

An efficiency measurement campaign on belt drives

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Abstract

In this paper, the state of the art concerning belt drive energy efficiency is discussed. The paper also discusses the construction of a belt drive test rig. This test rig is used to define or confirm certain statements concerning belt drive efficiency. The test rig construction is briefly described together with the measurement procedure. Finally, the results of a measurement campaign with several comparative tests are presented. This is done by using iso-efficiency maps, which show the efficiency in the entire operation range. Both V-belts and synchronous belts are tested and compared. Furthermore, the test procedure is used to reveal the influence of the pulley diameter, use of a belt tensioner and maintenance parameters such as alignment, wear and belt tension. These tests were performed in a range of 3 – 15 kW nominal transmittable power.

Introduction

Due to forced regulations and social awareness over the last years, a lot of research has been done on energy efficiency. New concepts of electrical motors with high efficiency have entered the market. However, when the coupling between an electrical motor and driven load is considered, there is a lack of information on energy efficiency of these traditional transmission components such as belts and gearboxes. In comparison to electrical motors and drives, there is very few mandatory regulations on these components, especially when it comes to energy efficiency. Information on efficiency can be found in catalogues but the reliability of these numbers is often doubtful because there are no measurement standards for belts and gearboxes.

An industry related project, started in 2012, took a closer look at the efficiency of gearboxes and belt drives. This paper focusses on belt drives. A dedicated test bench was constructed to measure belt drive efficiency in nominal and partial load. A wide variety of belts were tested and the impact of mounting and maintenance on the efficiency was investigated. The results of this measurement campaign are discussed in the paper.

The first part of the paper describes the available knowledge and the blind spots regarding energy efficiency of belt drives. This clearly shows a need for more research and testing on this topic. In a following section, the belt drive test bench is briefly described together with the developed measurement procedure [1]. The aim is to spark the standardization of such tests.

In the second part of the paper, the results of the measurement campaign are discussed. Measurements were done in the entire working range of the belts and represented in iso efficiency maps. The tested belt length varies between 1500 and 2000 mm and the input power ranges from 3 to 15 kW depending on the number of belts. Different types of V-belts and synchronous belts are compared and discussed. The test results also show the impact of pulley size on energy efficiency for V-belts as well as the use of a belt tensioner on synchronous belts.

State of the art and blind spots

The energy efficiency of belt drives is typically assumed to be between 90 to 98%. These values are given by manufacturers in their catalogs and always stated as 'up to', indicating lower values can be expected. Since there is no regulation on how to measure the efficiency, it is unclear how and under which conditions the manufacturers are testing, nor is it known e.g. what belt length and pulley diameter is used or what effect partial load operation has on the efficiency of the belt drive.

The mechanism of power transmission and losses in a V-belt drive was studied in the past. The oldest theory is the creep theory, which is based on the idea of V-belts being elastic [2]. Due to new production techniques, V-belts are virtually inelastic. Firbank's shear theory is based on this premise [3]. Recently, Gerbert postulated a new theory, based again on the elasticity of V-belts [4].

Since there is no generally accepted theory on power transmission in a belt drive, it is hard to obtain reliable efficiency values from theoretical models. Furthermore, as no regulation exists on how to measure the energy efficiency, catalogue values cannot be compared nor trusted in all circumstances. The previous observations supported the decision to build a test bench and to define a measurement procedure.

