The development of an electronic system to continually monitor, indicate and control, ‘belt slippage’ in industrial friction ‘V’ belt drive transmission systems

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Abstract. Belts have been used for centuries as a mechanism to transfer power from some form of drive system to a variety of load systems. Within industry today, many designs of belts but particularly friction, trapezoidal shaped ‘V’ belts are used and generally transfer power generated by electrical motors to numerous forms of driven load systems. It is suggested that belt systems, through their simplicity are sadly neglected by maintenance functions and generally are left unattended until high degrees of ‘belt slippage’ through loss of friction or ‘belt breakage’ provokes maintenance attention. These circumstances are most often identified through the reduced or loss of manufacturing production or the occurrence of catastrophic circumstances such as fire caused through excessive friction/ high belt slippage conditions. Obviously, these situations incur financial losses to companies and in some cases the near loss of the company’s main manufacturing plant. Consequently, a satisfactory, viable solution is currently sought by industry to improve on current labour intensive maintenance practices. This paper will present an account of the development of an industrially robust, accurate and repeatable electronic system which continually monitors and indicates the degree of ‘slippage’ in a ‘V’ belt drive transmission system and in the circumstance of belt breakage or high belt slippage will enable and control the switching off the drive motor.

1. Introduction
Friction drive systems have been used as a mechanism to transfer the power developed by a drive system to a load system for centuries. Even today, in a diversity of industries, the power developed by a drive system is transferred to a load system in a variety of configurations by belt drives. Commonly, the type of belt used has a ‘V’ shaped, trapezoidal cross section, yet belts with other cross sectional shapes are also used. These can be flat, notched, multiple ‘V’ and others.

The use of belts is considered to be an economically cheap method of connecting the two transmission elements together. Additionally, one drive system, through the use of a common drive shaft can transfer power to several load systems. Belt drives also offer a significant benefit to systems which present high inertial loads when starting. In these circumstances, the belts naturally ‘slip’ on the drive or load pulley’s and this phenomenon acts as a fault release mechanism avoiding damage to more rigid mechanical parts of the transmission system.

When belts are newly installed considerable care is usually taken to align the drive and load pulleys so that frictional forces derived between the belts and the pulleys are maximised. Additionally, the distance between the two pulleys is accurately set so that the tension of the belt aids the belt to
satisfactorily apply the frictional force. Logically, if the belt tension is below the required value i.e. ‘slack’, then unreasonable amounts of belt slippage will occur. Alternatively, if the belt tension is above the required value i.e. ‘tight’, then wear of the belts and the rims of the pulleys, the ‘sheaves’, relative to time is increased.

Understandably in use, the belts and the pulley sheaves will wear naturally, to the point where the phenomenon of belt slip occurs abnormally. In this circumstance it is reasonable to propose that the power developed by the drive is not efficiently transferred to the load. So, the efficiency of the power shift mechanism starts to reduce from the recognised initial figure of 98% and can reduce to 95-94%[1].

Given the size and quantity of belt transmission systems in place in manufacturing industry, the energy, man-power, production losses, environmental and general business implications due to belt slippage and belt breakage is proposed to be considerable. The system described subsequently, aims to present an accurate method for dynamically monitoring friction belt drive systems for the phenomena of belt slippage and breakage and alert personnel to these circumstances.

2. Current belt slippage detection techniques and condition monitoring

Methods to detect belt slippage are proposed to be very labour intensive. Real time methods include the use of an infra red camera to identify increased belt and pulley temperatures due to belt slip. Additionally, a stroboscope or tachometer can be used to first determine the rotational speed of each pulley from which a figure of differential speed can be derived, indicative of belt slip. However, the data acquisition time period of these methods are considered to be slow relative to the change in load and are rendered impossible to use if the belts are fully enclosed in a metal guard.

