STUDY OF ENERGY EFFICIENCY COMPARISON BETWEEN SMOOTH V-BELT AND COGGED V-BELT FOR POWER TRANSMISSION

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By

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The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled

STUDY OF ENERGY EFFICIENCY COMPARISON

BETWEEN SMOOTH V-BELT AND COGGED V-BELT FOR

POWER TRANSMISSION

Presented by Venkata Naga Likhith Peruri,

A candidate for the degree of Master of Science,

And hereby certify that, in their opinion, it is worthy of acceptance

---

Dr. Sanjeev Khanna

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ABSTRACT

In the United States, annually about 0.4 Trillion kWh of electricity is used in electric motors or mechanical drives. A good majority use belt drives for power transmission between the electric motor and mechanical load. The power transmission efficiency of the belt drives, according to most references and manufacturers in their catalogues, varies between 90 and 98 percent [1,2]. The aim of this study is to identify the key parameters to be measured, to determine the change in the efficiency of a cogged v-belt-driven motor over a smooth v-belt-driven motor. Cogged v-belts are typically estimated to improve power transmission by 3-6% in efficiency over smooth V-belt-driven systems [2,3]. Since there is no generally accepted theory on power transmission in belt drives, it is hard to obtain reliable efficiency values from theoretical models [1]. The outcome of this research will be an empirical approach to determine the potential increase in the energy efficiency of the system by replacing the smooth v-belt with a cogged v-belt. In addition, the belt drive parameters which affect the power transmission such as pulley diameter, belt tension, belt length, angular speeds of the pulleys, the motor speed [1,2,4-7] are evaluated as well. The approach will be developed with input from the tests done by varying the centre distance between the pulleys, pulley diameters, length of the belts, belt tension, motor speeds, and runtime of the system. The final objective of this research would be to develop a scheme to measure parameters during an assessment and use those to make an informed decision on the potential improvement in the energy efficiency of the system using a cogged v-belt over a smooth v-belt.

CHAPTER 1

Introduction

1.1 History

Since the industrial revolution in the 18^{th} century, motors have replaced humans and animals as the primary source of useful work. James Watt observed that a horse pulling 180 pounds of force made 144 trips around the circle in an hour, at an average speed of 181 feet per minute as shown in Figure1.1. The horse generated 33,000 ft. lbs. per minute, which Watt called one “horsepower” [8] as we know electrical motors are rated in horsepower or watt. At the time, generating 1 hp required a 1,000 pound, 6-foot-tall horse that in today’s dollars costs about $5,000 per year to board. Thus, motors are essential to our modern economy and can be viewed as a primary generator of wealth in today’s society.

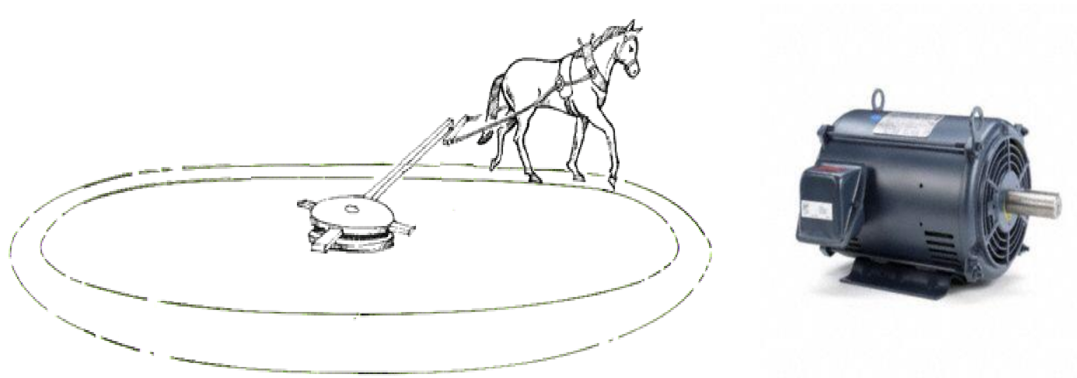

Figure 1.1 Motors replaced animals as the primary source of useful work [37,38]

As we know, motors used in various systems consume on average 65-70% of all the electricity used in the industrial sector [9,10]. Their energy consumption is evidence of their reliability, versatility, and efficiency. However, as motor drives consume an enormous quantity of energy which means that small improvements in motor drive system efficiency result in substantial savings. Due to forced regulations and social awareness over the years, a lot of research has been done on energy efficiency leading to new cost-effective concepts of electrical motors with higher efficiency are introduced [1].

1.2 Power transmission

Power transmission between shafts can be achieved in various forms. They are categorized into rigid systems such as gears, direct coupling between the shafts, and flexible element systems like belts and chains which are commonly used as shown in Figure 1.2.

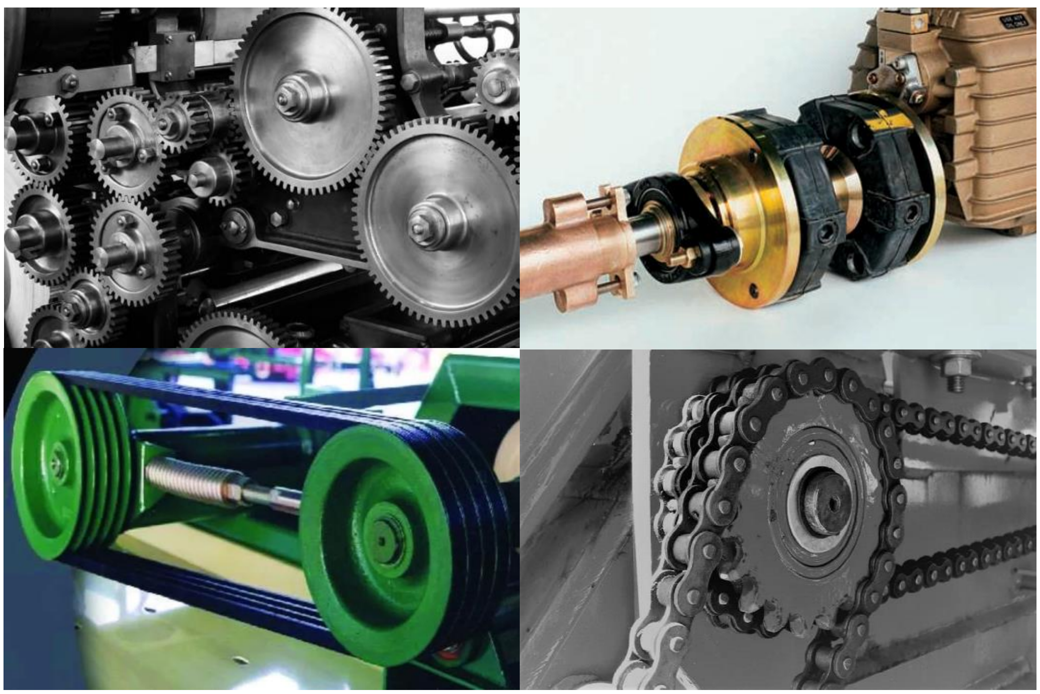

Figure 1.2 (a) Gears [39], (b) Direct coupling [40], (c) Belt drive [41] & (d) Chain drive [42]

1.3 Belt Drives

The mechanical belt drive, using a pulley machine, was first mentioned in the text, the Dictionary of Local Expressions by the Han Dynasty philosopher, poet, and politician Yang Xiong (53–18 BC) in 15 BC, used for a quilling machine that wound silk fibers on to bobbins for weavers' shuttles. The belt drive is an essential component in the invention of the spinning wheel [11]. The belt drive was not only used in textile technologies, but it was also applied to hydraulic-powered bellows dated from the 1st century AD [12]. Approximately one-third of the electric motors in the industrial and commercial sectors use belt drives [3,13]. A belt drive or belt transmission system consists of a set of pulleys, usually attached to parallel shafts, connected by a flexible belt that can serve by transmitting power from one shaft to another. These flexible systems allow power to be transmitted by shafts that are separated by a considerable distance, thus providing greater flexibility in the relative placement of driving and driven equipment as shown in Figure 1.3. Belts are the cheapest utility for the power transmission between shafts that may not be axially aligned. Belt drives run smoothly and with a little noise, and provide shock absorption for motors, loads, and bearings when the force and power are needed to vary. Belt drives provide flexibility in the positioning of the motor relative to the load.