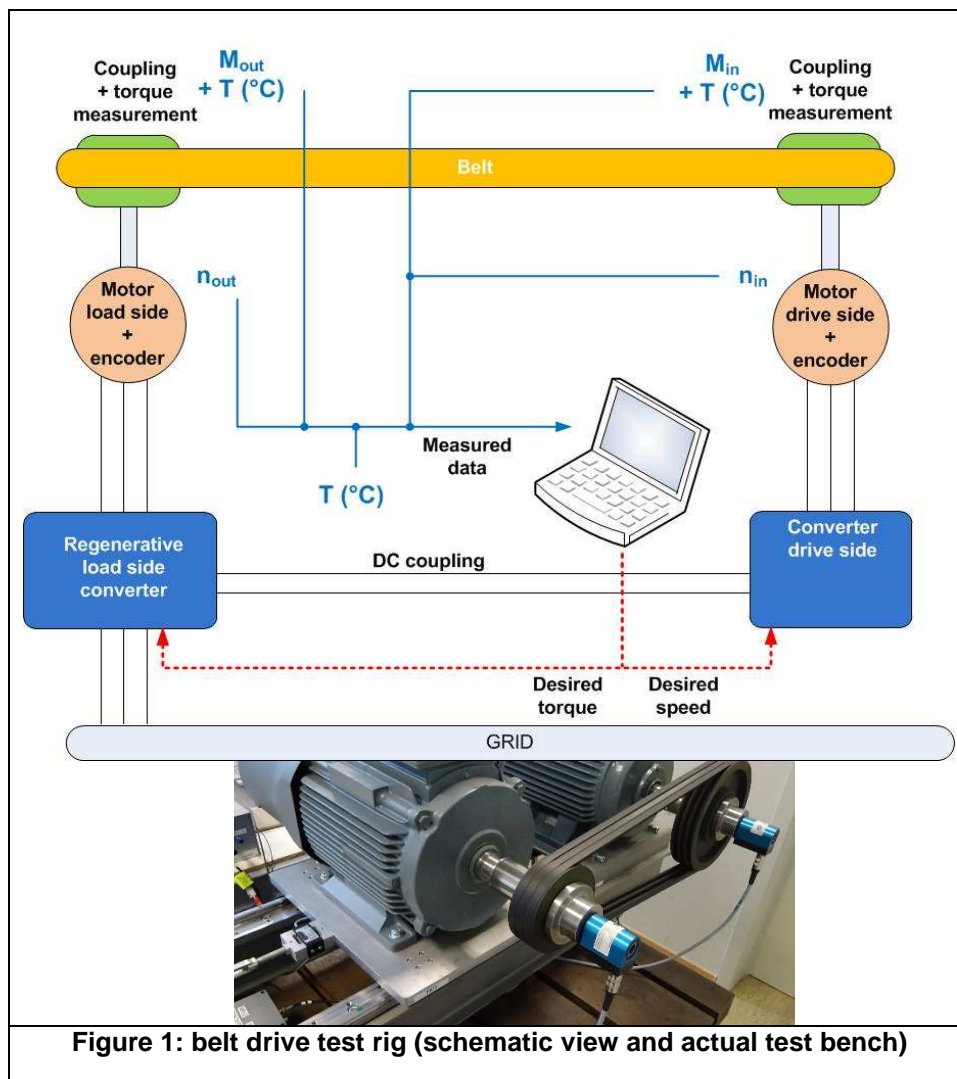


Figure 1: belt drive test rig (schematic view and actual test bench)

Belt drive test bench and measurement procedure

The test bench setup is based on comparing input and output mechanical power and speed and has been extensively discussed in [1]. The belt pulleys are mounted on dedicated 200 Nm torque sensors. The speed is captured by encoders on both 4p 15kW induction motors of which one is speed controlled (drive side) and the other is torque controlled (load side).

The measurement procedure is developed to guarantee reproducible and reliable results. First, two running in tests at constant speed and torque are performed to check for consistency between the results. When this is satisfactory, the efficiency is measured in 272 torque/speed measurement points for each belt test. This data grid makes it possible to create an accurate iso-efficiency map.

Measurement results

The set of belts tested and discussed in this paper was determined in close collaboration with the involved industrial partners and end-users in the related research project. V-belts (wedge SPA and moulded cogged XPA), poly V-belts and synchronous or timing belts (8M) with lengths varying between 1600 and 2000 mm were selected. Table 1 gives an overview of the tested products:

Table 1: range of tested belts during the project power

		State of the art on energy efficiency before the project	Tested belts	
Design	Nominal efficiency		Partly known	SPA – XPA – poly V – 8M
	Partial efficiency		Unknown	SPA – XPA – poly V – 8M
	Number of belts		Unknown	SPA – XPA – 8M
	Pulley diameter		Partly known	SPA – XPA
	Belt tensioner		Partly known	8M
Lifetime	Mounting	Alignment	Unknown	XPA
	Maintenance	Belt tension	Unknown	SPA
		Wear	Unknown	XPA

Nominal efficiency



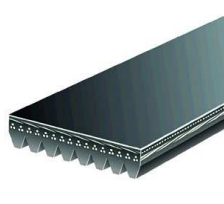

The first measurements focus on the nominal efficiency. This nominal efficiency can also be found in the manufacturers catalog. Comparing these values with the measured ones gives an idea of both the reliability of the manufacturers data and of our test setup (Table 2). It is clear that the given and measured efficiency values are very similar. The measured values are valid for belts with lengths between 1600 and 1800mm with a pulley size of 250mm.

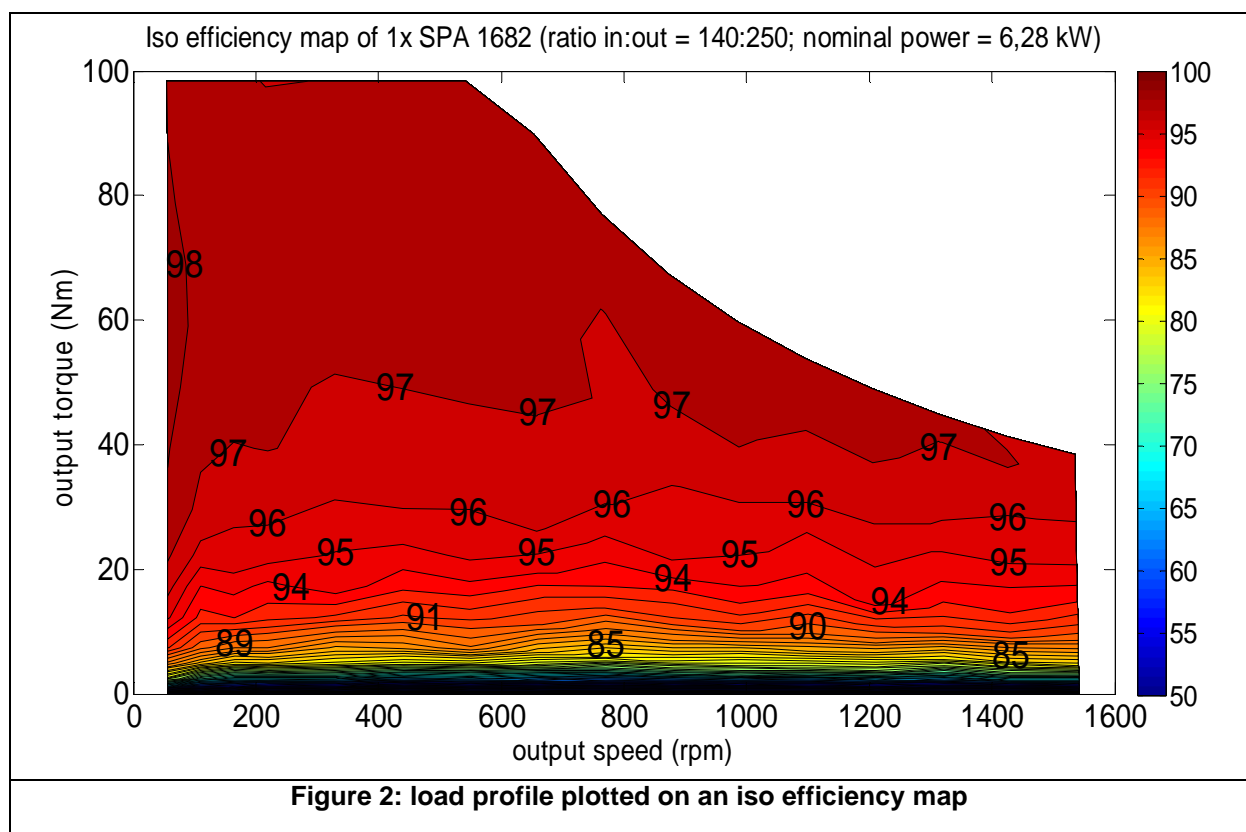
Another conclusion is that the timing belt has the highest efficiency of all types. This is also confirmed by the measurement results shown in figure 3.

