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State-of-the-Art Data Acquisition Equipment and Field Measurement Techniques for Conveyor Belts

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Accurate field measurements are essential when validating a conveyor design. They are fundamental in determining a conveyor's behavior, its long-term maintenance requirements, and the life expectancy/ condition of the installed equipment. Field measurements are also invaluable in forensic engineering, particularly when vital equipment has failed. This paper will discuss a wide variety of data acquisition equipment, field measurement techniques and accuracies achieved. State-of-the-art, custom designed monitoring equipment, as well as, "off-the-shelf" instruments and sensors, will be discussed.

INTRODUCTION

The primary reasons for obtaining field measurements on belt conveyors are

1. Validation of equipment and performance during commissioning
2. Forensic engineering
3. Verification and accuracy of the theoretical design calculations
4. Condition monitoring.

Of the foregoing reasons, the first is by far the most crucial. Unfortunately, it is also the most overlooked! In many cases the client is assured that the conveyor is operating within the design specifications, and there is no reason to believe otherwise. The conveyor appears to start and stop without any problems. The fluid couplings, brakes, holdbacks, and/or other equipment all appear to be operating normally. The conveyor reaches, or exceeds the design capacity. So why would there be any reason to take field measurements?

The reasons for obtaining field measurements during commissioning are simple. It validates the design of the conveyor, ensures that the control logic has been properly implemented, and verifies that all of the critical equipment is functioning properly. Just because the system is running at full capacity does not necessary imply that the system is functioning within the design parameters. What are the actual forces being imparted on the system? What is the real motor torque transmitted through the gearboxes and shafts. Are the brakes applying the rated torque? Is the drive base installed properly such that the bending stresses in the shafts are acceptable? Are there any anomalous shockwaves or dynamic effects during starting or stopping? As this paper will demonstrate, what *appears* to be happening with a particular system and what is *really* happening can be two very different things.

By obtaining a complete set of field measurements on a conveyor system during commissioning, a documented record exists that unequivocally shows the operating state of the system. In many cases these measurements detect areas of excessive wear, incorrect control logic, or malfunctioning equipment that may result in future failure of critical system components. It is much easier to solve a problem at the beginning than to try and determine the root cause once a failure has occurred.

This leads to the second reason for obtaining field measurements, which is forensic engineering. A drive, gearbox, bearing, holdback, coupling, pulley, or perhaps a combination of the above, has failed and now the question is why? Were the design tensions within acceptable limits? Was there a problem with the starting or stopping control logic? Or perhaps a conveyor that has been operating normally for 6 months fails to stop when a rare decline loading condition occurs. This in turn has caused excessive material buildup at a transfer point resulting in damage to the belt, transfer assembly, and pulleys. Now the braking system or PLC control logic may be the focus of investigation.

Forensic engineering is a fascinating topic. It is often equipment failures which force us to re-think our current theories and expand our ideas for new and improved solutions.

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The third reason for field measurements, validation of our theoretical models, is invaluable to the design engineer. Once the field measurements have been made, and the system is operating as expected, is it behaving as predicted? How accurate is the design theory? Is the dynamic response of the conveyor akin to the theoretical design calculations? Is the belt tracking in the horizontal curves as anticipated? Has the new low-rolling resistance belting compound reduced the conveyors' power consumption? Theoretical conveyor engineering software, and calculation methods, must be validated to ensure the system reliability and accuracy. Accurate field measurements have allowed us to push the limits for current conveyor designs and have paved the road for future projects.

FIELD MEASUREMENT EQUIPMENT AND TECHNIQUES

The following sections will highlight some of the most common, as well as the most unique, equipment currently used to conduct a variety of field measurements on belt conveyors. A description of each measurement will be presented, as well as supporting field data.

Data Acquisition System

The most universal piece of equipment used for all field measurements is the data acquisition recorder. This device digitizes the analog input signals, which can then be stored on a notebook computer or directly printed out. There is a wide variety of this type of device currently available, many capable of recording over 128 channels of continuous data at sampling rates above 1 kHz (1 ms). Sample rates depend on the item being measured and the desired accuracy of the results. High sampling rates are required to adequately capture starting/stopping torque spikes, holdback impact loads, and vibration measurements. Low sampling rates are used for recording long-term measurements such as weight scales, temperature, and motor power.