![Infra red heat detection](image1.jpg) ![Manual Inspection](image2.jpg)

![Stroboscope/Tachometer](image3.jpg) ![Belt breakage](image4.jpg)

**Figure 1.** Current V-belt slippage detection methods and condition monitoring.

Generally, belts systems are manually inspected, logically with the system at stand still. Here attributes such as belt tension, alignment, and condition as well as pulley condition are established using a variety of meters and gauges and then rectified if found abnormal. In some cases, maintenance of the belts is left unattended until the belts actually break. Subsequently, the belts are changed, however the underlying large cost overhead is often overlooked as with both of these steady state methods, costs in manpower, capital costs and production down time can be significant.
3. The need for an automatic belt slippage monitoring system

The need for an automatic belt slippage detection system was first brought to the attention of the author by personnel at the research establishment of a large pharmaceutical company. Here, they were experiencing problems with temperature control of long time period experiments where belt driven fans were used to supply and extract air. The fans were located in cellars or in roof spaces and were totally enclosed in acoustic hoods. Furthermore, they were seldom visited so consequently, the personnel only became aware of belt problems when the monitored temperature of the experiment fluctuated dramatically, ruining the long standing study and incurring a large cost overhead.

Given the authors steel industry background this triggered recollections of problems encountered on fan systems using belt drives in various parts of the steel production process. Here identification of the belts slipping frantically or the belts having broken was only identified by personnel when the particular associated process parameter exhibited abnormal measured values.

These two instances indicated to the author that a need for a system to solve the problem and improve numerous process efficiencies was justified.

4. System overview

The system functions and conforms to the assumption that any differential radial speed component is a consequence of belt slip phenomena.

So, by monitoring the radial speed of the drive and that of the load and deriving a figure for the differential speed, belt slip can be identified. Hence, consider equation (1), which describes the transmission system under a zero slip circumstance.

\[ n_{drive} - an_{load} = 0 \]  \hspace{1cm} (1)

Where, \( n \) = radial pulley speed (radians/sec)
\( a= \) diameter of drive pulley
diameter of load pulley

Alternatively, for a circumstance where a transmission system is exhibiting slip phenomena, equation (2) applies

\[ n_{drive} - an_{load} \neq 0 \]  \hspace{1cm} (2)

5. System apparatus

A block diagram of the system is shown in Figure 2 (a) and a picture of the ‘bench top’ feasibility prototype system is shown in Figure 2 (b)

(a) Block diagram of belt slip monitoring system.  \hspace{1cm} (b) ‘Bench top’ feasibility prototype system.

Figure 2. System apparatus.
Sensors are positioned to monitor the outer rim of each pulley and to detect the transition of reference points. On detection of a reference point, each signal is formatted and then applied to separate inputs of a microcontroller, an electronic ‘chip’ which, through a ‘real time’ software algorithm determines the speed of the drive and the load relative to the cyclic program speed of the microcontroller.

6. System software
The microcontroller operates with a 40MHz clock rate and has a CPU instruction time of 10MHz. The microcontroller program cycle time period was measured at 12µSecs and is structured in a modal form with five modes, which equates to a mode time period of 2.4 µSecs. Each mode is structured with several states which are conditional relative to phenomena in real time. Consequently, if a state is satisfied it will be acted upon yet if not the state will be overlooked and the next mode will be actioned. In essence this is similar to conventional real time, ‘time slicing’.

Now, when the microcontroller is triggered with a positive going transition edge signal from a sensor, the number of program cycle periods are counted until the next positive transition edge is detected. The total number of program cycle counts between the transition edge instances is directly proportional to the radial speed of the pulley. Subsequently, the number of program cycle counts for the drive and load are compared and a figure derived for the difference, which is, if other than zero, assumed to be accountable to belt slip.

7. Industrial trials
Industrial prototype monitoring systems were installed and configured to capture data representative of pulley speed on numerous V belt transmission systems in a range of manufacturing industries. Two of the prototypes were assigned to systems driving Archimedes screws located within a sewage treatment works of a large water company (Figure 3). The function of the screw ‘pump’ is to pull raw sewage up from a holding sump in to sewage treatments beds. The transmission systems comprised an 110kW ac induction drive motor and a gear box load, which were connected using 4 parallel V belts.