Part load efficiency with a single belt

A large number of belt drives is operated in variable speed systems. Knowledge of the efficiency of the belt in these part load conditions is crucial to determine the overall efficiency of the belt drive and of the system in which they are used. Iso efficiency maps provide this information for each steady state torque and speed combination in the operating range of the belt drive.

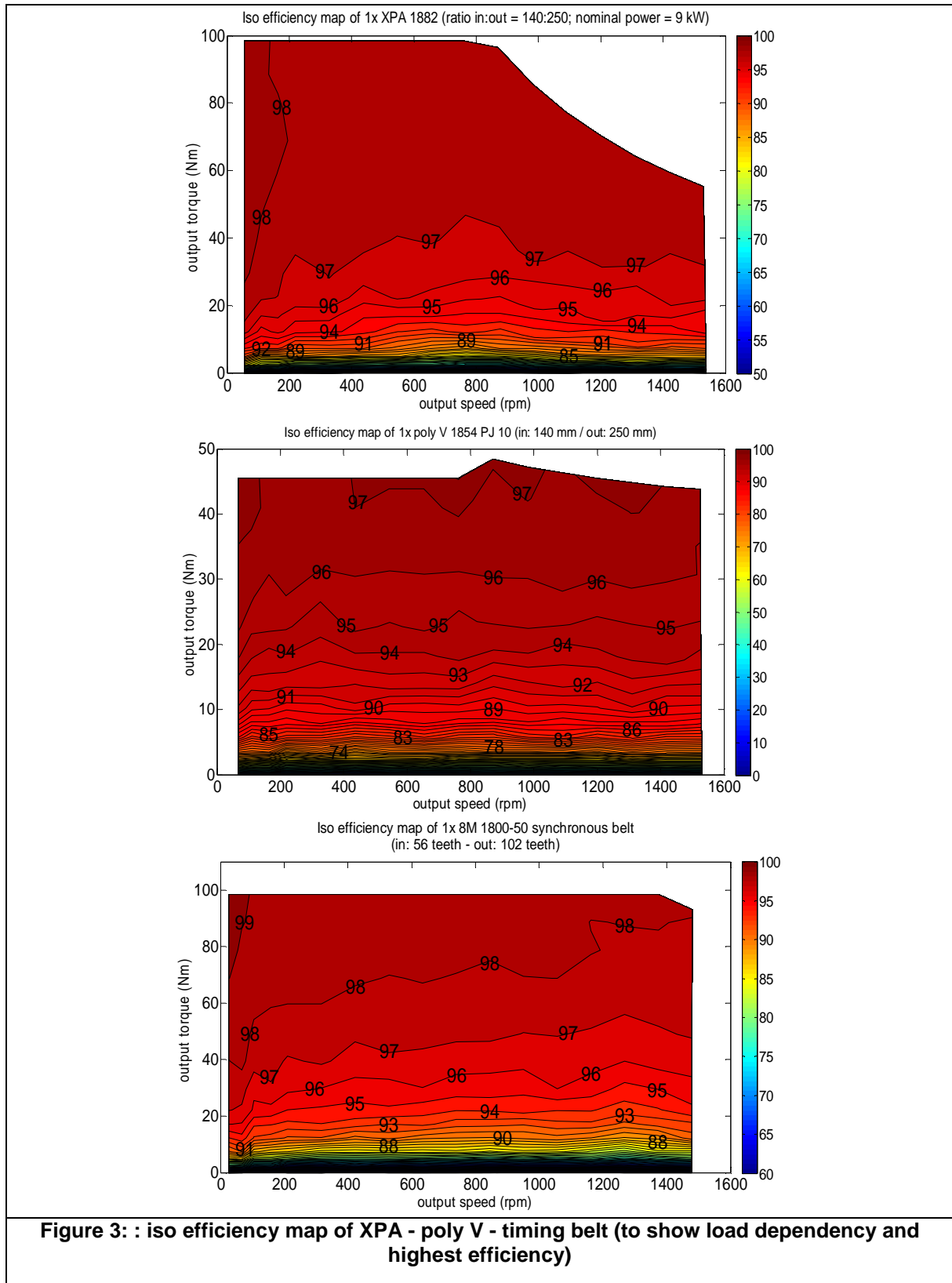
Table 2: nominal efficiency per type of belt (manufacturers data and measurements)

				
type	wedge belt (SP) or V-belt	cogged wedge belt (XP) or cogged V-belt	poly V- or ribbed belt	synchronous or timing belt
efficiency according to manufacturer	up to 97%	up to 97%	up to 96%	up to 98%
measured	up to 97%	up to 98%	up to 97%	up to 99%



An example of a load profile plotted on an iso efficiency map is given in **Fout! Verwijzingsbron niet gevonden..** The total belt drive efficiency can be calculated by multiplying the time and the respective efficiency.

$$\eta_{total\ load\ profile} = \frac{(1h * 97.5\% + 1.5h * 97\% * 0.5h * 95.5\% + 1h * 88\% + 0.2h * 95\%)}{(1h + 1.5h + 0.5h + 1h + 0.2h)} = 94.7\%$$



Comparing the total load profile efficiency to the catalog value results in a difference of more than 2%. It is clear that the use of only the catalog value for belt efficiency is not sufficient for a good estimation of the total efficiency for a certain load profile.