Figure 1.3 Belt driven equipment [43]

Another benefit of belt drives is easy in the change of speed ratio through the selection of different diving and driven pulleys sizes on the shafts as shown in Figure 1.4. Usually, belts are installed by approximating the shafts, wrapping the belt(s) over the pulleys. Only one surface of the belt comes in contact with the outer surface of the pulleys. A properly designed belt power-transmission system offers high efficiency, and low noise, which also gives an advantage requiring low maintenance and zero necessity of lubrication.

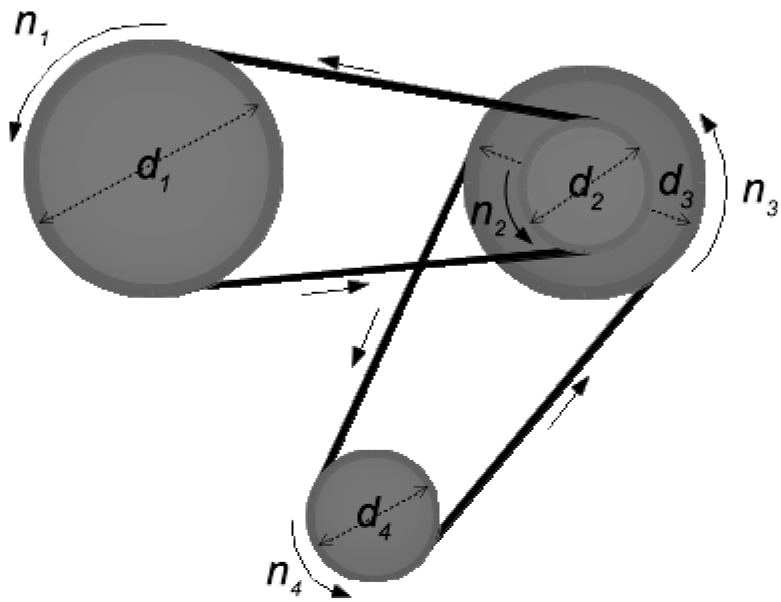

Figure 1.4 Change of speed ratio by change in diameter of the pulley [44]

In the simple case of a belt drive with only two parallel shafts, there are two possibilities of wrap the belt around the pulleys, the open configuration and the cross configuration as shown in Figures 1.5. In the open configuration, both pulleys rotate in the same direction while in the close they rotate in opposite directions. For the cross configuration to operate properly the two shafts must be misaligned, more precisely they must have a vertical angular misalignment.

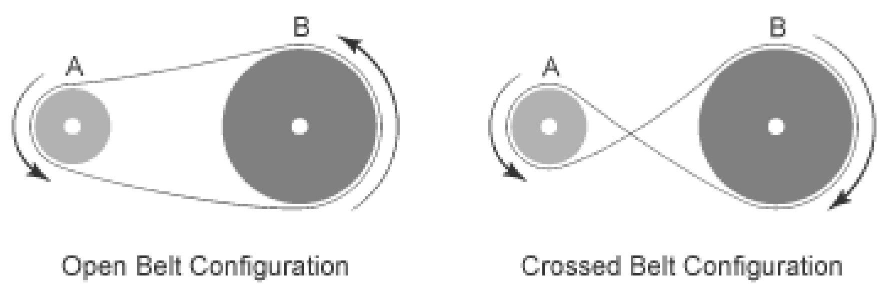

Figure 1.5 Open and Cross belt configuration [45]

1.4 Types of belts

There are four different types of belts used in the industry and commercial sectors like flat belts, synchronous belts, smooth V-belts, and cogged V-belts. Flat belts offer more flexibility over power transmission, while V-belts offer high power transmission capacity [13]. Cogged V-belts, on the other hand, combine these two properties. Whereas, synchronous belts have teeth that fit into a matching toothed pulley which helps to reduce the belts to slip. They are made of a layer of reinforcing cords as tension-carrying members, a protective cushion of rubber that envelopes the cords, a rubber backing, and ribs made of short-fiber-reinforced rubber as shown in Figure 1.6.

Figure 1.6 Cogged V-Belt [46]

1.4.1 Flat Belts

The center layer of the flat belt is normally made of extruded polyamide tapes bonded together and is responsible for giving the belt its traction strength. The speed or torque application requirements determine the thickness of this layer and the belt width. Polyamide gives the belt a high and stable elastic modulus. For high tensile strength applications, Kevlar can be used in the central core. Polyamide fabric layers are bonded on both sides of the central layer contributing also to the belt strength. The outer layers are made of elastomers having high friction coefficients. The elongation produces a tension that remains essentially constant during the belt lifetime. Normal shock loads are absorbed by the elasticity of the polyamides in the belt. The low thickness and the high strength-to-weight ratio allow flat belts to operate at high speeds. Due to their flat and symmetrical structure as shown in Figure 1.7 and their vibration damping elastomers, flat belts produce less noise. Special synthetic leather covers can be used in applications with oil contamination.

Figure 1.7 Flat Belt [47]

The efficiency of the flat belt, typically peaking at over 98%, is not only higher but the efficiency gap widens for lighter loads. Additionally, their lifetime is shorter, typically around 12,000 hrs which is roughly half of the other type of belts [13]. Flat belts have lower transmission losses due to the following reasons:

- For the same load, flat belts are much thinner than V-belts, leading to much lower hysteresis losses
- These belts sit on the surface of the flat pulleys and they do not have the friction losses of V-belts associated with wedging into and pulling out of the grooves
- Unlike V-belts, flat belts do not stretch with age, keeping a constant tension, and thus avoid slippage losses and the need for regular maintenance.

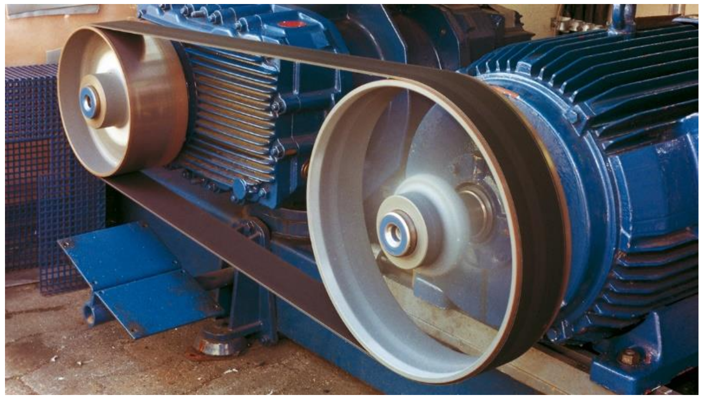

Figure 1.8 Flat belt system [48]

1.4.2 Synchronous Belts

Synchronous belts are toothed belts, the teeth of which fit in the matching grooves of toothed pulleys. The initial generation of synchronous belts used stretch-free fiber-glass tensile cords with neoprene as the filling material. Most synchronous belts also have a wear-resistant tooth facing material to protect the tooth surfaces. This material presents a low coefficient of friction to decrease the friction losses when the belt teeth enter and leave the sprocket teeth as shown in Figure 1.9. The critical elements in these belts are the fiber-glass cords, which wear due to their repetitive flexing, leading to a typical belt lifetime of around 12,000 hrs. Several manufacturers have recently introduced high-performance synchronous belts that use Kevlar tensioning cords and a polyurethane body. These belts have a substantially higher load-carrying capacity than the previous generation of belts. Additionally, their lifetime is longer, typically around 24,000 hrs [13].

Figure 1.9 Synchronous Belt [49]

Although these synchronous belts are more expensive than fiber-glass corded belts, they last longer, and use narrower and thus cheaper sprockets, so their total cost can be lower. Synchronous belts are stretch-free and can achieve higher efficiency than V-belts due to lower hysteresis, lower friction losses, and truly synchronous operation (no-slip; no creep) which is 98% at the rated load. The lower flexing losses result from the small thickness of the belt between the teeth. The absence of speed losses (slip and creep) is due to the positive mating of the teeth of the belt with the teeth of the sprockets. Synchronous belts are ideal for applications requiring accurate speed control of the load. As there is no slip, there is an exactly fixed ratio between the input and output speeds equal to the ratio of the number of teeth in the sprockets. They are not, however, suited for shock loads, where abrupt torque changes can shear belt teeth. Polyurethane synchronous belts feature higher resistance to shock loads than the previous designs that used neoprene rubber. With loads that show a strong relationship between speed and power consumption, it is very important not to waste the energy savings achieved with synchronous belt operation through the higher operating speed of the load. It is essential to choose the sprockets to consider the absence of slippage in the synchronous belt transmission and thus drive the load at a speed no greater than required. With the exception of high-torque, very-low-speed applications, synchronous belts can successfully replace chain drives with an efficiency similar to a well-maintained chain drive. Synchronous belts can also operate in dusty or wet (water or oil) environments.