The latest advancement in data acquisition systems is not in the hardware but in the software. Many systems now offer Internet-ready solutions. These setups allow users to monitor and record data via the Internet (and thus anywhere around the world). These types of systems are becoming more and more commonplace as technology continues to march forward.

Conveyor Power and Motor Torque

Accurate power measurements are required to confirm theoretical design calculations. In general, there are three common methods for measuring conveyor power.

The first method to measure motor power is by monitoring the motor RPM. Using this, in conjunction with the motor power slip curve, the approximate power can be estimated. This method, however, is only applicable to specific drives types (for example, it cannot be used for variable frequency drives). Furthermore, it is only accurate for measuring steady-state running power consumption.

The second method for measuring motor power is by using a power transducer (wattmeter). A power transducer measures all the current and voltage going into a drive system. This can then be converted to a motor power. When properly calibrated, these devices can give accurate readings for steady-state operations. However, there are various types of wattmeters, some far more accurate than others. Some systems only measure one phase of the motor current. This arrangement cannot calculate the power factor (or phase lag) of the system, and therefore can be off 5%–10% from the start. More accurate wattmeters monitor all input lines and internally calculate the resulting power factor. This results in a much more accurate reading (1%–3%). Unfortunately, the power measured in this manner still includes losses in the motors, gearboxes, and fluid couplings, as well as other losses. An engineering guess must therefore be made as to the exact losses of each of these components in order to determine the **exact** power consumed by the conveyor belt itself. Additionally, the resulting output signals from these devices tend to filter and "smooth" the real data, masking high frequency and damaging impact loads that can often be the root cause of gearbox and coupling failures.

Although the above methods allow the motor power to be calculated, neither supplies any information whatsoever about the braking forces, coupling and gearbox loads, or holdback torques. This is where the true beauty of the third, and most accurate, method for measuring conveyor power comes into play. By applying strain gauges on the pulley shafts themselves, the deflection of the shaft can be measured. This is a direct result of the applied motor torque and contains the precise loads, which are transmitted through the entire system.

Figure 1 shows the equipment and setup for acquiring torque measurements. Strain gauges are mounted on the gearbox and/or pulley shaft. The strain gauges are applied in such a fashion as to negate all bending and longitudinal forces, thereby resulting in a pure torsional measurement. Due to the shaft's rotation, wires cannot be directly connected from the data acquisition equipment to these gauges. Instead, either slip rings or wireless methods must be used. Slip rings are typically unacceptable for this type of application as they produce excessive noise, and the physical geometry of the system does not warrant their installation. Wireless methods have proven to be accurate, acceptable, and very reliable.

A small battery-powered transmitter and transmitting antenna is mounted on the rotating shaft. The transmitter functions as both the power supply and amplifier for the strain gauge bridge mounted on the shaft. The transmitter converts the strain gauge output into a pulse modulated FM signal. This signal is then transmitted to a stationary receiving antenna fixed around the outside of the shaft. This antenna is connected to a receiver unit, which converts the FM signal back into a DC voltage. Finally, the voltage is recorded by the data acquisition system.

Figure 2 shows a typical result of torque measurements from a wound rotor motor startup. The holdback and steady-state torques are shown. Each of the 25 resistor steps and their corresponding firing sequences can be easily identified. This graph clearly, and accurately, shows the actual forces that are being transmitted for the motors, through the gearboxes and couplings, and into the drive pulleys. The accuracy and resolution of direct torque measurements greatly exceeds that of most current transducers and also includes brake and holdback loadings interactions.