From Figure 2 it follows that the efficiency is mostly torque (y-axis) dependent and the speed (x-axis) has little influence. Moreover, the efficiency for low speeds remains rather constant when the load torque varies. Measurements on other belt types lead to the conclusion that this observation is valid for all belt types (**Fout! Verwijzingsbron niet gevonden.**).

Number of belts

In industry, belt drives with a number of parallel belts are often used. They allow more power transmission and a more reliable and safe operation of the system, for example during a direct on line start of the system. Although for each belt, the efficiency remains relatively high at torques below half of the nominal value, one should take care to dimension the drivetrain correctly. A case study performed during the research project showed that an overdimensioned drive train with 3 paralleled belts could be ran without problems with only 1 belt. This resulted in an efficiency increase of 2%. In the original setup with 3 belts the belts were not fully loaded, from 97% to 95% (figure 4). Apart from the efficiency gain, the maintenance costs also reduce when reducing the number of belts. Only 1 belt needs to be replaced.

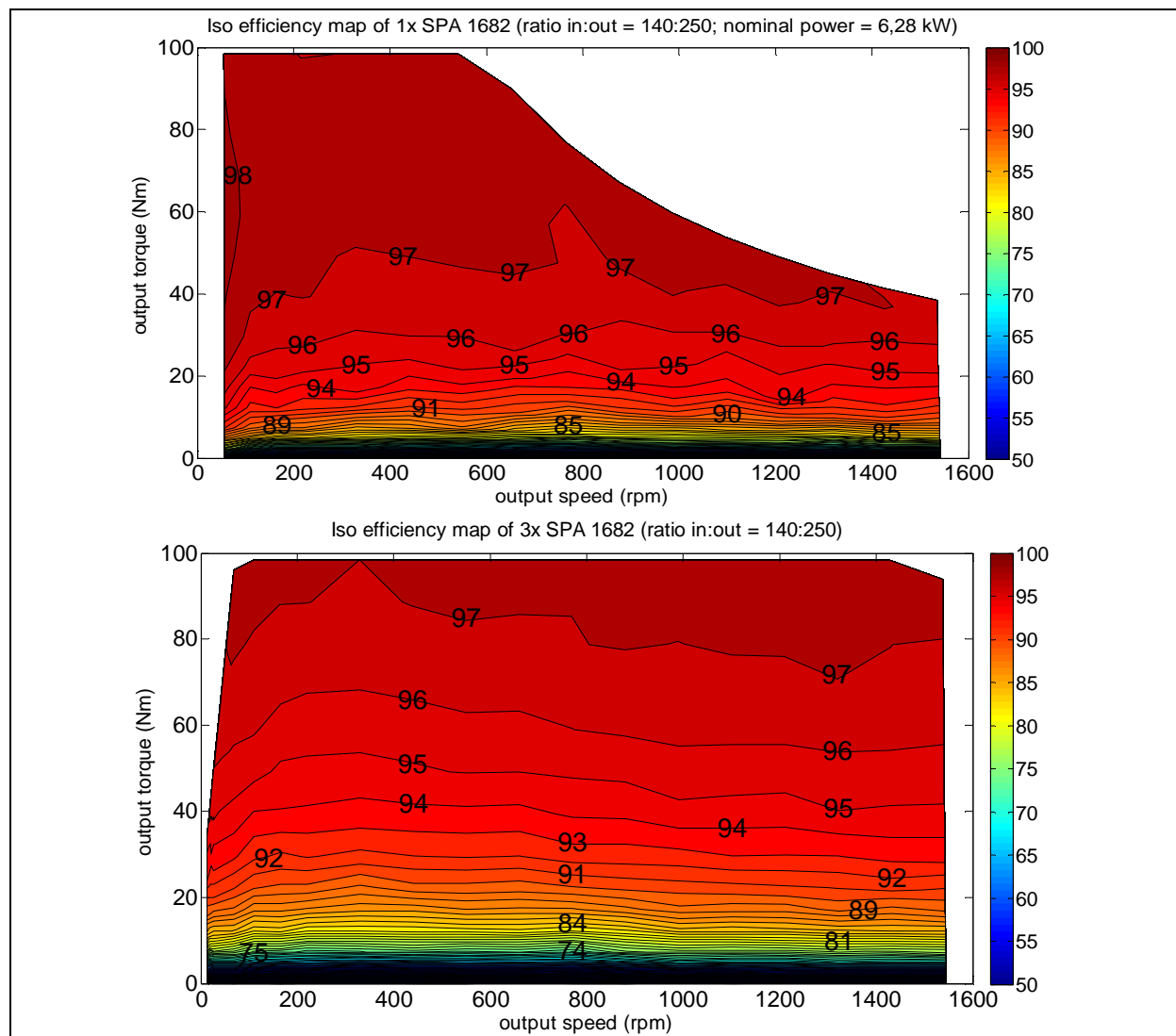


Figure 4: effect of too much belts on a drive train (from 97% to 95% efficiency), 4.A Single belt drive, 4.B Belt drive with 3 paralleled belts.