![Archimedes Screws](image1)

![No. 1 Screw, V Belt Prototype V belt Monitoring System.](image2)

Figure 3. Industrial trials, Caldervale Sewage Treatment Works, Wakefield, UK.

A third prototype system was installed on a waste gas fan belt drive system located within a large steel mill (Figure 4). The fan system comprised of an 90kW ac induction drive motor coupled to the fan using 5 parallel V belts. The function of the fan was to extract waste gases from a large steel billet reheating furnace.
Further prototype systems were installed on a dust extraction fan within a cardboard manufacturing process (30kW motor), on air cooling fans within a glass bottle manufacturing process (110kW motors), a slurry pump within a sand quarrying process (90kW motor), and also on a carbon mixer in an aluminium smelting, anode forming process (160kW motor).

8. Results
The following figures present data captured from the two prototype systems monitoring the Archimedes screws at the Caldervale Sewage Treatment Works, Wakefield and the billet mill waste gas fan at Stocksbridge Steel Works, Sheffield. Each prototype system was most similar in hardware and software configuration.

![Figure 4](image1.png)

**Figure 4.** Industrial trials, Tata Steel, Stocksbridge, Sheffield, UK.

Figure 5 (a) indicates the dynamic nature of belt slippage occurring in screw No. 1 (Top) and screw No. 3 (Bottom). The time period of data capture was approximately eight days over the Christmas period, 2008. Good correlation is exhibited between each data set and also to the flow through the plant which is shown in Figure 5(b).
Figure 6, presents data representing belt slippage (Bottom) and motor current (Top) in the waste gas fan system. Again good correlation is upheld between the two data sets. Data was captured over a time period of three days.

Real time belt slip data was recorded and presented as a function of the number of microcontroller program scan counts as previously discussed. This was accomplished with the use of a data logging device and latterly via an array of coloured, illuminating LED’s positioned on the front of the monitoring system.

![Figure 6. Data representing belt slip (Bottom) and motor current (Top) – Billet Mill Waste Gas Fan, Tata Steel Stocksbridge, Sheffield, UK.](image)

9. **Key findings**

The industrial trials of the prototype system carried out at numerous sites were conducted over a period of approximately 12 months and indicated that the design of the monitoring unit and sensors presented a very robust, accurate and repeatable system for measuring and presenting a measurement of belt slip, the radial speed of the drive and load and also the operational state of the transmission system, i.e. stopped, running, belts broken or sensor fault.

Collectively, the industrial prototype presented a localised monitoring system, however engineers requested remote access to the data, so a current transmitter (4/20mA) and wireless technology was appended to the system allowing the data to be observed on asset management systems located at a central location.

Engineers also asked for the data to be presented in a more understandable, explicit format. Consequently, belt slip data was dimensioned as a percentage of drive speed in line with belt manufacturer’s specifications [2] and derived using the following equations.

\[
\% \text{ belt slip} = \left( \frac{\text{calculated load speed}}{\text{actual drive speed}} \right) \times 100
\]

(3)

Where

\[
\text{calculated load speed} = \frac{\text{actual load speed}}{\text{pulley ratio}}
\]

(4)

So, what does a percentage degree of belt slip represent in real engineering terms? What is an acceptable and unacceptable amount of belt slippage?

10. **Relative degree of belt slip an engineering perspective**

Much of friction belt drive literature presents figures for the efficiency of the variety of belts and it is accepted that when newly installed and tensioned that the belts are 98% efficient [1].