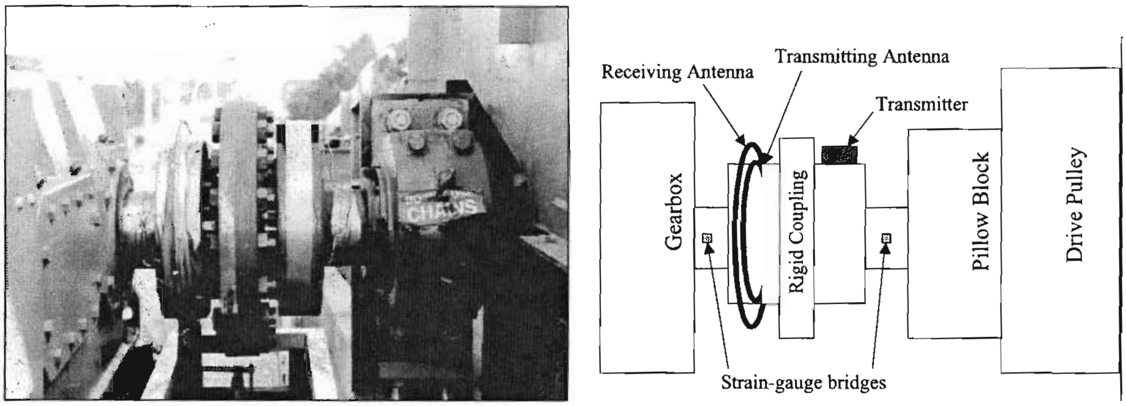

FIGURE 1 Strain gauge assembly used to measure shaft torque and conveyor power

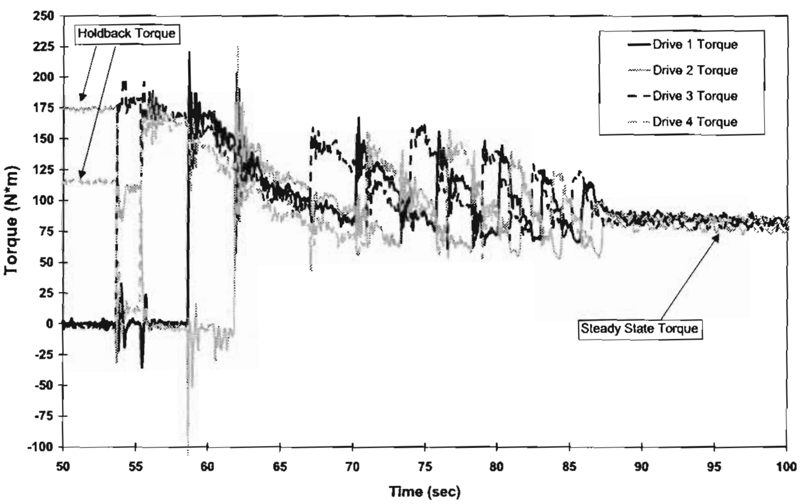

FIGURE 2 Torque measurements for a wound rotor motor startup

Figure 3 shows another startup torque curve acquired via torque measurements. This figure is particularly interesting since two independent companies obtained the measurements. This specific job required over twenty telemetry signals to be acquired at various shaft locations, and several drives simultaneously. CDI worked together with WBM Consulting Engineers in Australia to provide enough equipment to perform the required measurements. On one particular drive, both CDI and WBM recorded the shaft torque. This data is shown in Figure 3. It should be noted that each party worked separately from one another. The strain gauges, telemetry gear, preparation methods, and calibration procedures were specific to each company. However, the resulting measurements are within 2% of the motor nameplate ratings of one another. This clearly demonstrates that accurate, reliable, and repeatable results can be obtained from these types of measurements.

Figure 4 shows the results from a fast Fourier transform (FFT) performed on a steady-state torque signal. This system consisted of a squirrel cage motor, fluid coupling, gearbox, and drive pulley. A strain-gauge bridge was mounted on the shaft between the gearbox and drive pulley. The x-axis of Figure 4 has been converted from a frequency spectrum to an equivalent shaft RPM speed. In this case, the high-frequency torque components from the fluid coupling were transmitted through the gearbox to the pulley shaft. These frequency components allowed the slip across the fluid couplings to be calculated. Furthermore, by knowing the motor RPM, the torque could be back-calculated from the motor slip curve. This torque agreed within 3% of the actual measured torque. Additionally, the pulley shaft RPM was clearly present, and the conveyor velocity could be calculated. The remaining frequency spikes correlate to the gearbox reduction steps and their higher harmonics. Although each of these components can be calculated individually, they demonstrate the accuracy of the torque measurements.

Brake Torque

Brake torque measurements are required to verify that the brake system is performing in accordance to the manufacturer and design specifications. Brake torque is measured using the same techniques as motor torque. A typical arrangement for measuring brake torque is shown