Pulley diameter

Another aspect important to designers is the pulley diameter. It is generally accepted that a larger diameter is better for efficiency as the belt bends less. On the other hand a trend towards smaller devices is visible in machine building.

A test setup with both SPA and XPA belts is created. A comparison is made between a drive train with two pulleys of 140 mm and another with two pulleys of 250 mm. The pulley ratio is 1:1 to exclude as many other influences as possible.

Table 3: effect of pulley diameter on efficiency

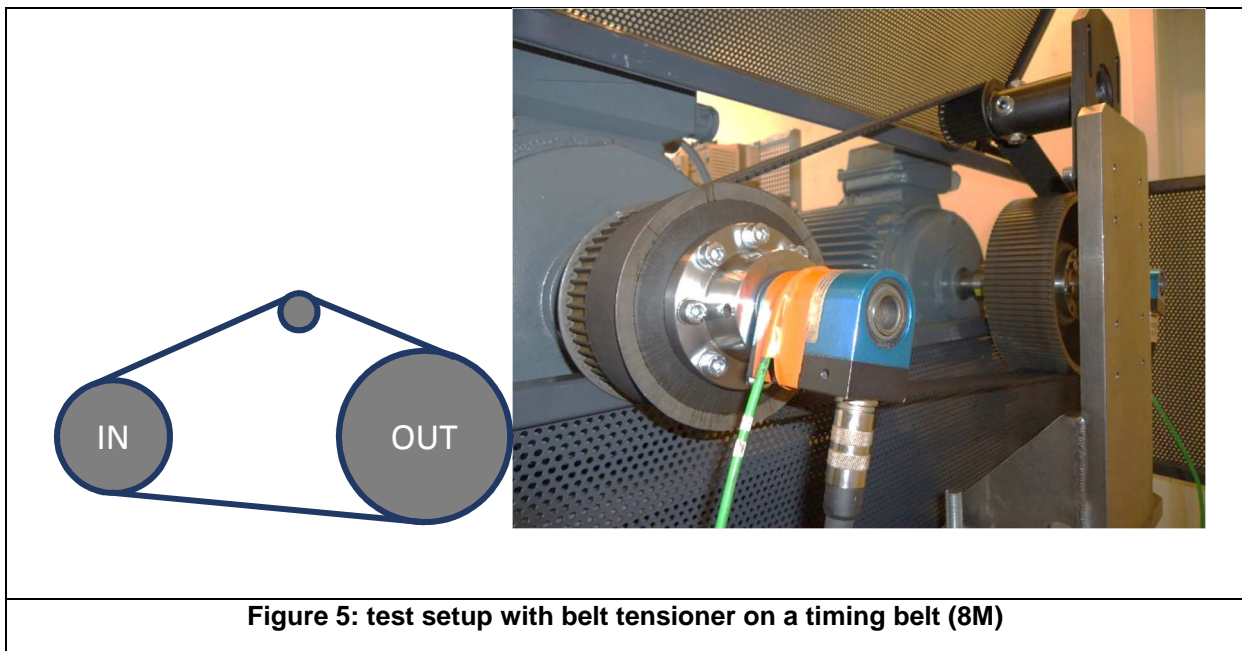
Pulley diameter (mm)	140:140	250:250
SPA	94%	96%
XPA	96%	98%

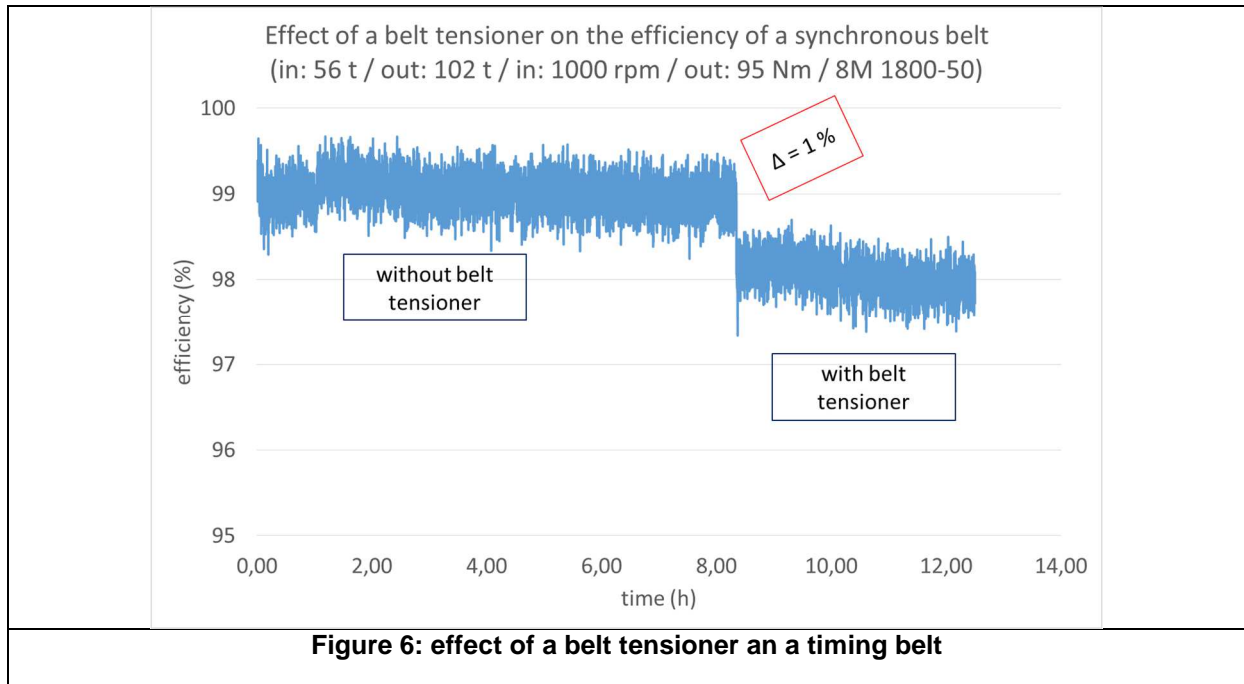
Fout! Verwijzingsbron niet gevonden. shows a significant 2% difference for both SPA and XPA belts. If space requirements are flexible, larger pulleys are to be preferred. The higher cost of the bigger pulley and the longer belt should be taken into account. When applied to a specific industrial case, the payback time to switch to larger pulleys was less than one year.

