbox is still considerably high.

Conclusions

This paper discusses a gearbox measurement campaign on industrial gearboxes. The current available information on gearbox efficiency is highlighted and the gearbox test bench and measurement flow chart are briefly explained. Thirteen commercial gearboxes were extensively tested. The results and the impact gearbox parameters on the efficiency are discussed.

The literature study reveals that availability of research results on gearbox efficiency is very limited. Moreover, the efficiency information in catalogs is limited. Typically only one efficiency value is stated for a large range of different gearboxes with varying ratio, power and technology. The literature study also made clear no standards exist on gearbox efficiency. This makes is hard to compare the efficiency of gearboxes of different brands.

The measurements reveal a significant difference between measured efficiencies and catalog values at nominal conditions. The difference between the catalog and measured efficiency is discussed and confirmed with information of a manufacturer. Manufacturers now determine the efficiency in different ways, with different ambient temperatures, based on theoretical calculations, etc. As a result, the catalogue values cannot be compared.

The efficiency in the entire working area is presented by means of efficiency contour maps. It is shown that the efficiency is mainly torque dependent. When the gearbox power range increases or the ratio decreases, this efficiency variation is smaller. Currently such information is not available for gearbox customers causing them to make a selection for a particular machine which is not optimal in terms of energy efficiency. In general the efficiency is higher for gearboxes with a higher power range. This is similar to electrical motors. When the ratio of a gearbox decreases the efficiency is higher. This was already stated in most worm gear catalogs but also helical and helical bevel gearboxes follow this trend. The latter is not yet stated in commercial catalogs. This indicates a clear lack of knowledge with respect to the use of the Extended Product Approach suggested in EN 50598.

Straight and right-angled bevel gears have similar efficiency but the price difference is high. Comparing a bevel and worm gear shows a higher efficiency for the bevel gear in the entire working range.

In this paper other external parameters, such as temperature, kind of lubricant and the oil level, were not discussed but surely also have an impact on the gearbox efficiency. Further research on the gearbox efficiency can certainly be interesting.

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