1.4.3 Smooth V-Belts and Cogged V-Belts

V-bets, as the name indicates, are characterized by having a V-shaped cross-section. Both smooth and cogged v-belts have a similar structure as shown in Figure 1.10 and both can run on the same kind of pulleys. The tensile strength is provided by polyester cords and the envelope body is made of neoprene or other synthetic rubber. Cogged v-belts can substantially reduce the hysteresis losses since the presence of the cogs results in less compression and decompression of the rubber material [13].

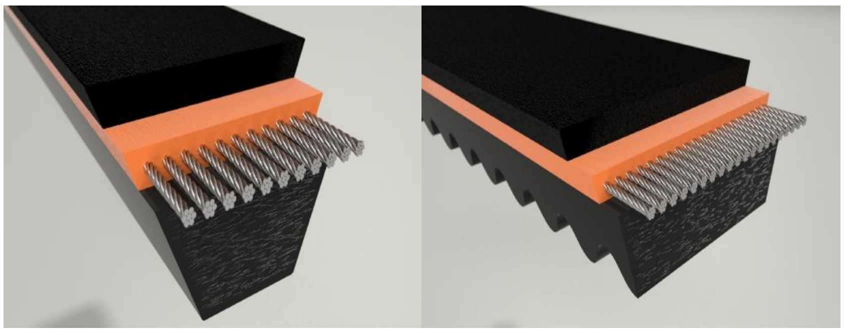

Figure 1.10 Smooth v-belt and Cogged v-belt [50]

The amount of energy savings is highly dependent upon the pulley diameters. The pulley diameter strongly affects the efficiency, especially of conventional smooth v-belts [2,4-7,13-15]. During a partial load operation, the efficiency gain of cogged v-belts over conventional smooth v-belts is larger than at full load since the hysteresis losses are the most significant contribution to the total losses. While there is a wide range of improvement due to load and sheave diameter variations in specific applications, on average a 3% efficiency improvement can be expected by switching from smooth v-belts to cogged v-belts. Because of lower losses and better heat dissipation (larger surface and induced air turbulence), cogged v-belts run cooler, and thus achieving a longer lifetime which is around 24,000 hours [13]. Cogged v-belts also have a raw rubber edge, which has several effects. On the one hand, by eliminating the cloth wrapping on the belt, more tensile cords can be used, increasing the belt load capacity. Some manufacturers also claim that the raw edge improves the friction coefficient between the belt and the sheave. Some users complain that this improved friction factor leads to reduced pulley lifetime.

1.5 Power losses in belt transmission

Efficient belts can provide the same magnitude of energy savings as energy-efficient motors. Therefore, belt drives deserve greater attention, so that their losses can be minimized. The power loss mechanisms may be classified into two categories: torque loss and speed loss, which have been extensively analyzed for the past 30 years [4-6,13,17-19].

Anibal De Almeida [13] further explained the torque losses include hysteresis losses, friction losses, and windage losses. Hysteresis losses occur due to the belt bending/unbending around the pulleys; therefore, reveal at the entrance and exit region. To minimize the hysteresis losses either the belt thickness should be decreased or pulley diameter should be increased to reduce the imposed stresses on the belt material. An increase in driver-pulley speed significantly increases the hysteresis power losses, which are independent of loading.

Frictional losses are between the sidewalls of the belt and the inside walls of the pulley. These losses occur whenever the belt enters and leaves the pulley. In v-ribbed belts, there are small frictional losses associated with the entrance and the exit of the belt, which grows directly with the speed of the operation and show little variation with the load.

Windage losses are associated with the kinetic energy which is transferred to the surrounding air due to the belt motion. The smoother the belt surface, the smaller these losses will be. Although these losses grow steeply with the belt speed, they are relatively small losses when compared to the other belt losses. Windage losses are essentially constant as a function of the load.

The second category in the power loss mechanism is speed losses which do not occur in timing belts and include slip losses and creep losses. Slippage occurs when there's not enough belt tension to provide static friction between the belt and the pulley. Firbank [16] discovered that speed loss between the driving and driven pulleys was mainly due to creep arising from shear strains in the belt envelope. Childs and Cowburn [17] performed a series of measurements on the power loss of flat and v-belts associated with a very small pulley. They found that the reduced efficiency of belts that do not match their pulley groove angles may be due to greater radial compliance of these belts. In the companion paper [18], the experimental study quantified the effects of pulley radius, belt tension, and belt deformation properties on speed and torque losses during power transmission.

Since the year of 1972, Gerbert [20-24] has done a thorough investigation of the mechanics of rubber v-belt drives. The well-known "belt slip" was found originally by Reynolds [25]. The slip phenomenon featuring the decrease of rotational speed was characterized as the relative motion between belt and pulleys caused by belt stretch. Gerbert [20] summarized the slip theory and classified the loss mechanisms of belt slip into a creep, radial compliance, shear deformation, seating, and unseating. Belt slip featuring the speed loss of belt drives account for a minor portion (less than 3%) of power loss. However, it may seriously affect both the belt life and accuracy of precision transmission.

For the evaluation of power loss and transmission efficiency of the belt drive system, the following equations are frequently employed. First, the efficiency of a belt transmission can be defined by equation (1.1)

$$\eta = \frac{P_{\text{output}}}{P_{\text{input}}} \qquad (1.1)\ [26]$$

Where,

η is the transmission efficiency,

P is the power transmitted.

Second, the power transmission in the system can be defined by the equation (1.2)

$$P = \tau * \omega \qquad (1.2)\ [27]$$

Where,

P is the power transmitted in W

τ is the torque,

ω is the angular velocity.

1.6 Misalignment

Proper alignment and tensioning are required according to the manufacturer’s guidelines to reduce the wear and tear of the system. Misalignment is one of the most common causes of premature belt and system failure. The problem gradually reduces belt performance by increasing wear and fatigue. Basically, any degree of misalignment, angular or parallel, decreases the normal service life of a belt drive [28].

1.6.1 Parallel Misalignment

The misalignment in belt drives can be described as a combination of independent misalignments, one of them being parallel offset between the sheaves, which is pulley arrangement is non-linear, as shown in Figure 1.11

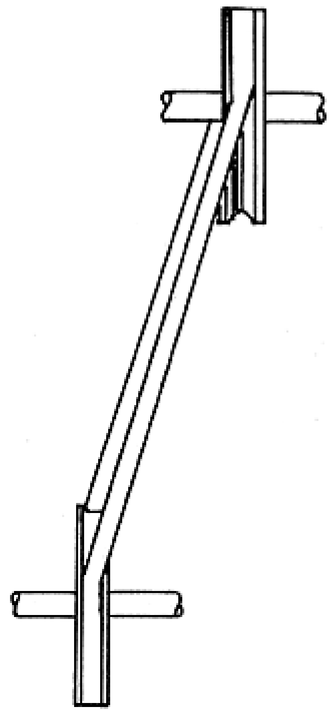

Figure 1.11 Parallel misalignment [51]

1.6.2 Angular misalignment

The angular misalignment can be differentiated into two distinct independent configurations, horizontal angular misalignment, and vertical angular misalignment as shown in Figure 1.12 results in accelerated belt/sheave wear. The first one resulting in the shafts being co-planar and coincident, as shown in Figure 1.12a, and the other resulting in the shafts being non-co-planar and keeping their minimal distance equal to the parallel configuration, as shown in Figure 1.12b.