Belt tensioner

Belt tensioners are frequently used by manufacturers. It is obvious that an extra element will cause extra losses. From an economical point of view, it is good to have some actual numbers on this. Therefore a dedicated test setup was built for an 8M timing belt (**Fout! Verwijzingsbron niet gevonden.**).

The measurement was conducted at one specific speed and torque, as this was most relevant for the company involved. **Fout! Verwijzingsbron niet gevonden.** shows a reduction of the efficiency with 1% when the tensioner is used.





Alignment

When the design of the belt drive is finished, it needs to be properly aligned and tensioned. Proper alignment and tensioning according to the manufacturers guidelines reduced the wear and tear. Here, the impact of misalignment on the efficiency is considered.

Misalignment may come in various forms, such as angular - or parallel error. Here the results are discussed for the latter error (**Fout! Verwijzingsbron niet gevonden.**) of 1 cm on a center distance of 60 cm.

It is expected that a XPA belt is harder to twist due to misalignment than a SPA belt. Therefore a test with a XPA belt is done. In **Fout! Verwijzingsbron niet gevonden.** there is no noticeable difference as depicted in the left and right part of Figure 8. Although misaligning does not have an impact on the efficiency, it should be avoided in order to limit the wear on the belt. Considering a timing belt, here a misalignment would lead to the belt running off the pulleys, comparable to a conveyor.

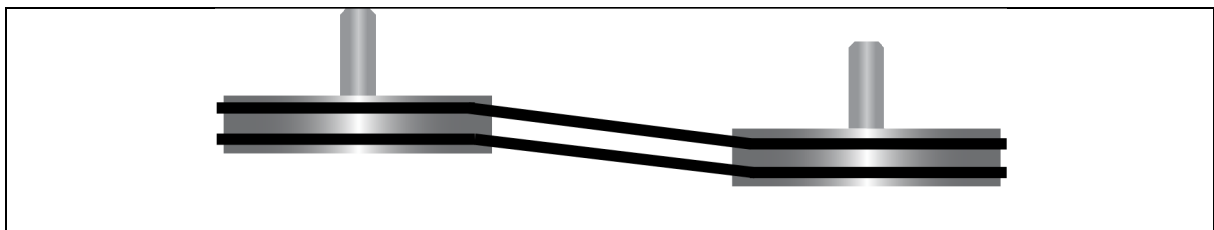


Figure 7: parallel error of belt drive pulleys

Belt tension

For good operation of a belt, it needs to be properly tensioned. Although tensioning testing tools are commercially available, many belts are tensioned based on experience without using this test equipment. The test bench used in this paper allows modifying the belt tensioning during operation. The tension is measured before start-up and after shutdown with a frequency meter. A load cell allows to follow the evolution during the test. It is expected that a lower belt tension than prescribed causes slip

and thus extra losses. Tensioning the belt too much will overload the bearings, but the effect on efficiency is less clear to estimate.

In **Fout!** **Verwijzingsbron niet gevonden.** a SPA belt was first tensioned correctly at 54 Hz. When reducing the tension to 38 Hz, speed went down by 5 rpm at the load side (the “machine side”). Raising the tension to 64 Hz did not notably change the speed or decrease slip.

The losses due to the increase of slip by 5 rpm are somewhere around 35 Watts on a 6 kW mechanical input power. For a fan application, the gain due to a lower speed will outnumber the loss due to slip. But from a production point of view, applying the correct tension makes the belt last longer and trouble-free. A higher tension has no advantages in terms of efficiency, as the speed does not increase.