- What does this figure actually mean?
- What factors constitute the 2% loss in efficiency?
- How has this figure been determined?
- Is it correct to assume that the 2% loss is due to belt slip?
To give some insight into these conundrums and to try to set a datum to define an absolute value for a degree of belt slip, data from all of the trial systems was scrutinised (41 trials). Figure 7 presents data with the largest amount of variance in the percentage of belt slippage. The data was obtained from an inter stage screw pump located within a sewage treatment works. Here the trial system was installed when the belts and pulleys had been in use for some time. When inspected, the belts and pulleys were judged to be worn and the belts required tensioning having a large amount of axial movement. The data of Figure 7, indicates that belt slippage was cyclic in manner again correlating with the cyclic load nature of the sewage treatment process and the maximum belt slip was measured at 3.8%.

![Graph indicating belt slippage - Inter stage screw pump](image1)

![Sewage treatment inter stage screw pump (30kW drive)](image2)

**Figure 7.** Image of sewage treatment inter stage screw pump and V belt slippage data.

Further unverifiable laboratory tests, were undertaken on a test rig comprising a 2kW ac inverter fed induction motor running at 1500 rpm, driving a centrifugal fan unit using a single V-belt, the fan presenting a constant load to the system. Belt slippage was induced by repositioning the drive motor by incrementally moving the motor towards the fan load via a worm screw mechanism. The maximum amount of slippage obtained was approximately 4%. At this point the belts were wildly flapping and further adjustment of the screw mechanism caused the fan to stop rotating with the belt slipping on the motor drive pulley.

Given these results and observations correlated to percentage slip measurements, it is reasonable to adopt in the first instant the following scale (Table 1) of percentage degree of belt slip relative to the need for engineering attention based on belt action/condition. Tests are ongoing at this time to give further insight and accuracy to this data set.

**Table 1.** Table of data representing percentage degree of belt slip relative to the need for engineering attention based on belt action/condition.

| Belt Slippage (%) | Belt Action | Engineering Need                      |
|-------------------|-------------|---------------------------------------|
| 0 - 1.5           | OK          | None, belts OK                        |
| 1.5 – 3           | Flapping – some audible distress | Required, start to schedule maintenance |
| 3 - 4.5           | Flapping Wildly – much audible distress | Urgent – possible belt breakage. |

11. **Commercial prototype system**

Based on the success of the trials of the industrial prototype system, a range of commercial prototypes was presented to the market in September 2010 (Figure 8).
The range of systems, presented under the trade banner, SENSSLIP® subdivided the possible benefits of the system identified by the industrial trials and presented a monitoring system based on each case,

- SENSSLIP® ENERGY – Presenting an indication of energy wastage.
- SENSSLIP® MAINTENANCE - Presenting a need for belt/pulley/general transmission maintenance.
- SENSSLIP® CRITICAL - Health and safety – Controlling belt slip and averting catastrophic circumstances due to high slip circumstances and belt breakage by switching the drive motor OFF.

12. Market up-take
At the time of writing, in the 16 months since introducing the product to the market the up-take has been slow but positive based on the potential benefits offered by the commercial prototype unit. Currently a new commercial product is being developed based on market demand identified when installing, servicing and using the commercial prototype, principal among these being the requirement for the system to be certified as ATEX compliant.

A major starch manufacturer experienced a costly process ‘back up’ due to belts breaking on a critical piece of machinery, located in a restricted access, ATEX zone. Subsequently, the system has been fitted with ATEX intrinsically safe sensors within the zone.

13. Conclusions
- Given that the difference in radial speed of the drive and load is accountable to belt slippage then the results indicate that the developed V-belt monitoring system is very accurate at measuring this phenomenon.
- The system is robust, repeatable and capable of logging the difference in radial speed of the drive and the load over a long time periods and therefore is capable of indicating when belt slippage phenomenon becomes excessive and hence can present to some degree the need for maintenance action on the system.
- The system can accurately determine the running state of a transmission system and present this with belt slip data locally and remotely.
- Since a lot of transmission systems are located in inaccessible places and are often obscured from view then the use of the system is proposed to be a necessity.
- Additionally, since belt drive systems are potentially dangerous, then the system alleviates, to a great degree, the need to expose personnel to hazards when working near, on or monitoring the performance of the systems.
References

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