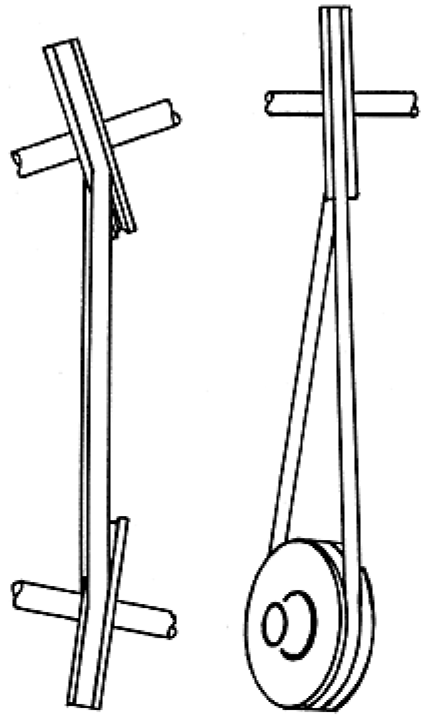

Figure 1.12 Angular misalignment [51]

1.7 Problem Statement

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 generally accepted theory on power transmission in belt drives, it is difficult to obtain reliable efficiency values from theoretical models. Moreover, there is no standardization on how to measure the efficiency, so 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, speed of the pulleys, the runtime of the system has on the efficiency of the belt drive. Therefore, the catalogue values cannot provide accurate estimates in all circumstances.

1.8 The objective of this work

As the parameters used by the manufacturers for testing the belt efficiency are not based on any standards that should be used to acquire the results, the belt efficiencies vary with the systems and with different parameter sets. In an effort to overcome the inadequacies in obtaining an accurate estimate of the efficiency of a belt-drive, we have built a test bench to identify the key parameters to be measured to determine the change in the efficiency of the cog belt-driven motor over the smooth v-belt-driven motor. In addition, the belt drive parameters which affect the power transmission such as pulley diameter, belt tension, belt length, speeds of the pulleys, the motor speed, and runtime of the system were evaluated as well. The outcome of this research would be an empirical formulation based on the acquired test data to determine the potential change in energy efficiency by replacing the smooth v-belt with a cogged v-belt. The final objective would be to develop a scheme to measure parameters like motor speed, pulley speed, belt length, pulley diameter, installation date of the belt during an energy assessment and use those to make an informed decision on the potential improvement in the energy efficiency of the system using a cogged v-belt over a smooth v-belt.

1.8 The layout of this thesis

The writing of this research has been organized into the following sections:

+ Chapter 1 comprises an introduction, literature review, problem statement, and objective of this study
+ Chapter 2 illustrates the construction of the test bench and the instruments used
+ Chapter 3 describes the experimental approach, formulae, and calculations required to quantify the effect of parameters on the efficiency of the system
+ Chapter 4 addresses the analysis of preliminary data acquired by varying the parameters, discussing the outcomes from the tests carried out, an acknowledgment of the test data required to accomplish the goals, and conclusions drawn from them and ongoing work required to achieve the final objective based on the current study

CHAPTER 2

Experimental Setup

2.1 Test Bench

The primary intent of the setup schematically depicted in Figure 2.1, is to measure power transmission efficiency and energy loss of the two different belt-driven motors. We overcame numerous challenges that came with constructing this belt drive test bench. The driver pulley is coupled and actuated with an electric motor shaft on a motor platform [1,2,4-7,19,29]. The motor platform is mounted on an adjustable motor base and the motor is controlled by a variable frequency drive. The driven pulley is coupled with the generator shaft, which is loaded by a resistive load bank. This machine is speed controlled to impress a specific load profile on the belt drive.

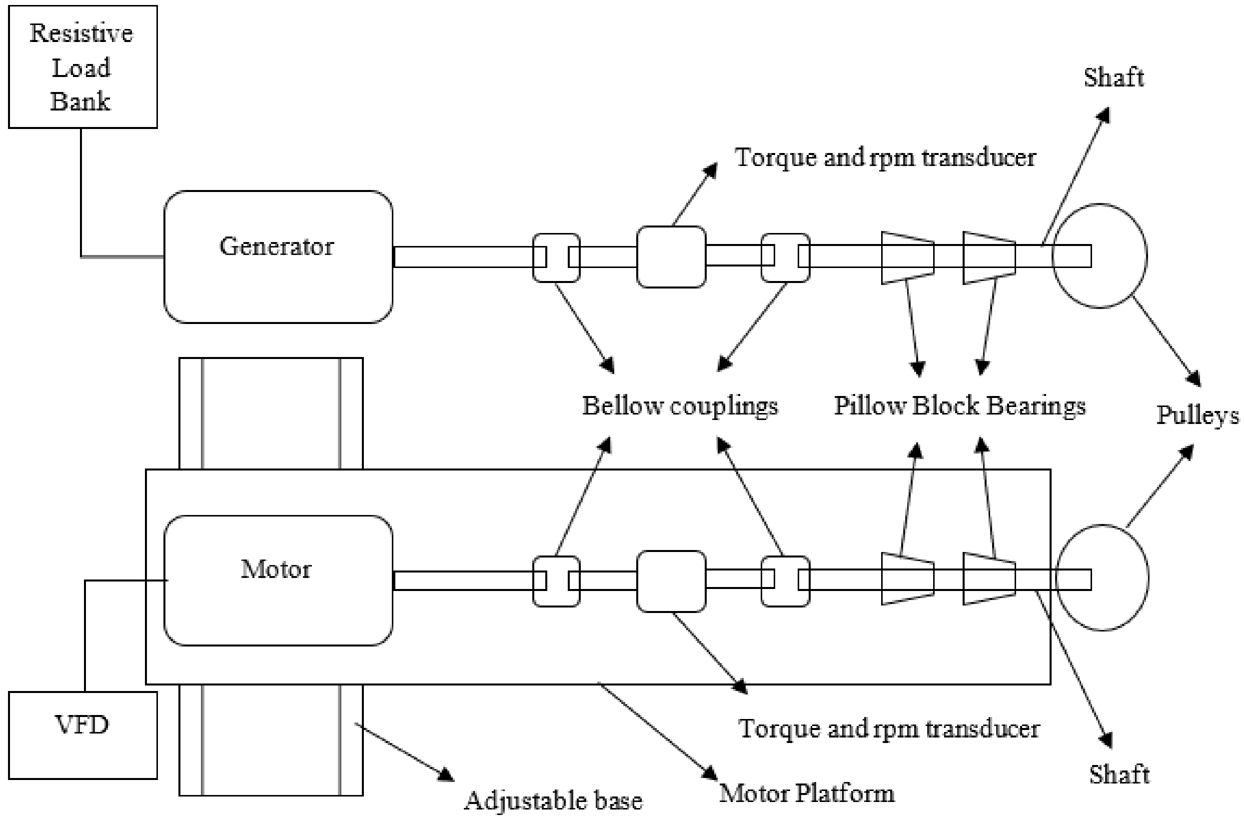

Figure 2.1 Schematic view of the test bench

2.2 Instrumentation

The driver pulley is actuated by a 7.5kW, three-phase Marathon induction motor which is controlled with Altivar 320 Variable Frequency Drive and the driven pulley is loaded by a 10.2kW single-phase S20W-130 Mecc Alte generator which is controlled with Eagle Eye LB-60-30 AC Resistive Load Bank. Substantially the efficiency must be determined with high accuracy because of low losses in a belt drive. This requires transducers with high precision and accuracy. In order to quantify the power transmission efficiency, it is necessary to measure the torque and speed losses at the input (driver) and output (driven) pulleys. Here, dedicated Lorenz Mess Technik transducers which can measure both torque and speed at each pulley with a ±0.05% full-scale accuracy and 100 Nm range are used. These transducers are calibrated with the Interface 9894 Analog Input Process Indicators by the manufacturer for data acquisition. Because the belt drive systems require tensioning of the belts, the transducer is coupled with bellow couplings, which are not influenced by the radial forces due to belt tension. To minimize the radial loads on both motor and generator shafts NTN pillow block bearing supports are used at the ends. An overview of the initial test bench and final test bench is shown in Figure 2.2 and Figure 2.3 respectively. One of the challenges we have faced after constructing the test bench is how to overcome the high surface temperature of the pillow block bearings at both motor and generator shafts. These high surface temperatures on the pillow blocks are triggered by high radial loads on the bearings which are caused by running the motor at 3,500 RPM. To compensate for the high radial loads on the bearing supports we built an additional pillow block bearing support on the motor and generator shaft which helped to bring back the surface temperature of the supports to the operable range. FLIR infrared camera and contact thermometer are used to measure the equipment temperature is operating at the manufacturer's recommended range. Furthermore, the test room is equipped with an air-conditioning unit to limit the ambient temperature variation. The setpoint for the ambient temperature in the room is 75ºF.