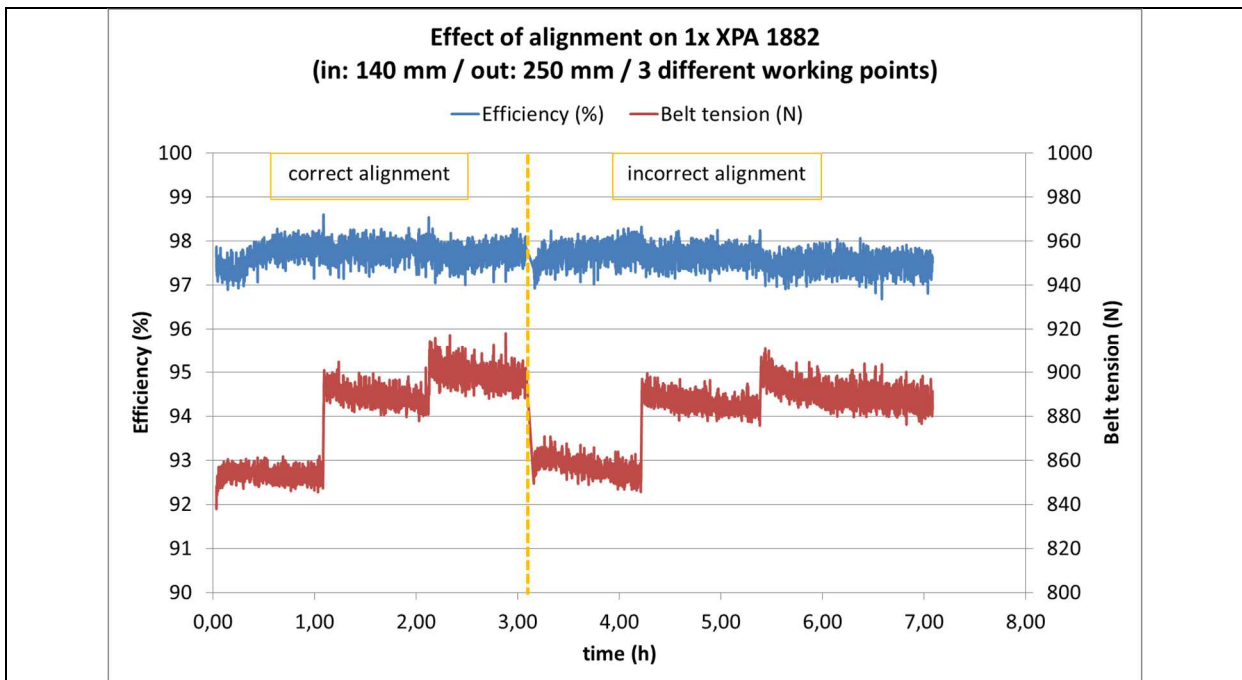


Figure 8: effect of alignment on the efficiency

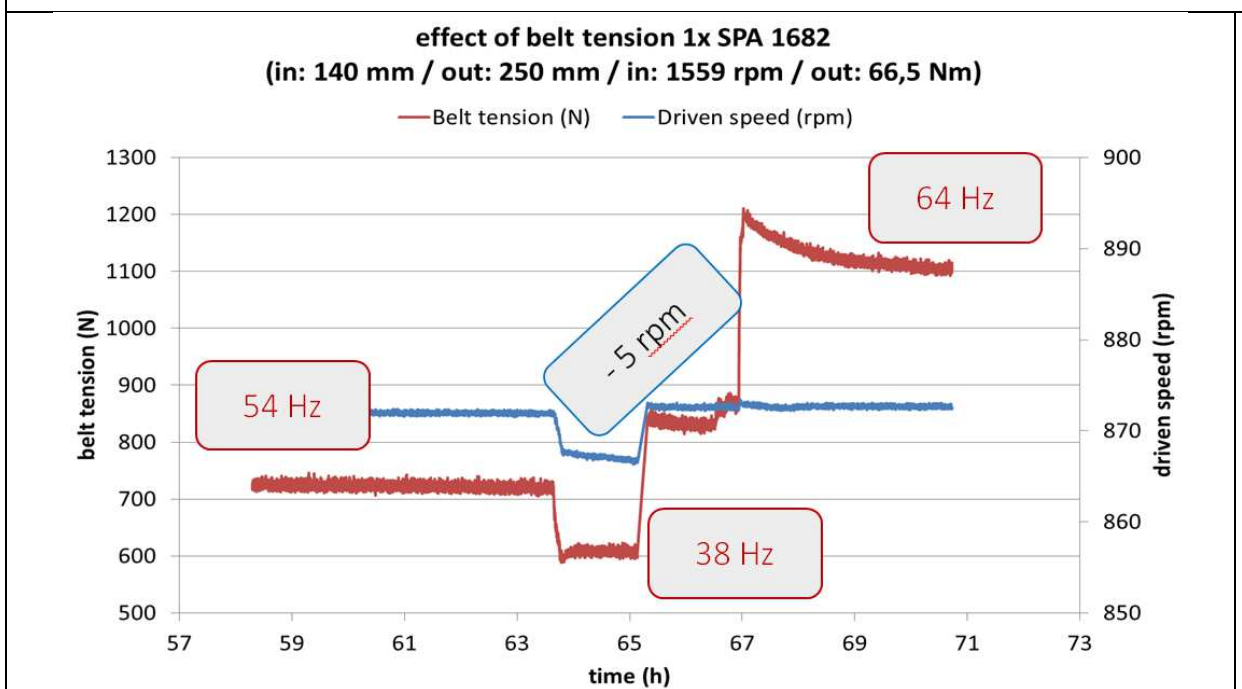
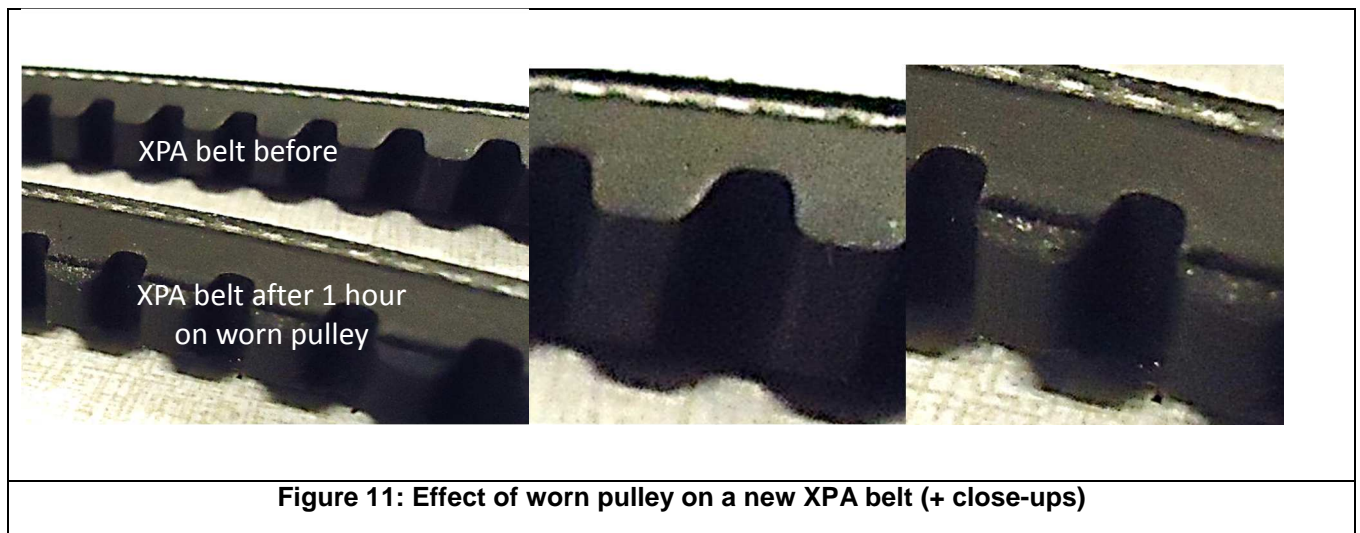
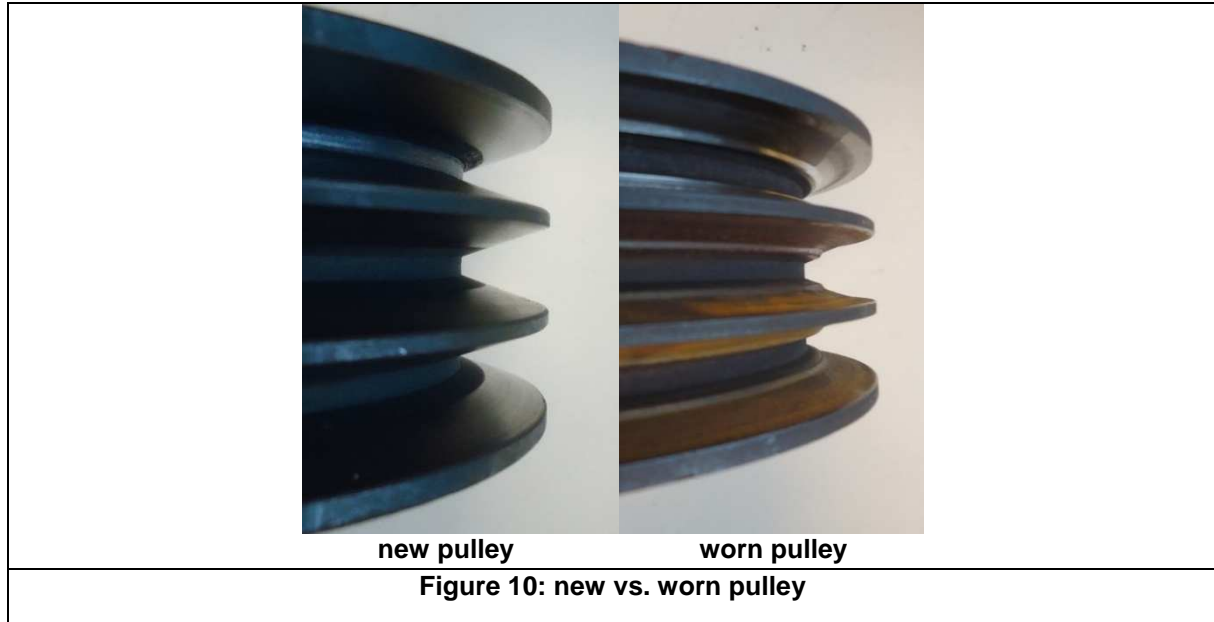


Figure 9: effect of belt tension on the efficiency

Wear

The belt drive suppliers involved in the project sometimes see worn pulleys (right in **Fout! Verwijzingsbron niet gevonden.**) on which new belts are mounted. A test was set up to analyze the effect on the efficiency. Within the first hour of the test with one XPA belt, the efficiency dropped 3%. Also, the belt showed already clear signs of wear (**Fout! Verwijzingsbron niet gevonden.**). This result shows that using worn pulleys with a set of new belts is not worth the savings of not buying new pulleys.



Conclusion

The paper discussed design, mounting and maintenance parameters and their relation to energy efficiency for belt drives.

When using asynchronous V-belts, the XP type is the most efficient. However, the timing belt is the most efficient of all belts. On the other hand, mounting a timing belt is notably more difficult as it does not allow misalignment. Furthermore, the theoretical lifetime of asynchronous belts is 25000 hours vs. 8000 hours for timing belts.

Iso efficiency maps give the possibility to plot a load profile and calculate the total efficiency of a VSD driven system. Adding extra belts for safety should only be done when necessary as efficiency drops when using an overdimensioned belt transmission. This also reduces maintenance costs. It is also shown that larger pulley diameters have a positive effect on the efficiency. Efficiency of a belt drive with a belt tensioner on the contrary dropped.

Aligning the belt is good for belt lifetime but the test campaign discussed in this paper shows no significant influences on the efficiency. However, the belt tension should be applied correctly to avoid slip or too high loads on the components. Belts should be retensioned from time to time, although there are maintenance-free belts on the market. Finally, worn pulleys should always be avoided.

References

- [1] S. Dereyne, P. Defreyne, E. Algoet and K. Stockman, "Construction of an energy efficiency measuring test bench for belt drives," in *EEMODS 2013*, Rio De Janeiro, Brazil, 2013.
- [2] L. Kong and R. Parker, "Mechanics and Sliding Friction in Belt Drives with Pulley Grooves," *Journal of Mechanical Design*, pp. 494-502, 2006 (vol. 128).
- [3] T. Firbank, *Mechanics of the Belt Drive*, 1970.
- [4] G. Gerbert, "Belt Slip - a Unified Approach," *Journal of Mechanical Design*, pp. 432-438, 1996 (vol. 118).