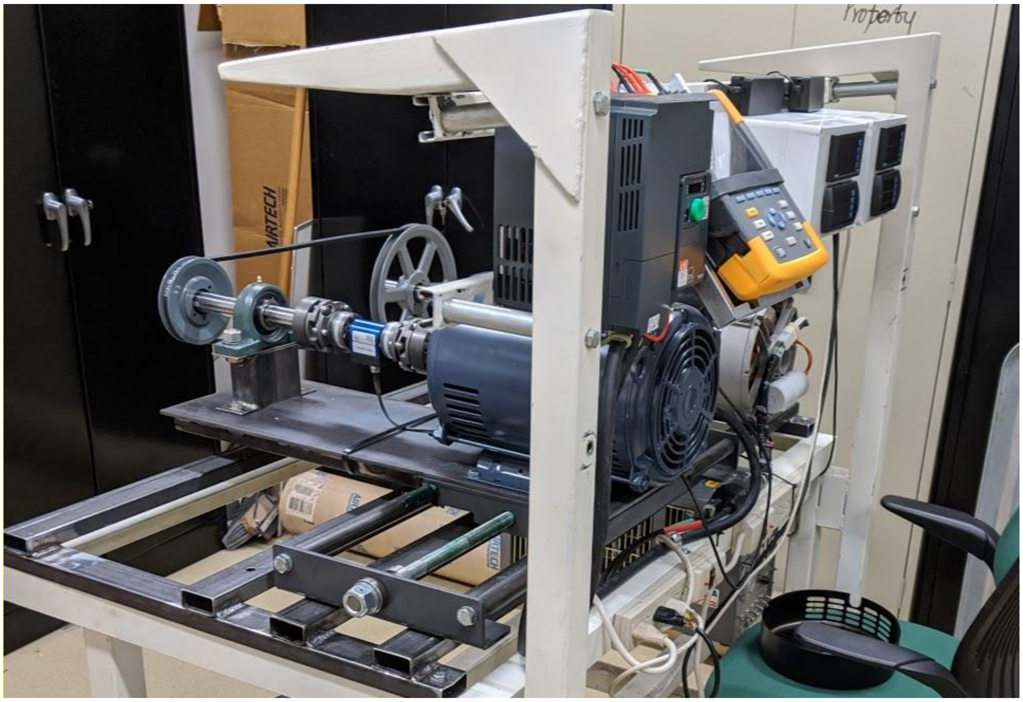

Figure 2.2 Initial test bench

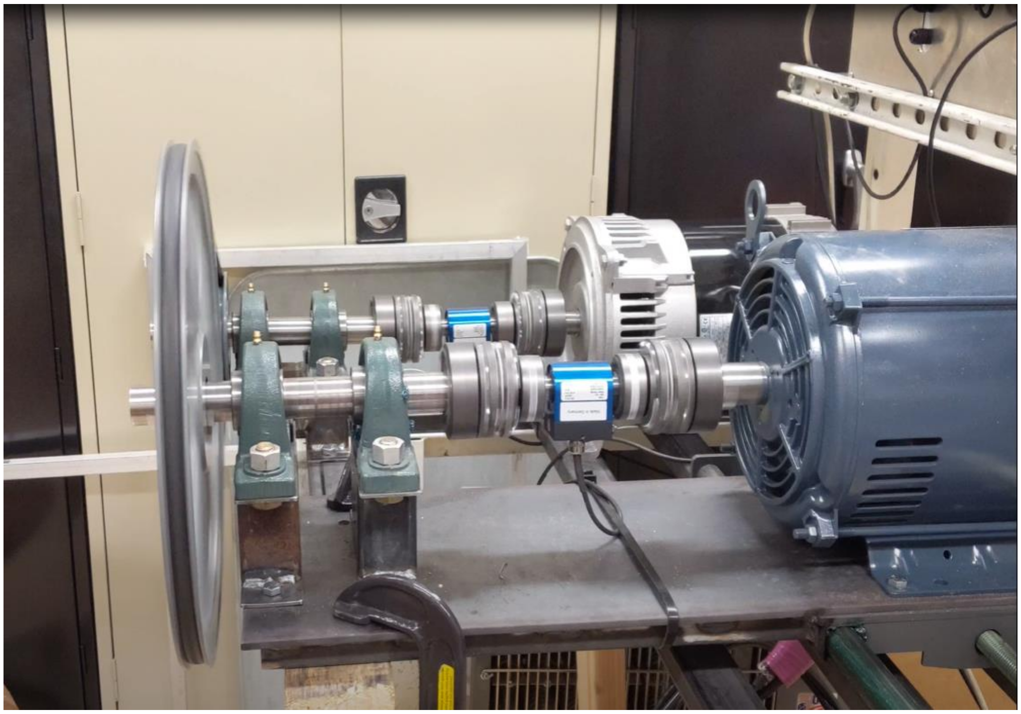

Figure 2.3 Final test bench

CHAPTER 3

Methodology

3.1 Experimental Study

In an electric motor, mechanical power is defined as the speed times the torque. Mechanical power is typically defined as kilowatts (kW) or horsepower (hp) with one watt equaling one joule per second or one Newton-Meter per second. The power output can be calculated as shown below in equation (3.1).

The power output (P) can be calculated as:

$$P = \frac{\tau * \mathrm{RPM}}{5252} \qquad (3.1)\ [30]$$

Where, τ is the transmitted torque,

RPM is the speed of the pulley.

Efficiency is simply the measure of the peak level of performance that uses the least amount of input energy to achieve the highest amount of output energy as shown in equation 3.2. The intend of this study is to quantify the efficiency of cogged v-belt over smooth. The energy efficiency η of a belt drive system can be calculated as shown below in equation 3.3.

$$\eta = \frac{P_{output}}{\mathrm{P}_{input}} \qquad (3.2)\ [26]$$

$$\eta = \frac{\tau_{driven} * \mathrm{RPM}_{driven}}{\tau_{driver} * \mathrm{RPM}_{driver}} \text{ x } 100 \qquad (3.3)$$

Where, τ_{driver} is the torque of the driver pulley,

RPM_{driver} is the speed of the driver pulley,

τ_{driven} is the torque of the driven pulley,

RPM_{driven} is the speed of the driven pulley,

As discussed in the earlier chapter, the belt drive power transmission losses are a combination of torque losses and speed losses. The torque losses can be further broken down into hysteresis losses, friction losses, windage losses, and speed losses also can be further broken down into creep losses and slip losses. Thus, to evaluate and identify the losses and efficiency in the system, torque and speeds are the fundamental data to be measured at both driver and driven pulleys. Therefore, the torque and speed read-outs transmitted from each Lorenz Mess Technik transducer on motor and generator shafts were logged for all the tests with the help of Interface 9894 Analog Input Process Indicators and used to calculate the slip and efficiency of the system. By varying the following parameters helps to understand and quantify the effect of power transmission loss mechanisms on efficiency in the belt drive system:

+ The diameter of the pulley and motor speeds
+ Belt tension in the system
+ The runtime of the system

From the speed readouts transmitted by the transducers, the percentage of slip (S) can be calculated as shown below in equation (3.3):

$$S = \frac{\omega_{driver} - \omega_{driven}}{\omega_{driver}} \times 100 \qquad (3.3)\ [4]$$

Where, ω_{driver} is the rotational speed of the driver pulley,

ω_{driven} is the rotational speed of the driven pulley.

3.2 Effect of pulley diameter

Three different pulley diameter ratios 1:1, 2:1, and 3:1 (driver: driven) combination were used to observe and understand the impact of hysteresis losses i.e. bending/unbending of the belt while running through the pulley on the efficiency of the system. As the diameter of the pulleys and center distance between the pulleys change, the length of the belt also changes. The length of a belt can be calculated as shown below in equation (3.5).

$$\text{Belt length} = (D_{driver} + D_{driven})\frac{\pi}{2} + 2L + \frac{(D_{driver} - D_{driven})^2}{4L} \qquad (3.5)\ [28]$$

Where, D_{driver} is the diameter of the driver pulley,

D_{driven} is the diameter of the driven pulley,

L is the center distance between the driver and driven pulleys

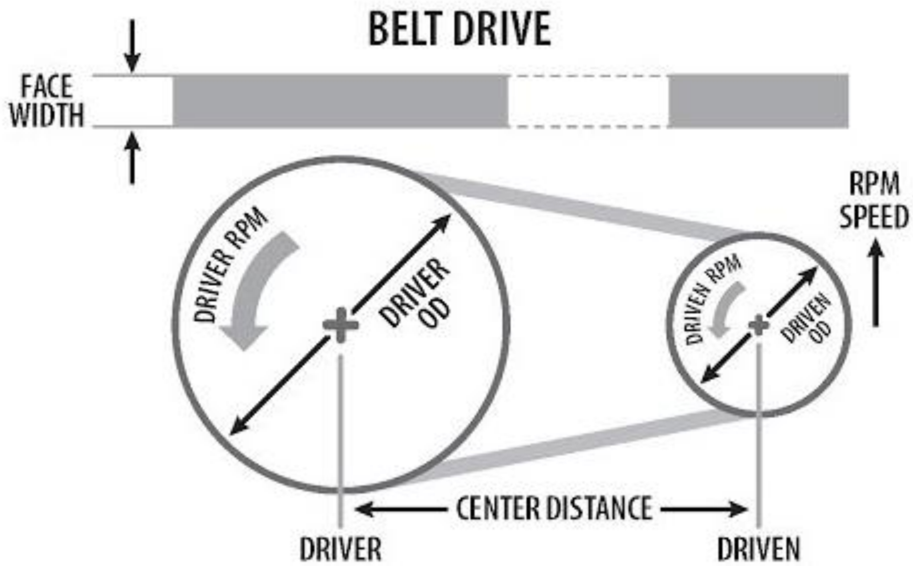

Figure 3.1 Belt drive [52]

The S20W-130 Mecc Altee generator in the test bench cannot produce amperage below 2,800 RPM. Due to limitations, we have the pulley diameter of the generator shaft is set to be constant which is 5-inch. The period for each test carried out with 5, 10, and 15-inch pulley diameters on the motor shaft for a 30-min each.

3.3 Effect of belt tension

Belt tension in the system was changed manually to observe and understand the impact of frictional losses and speed losses on the efficiency of the system. These losses occurred whenever the belt enters and leaves the pulley in the form of a slip. Slippage occurs when there's not enough belt tension to provide static friction between the belt and the pulley. With the help of the adjustable motor base and Power drive v-belt tension checker, the belt tension was changed and measured as shown in Figure 3.2 respectively. The tests are performed with belt tensions 3.5, 3, 2.5, 2 pounds for 6 hours each.

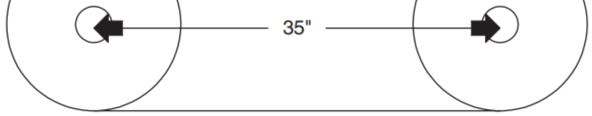

Figure 3.2 Measuring the tension in the belt [53]

3.4 Effect of runtime

The impact of frictional, slip, and creep losses on the efficiency of the system was observed with runtime without re-tensioning the belt during the test period. The runtime for each test without re-tensioning the belt was 15 days.

CHAPTER 4

Data Analysis, Results & Conclusion

In an experimental study, good measurement systems are important to produce credible data that will lead to reliable conclusions. One of the most common reasons for low-quality data is too much variation. Much of the variation in a set of measurements may be due to the interaction between the measurement system and its environment. That makes interpreting the data and the measurement system more difficult. If the interaction generates too much variation, then the quality of the data may be so low that the data are not useful. The variability is often divided into two components: the first caused by the operator, and the other by the measuring system. The construction of this test bench is to collect and measure the data which is reliable i.e. repeatable and reproducible data. Repeatability is the variation in repeated measurements taken by the same operator under the same experimental conditions. Reproducibility is the variation in data obtained by different operators taking the measurement with the same setup under the same conditions. These are measures of the consistency and precision of the data [31]. As the repeatability of the measurement is also a major concern for reliable results. Comparing different appropriate belts [32] requires mounting and demounting of belts and pulleys. Thus, this mechanical work was performed with great care to introduce no additional errors or losses other than the actual belt drive losses [33]. Measurement tools are used to analyze the misalignment of the pulleys and to check the belt tension whenever mechanical changes are made. To apply a certain belt tension, we used an adjustable motor base and v-belt tension checker to confirm the desired or manufacturer-recommended tension in the belt [34-36].

4.1 Preliminary Data Analysis

The tests are performed on both smooth and cogged v-belt equipped systems by varying parameters we discussed in the earlier chapter. In the entire testing process variable frequency drive, resistive load bank, adjustable motor base, and belt tension checker were used to control the motor speed, apply the resistive load, adjust the belt tension and measure the belt tension respectively. In all the following figures below, the blue line represents smooth v-belt and the orange line represents cogged v-belt data.

To observe the effect of hysteresis losses on the power transmission, a set of preliminary tests were carried out with 5-inch, 10-inch, and 15-inch pulleys driving the motor shaft, 5-inch pulley driving the generator shaft, and keeping the center distance between the generator and motor shafts 18-inch. The runtime for each test is 30 minutes. Figures 4.1, 4.2, 4.3 represents test data for 5-inch, 10-inch, 15-inch pulleys equipped on motor shaft respectively, keeping the pulley size 5-inch on the generator shaft constant for all the tests. From the test data of the system with 5-inch pulleys driving the motor and generator shafts in Figure 4.1, we can say that efficiency of the system with smooth v-belt drops from 93.61% to 79.38% with an increase in generator speed from 3,000 to 3,600. On the other hand, comparing with the cogged v-belt equipped system, the efficiency changes marginally from 88.53% to 90.32% and stays substantially the same with an increase in generator speed from 3,000 to 3,600.

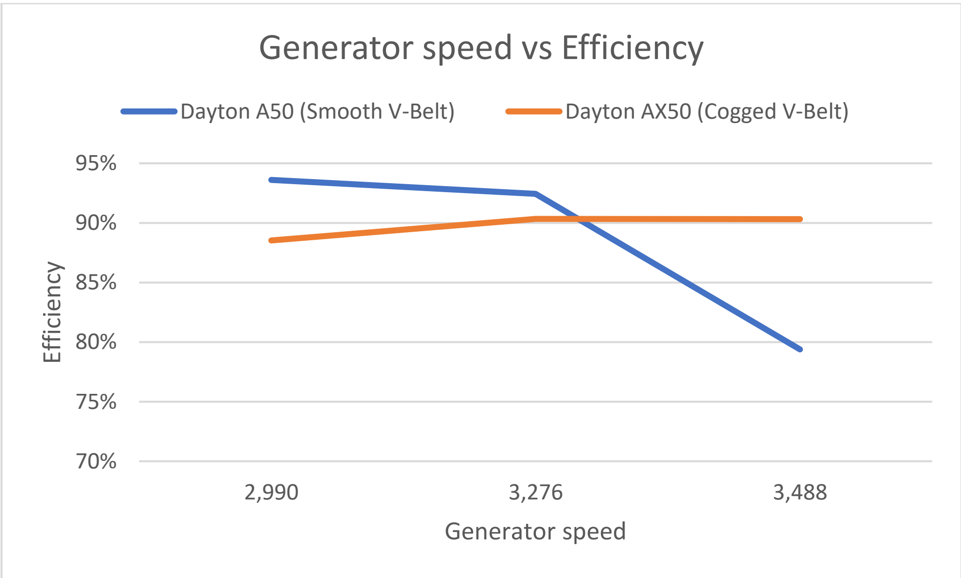

Figure 4.1. Speed vs Efficiency for smooth and cogged v-belt with 1:1 pulley ratio

From the test data of the system with a 10-inch pulley driving the motor shaft and a 5-inch pulley driving the generator shaft in Figure 4.2, the efficiency of the system with smooth v-belt increases from 82.79% to 92.62% with an increase in generator speed from 3,000 to 3,600. The efficiency of the system equipped with cogged v-belt increases from 84.40% to 89.40% and stays substantially the same with an increase in generator speed from 3,000 to 3,600.

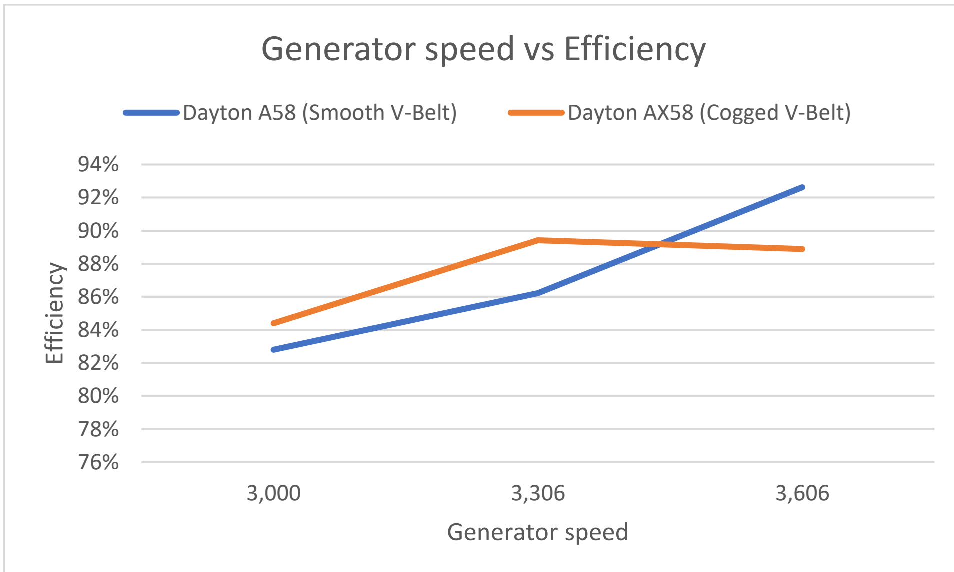

Figure 4.2. Speed vs Efficiency for smooth and cogged v-belt with 2:1 pulley ratio

From the test data of the system with a 15-inch pulley driving the motor shaft and a 5-inch pulley driving the generator shaft in Figure 4.3, the efficiency of the system with smooth v-belt increases from 78% to 88% with an increase in generator speed from 3,000 to 3,600. In comparison the efficiency of the system equipped with cogged v-belt increases from 74% to 89% with an increase in generator speed from 3,000 to 3,600.

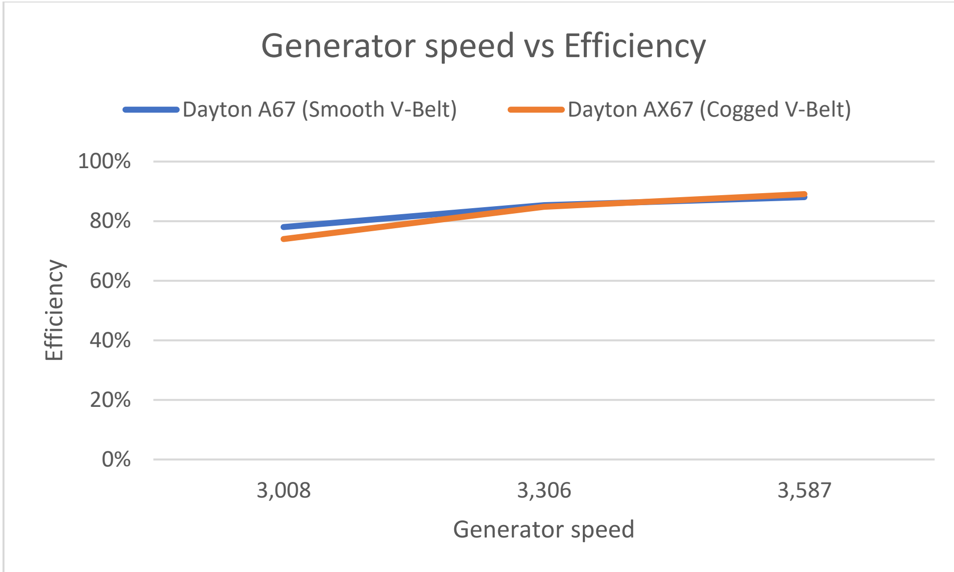

Figure 4.3. Speed vs Efficiency for smooth and cogged v-belt with 3:1 pulley ratio

To observe the impact of frictional losses and speed losses on the efficiency of the system, preliminary tests were carried out with 5-inch pulleys driving the motor and the generator shafts. The runtime for each test was 6 hours, keeping the center distance between the generator and motor shafts was 30-inch. From the test date in Figure 4.4, we can say that the belt slip in the system with smooth v-belt is greater with drop-in belt tension over the belt slip in the system with cogged v-belt. Figure 4.5, depicts that the efficiency of the system with smooth v-belt falls from 90.17% to 88.95% with drop-in tension from 3.5lbs to 2lbs. Whereas, the efficiency of the system with cogged v-belt falls marginally from 90.75% to 90.71% with drop-in tension from 3.5lbs to 2lbs.

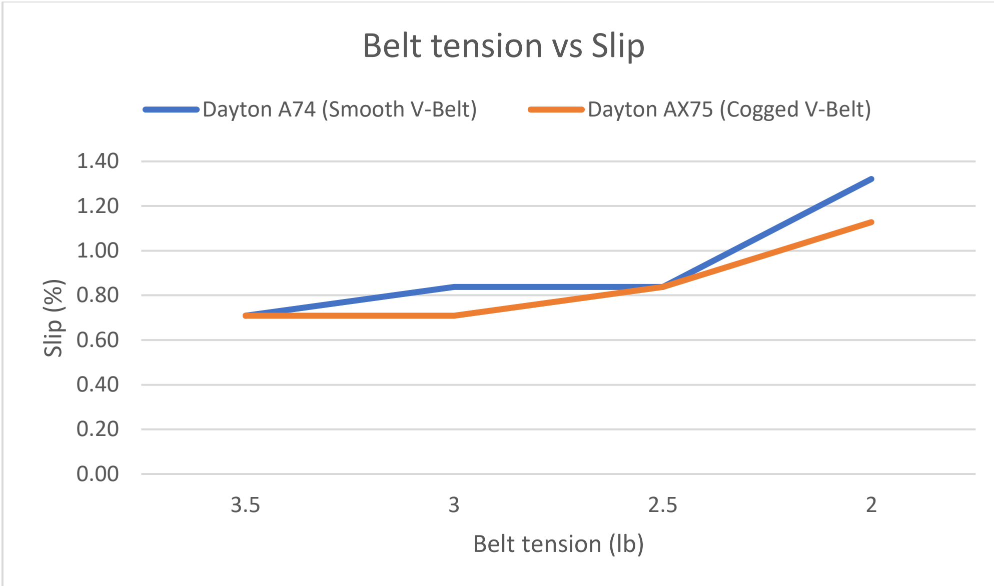

Figure 4.4. Belt tension vs Slip for smooth and cogged v-belt with 1:1 pulley ratio

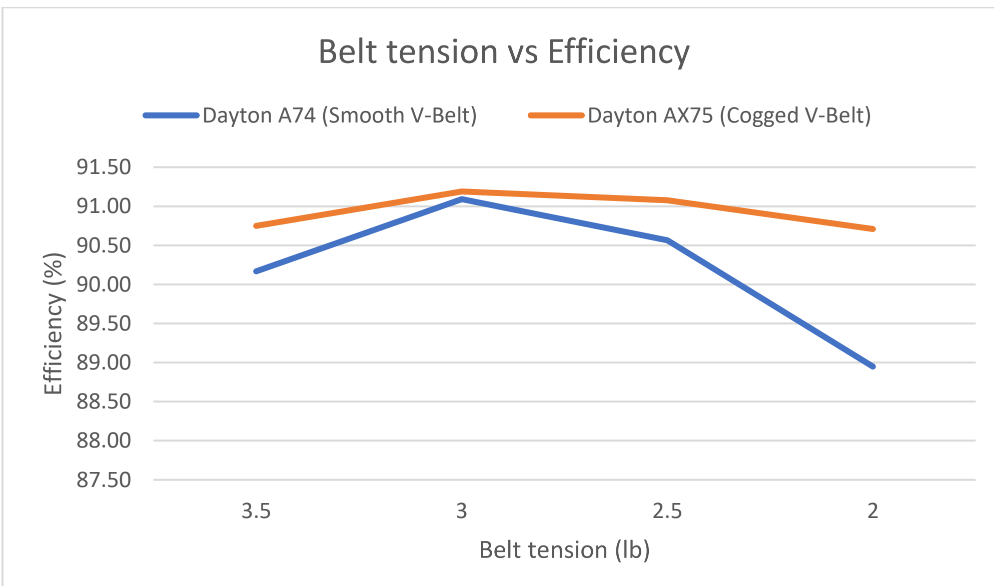

Figure 4.5. Belt tension vs Efficiency for smooth and cogged v-belt with 1:1 pulley ratio

The impact of frictional, slip and creep losses on the efficiency of the system, preliminary tests were carried out with 5-inch pulleys driving the motor and the generator shafts. The runtime for each test was 15 days, keeping the center distance between the generator and motor shafts

30-inch. From the test date in Figure 4.6, the belt slip in the system with smooth v-belt is constant for almost 10 days and a marginal change after that with the runtime. On the other hand, the belt slip in the system with a cogged v-belt follows the same pattern but at a lower scale. Figure 4.6, depicts the efficiency of the system with a smooth v-belt range from 87.30% to 88.22% over the runtime. Whereas, the efficiency of the system with a cogged v-belt range from 89.92% to 90.16% over the runtime.

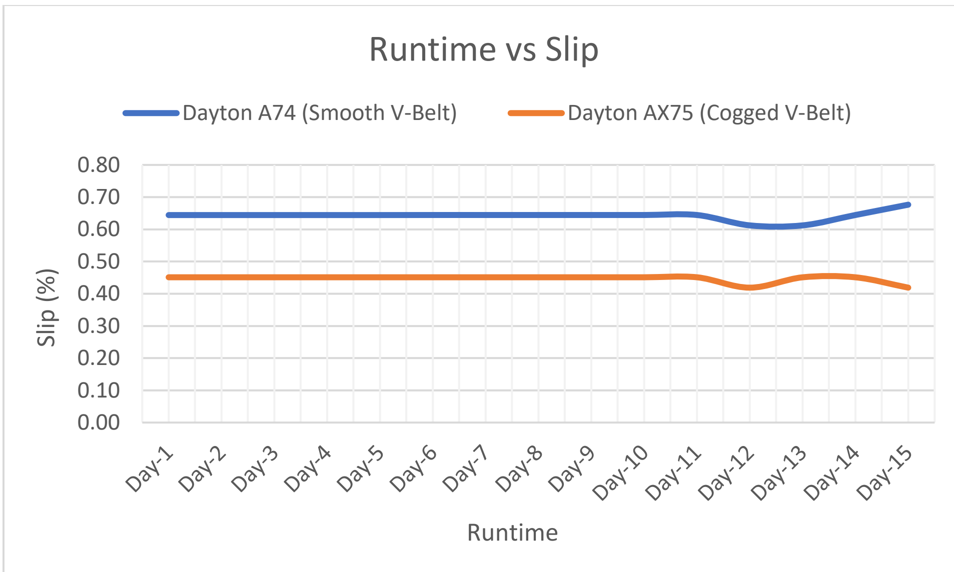

Figure 4.6. Runtime vs Slip for smooth and cogged v-belt with 1:1 pulley ratio

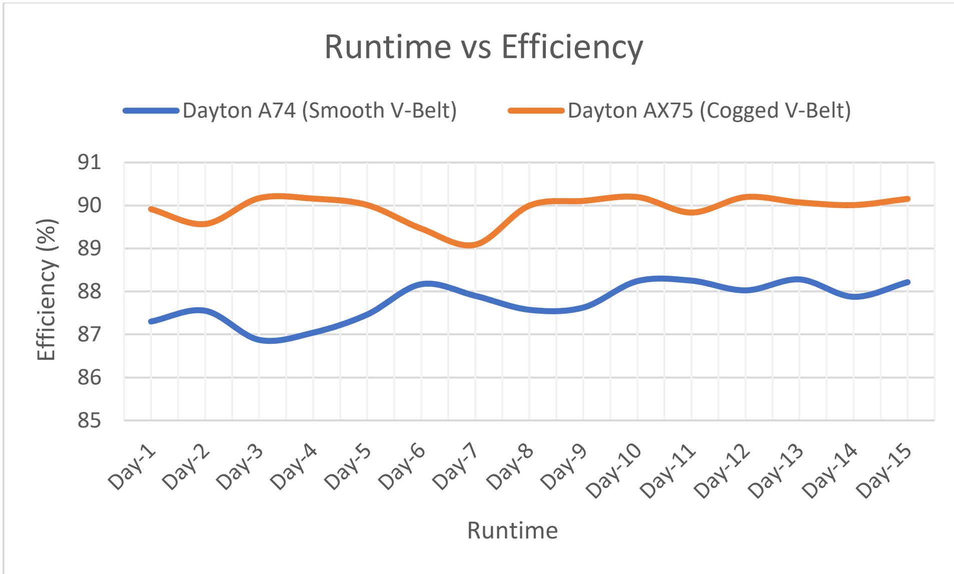

Figure 4.7. Runtime vs Efficiency for smooth and cogged v-belt with 1:1 pulley ratio

4.2 Preliminary results

From the test data in Figures 4.1, 4.2, 4.3, the runtime of each test for observing the impact of hysteresis losses on the efficiency of the system was 30 minutes which is not sufficient. The test data we have wasn't sufficient and reliable enough to estimate the difference. But we can say, as the diameter of the pulley decreases, the efficiency of the system equipped with cogged v-belt increases over the system with a smooth v-belt.

From the test data in Figures 4.5, the runtime of each test for observing the impact of frictional losses and speed losses on the efficiency of the system was 6 hours which is also not sufficient enough as we said before. But we can say, as tension in the belt drops the efficiency of the system with the cogged v-belt drop is minimal over the efficiency of the system with a smooth v-belt.

From the test data in Figures 4.7, the runtime of each test for observing the impact of frictional, slip, and creep losses on the efficiency of the system was 15 days which is also not sufficient enough for the system to stabilize and acquire reliable data as we said before but we started to see the effect of losses on the efficiency after 10 days of runtime and realized that we need a minimum of 30-day runtime to stabilize the system and acquire a reliable data. We can also say that as the runtime increases the efficiency of the system with a cogged v-belt is over 2% the efficiency of the system with a smooth v-belt.

The above results show the feasibility of measuring the various parameters that affect the performance of smooth V-belts vs a cogged V-belt drive. Based on the test data from the preliminary analysis, we cannot explicitly formulate the efficiency gain in the system equipped with a cogged v-belt over the smooth v-belt due to the impact of torque and speed losses because of the runtime of the tests opted and lack of additional test data. As the creep, slip, and tension in the belt are time-dependent, an increase in the runtime of the tests helps the system to stabilize and acquire reliable data. The plan for running these tests for longer durations is provided in the next section “Ongoing Work”.

4.3 Ongoing Work

Based on the parameters used and test data acquired during this preliminary study, the following work helps to formulate the efficiency gain in the system equipped with a cogged v-belt over the smooth v-belt due to the impact of torque and speed losses.

1. Effect of pulley diameter

Two different pulley diameter ratios 1:1 & 2:1 (driver: driven) combinations are required to observe and understand the impact on the efficiency of the system. The S20W-130 Mecc Altee generator in the test bench cannot produce amperage below 2,800 RPM. Due to the limitations we have, the pulley diameter of the generator shaft should be a smaller size for all the tests. The period for each test to carry out all the pulley diameters will be 30-days.

2. Effect of belt tension

The tests with belt tensions 6, 5.5, 5, 4.5, 4, 3.5, 3, 2.5, 2, 1.5, 1, 0.5 pounds for 1 day each are required to quantify the efficiency change.

3. Effect of runtime

The impact of frictional, slip and creep losses on the efficiency of the system can be observed with runtime without re-tensioning the belt during the test period. The runtime for each test without re-tensioning the belt will be 30-days.

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