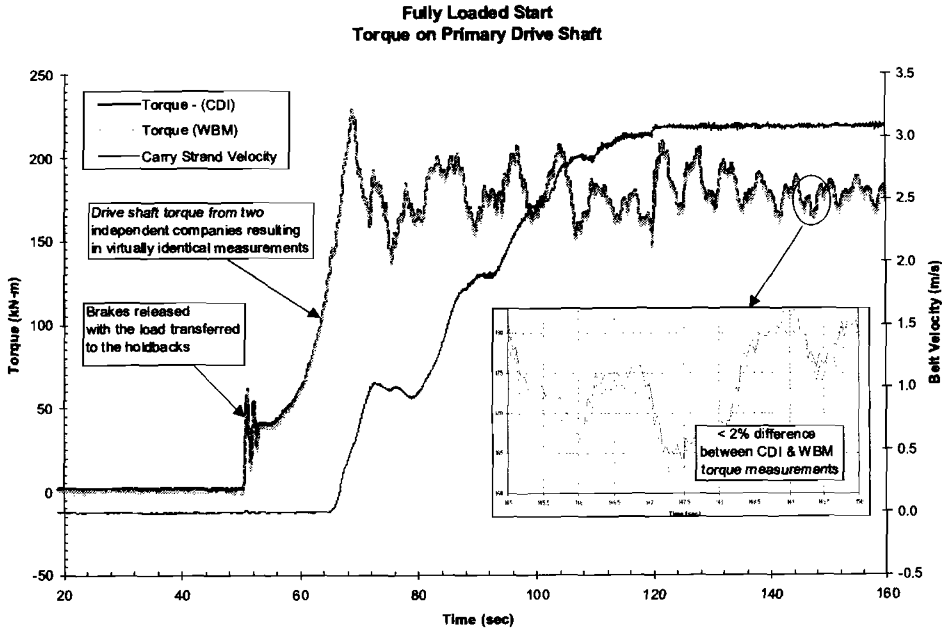

FIGURE 3 Independent measurements by CDI and WBM are within 2% of each other

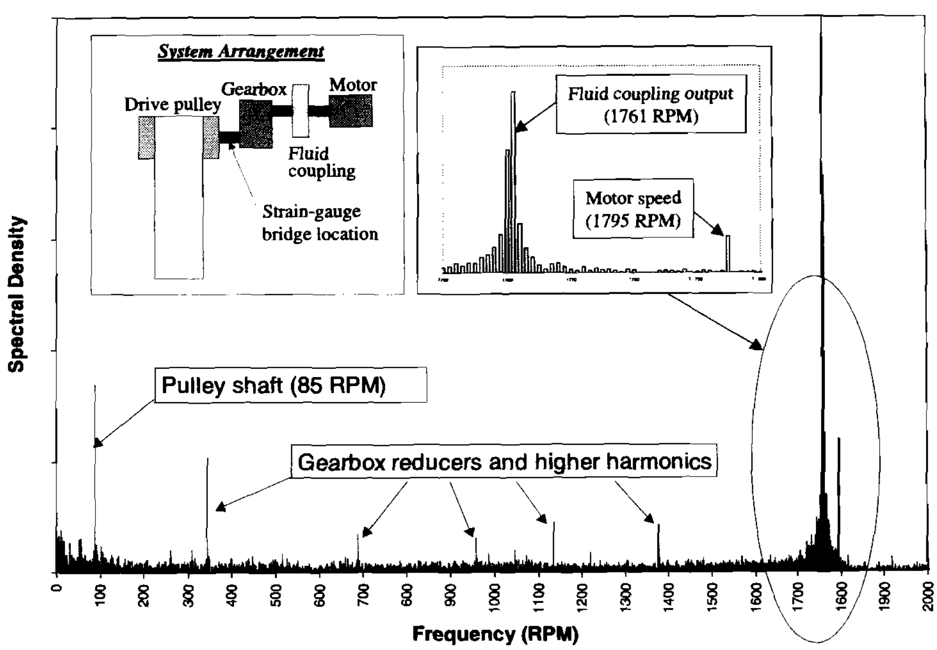

FIGURE 4 FFT on a raw torque signal shows fluid coupling slip and other information

in Figure 5. For this decline conveyor system, the brake is located between the output shaft of the gearbox and the conveyor's tail pulley. Although only one side of the disk brake is shown, both sides have been instrumented with strain-gauge bridges. This allowed each torque component to be determined separately. These components can then be subtracted from one another to determine the resulting brake torque.

Figure 6 shows the brake torque during an operation stop. The stop is initiated 6 seconds into the test. Prior to that time, the conveyor power is regenerative and running at steady state. During steady state, the two torque signals (which are on different shaft diameters and wall thickness) are within 2% variation of each other. At 6 seconds, the brake is applied. Part of the braking torque is utilized to stop the conveyor while the

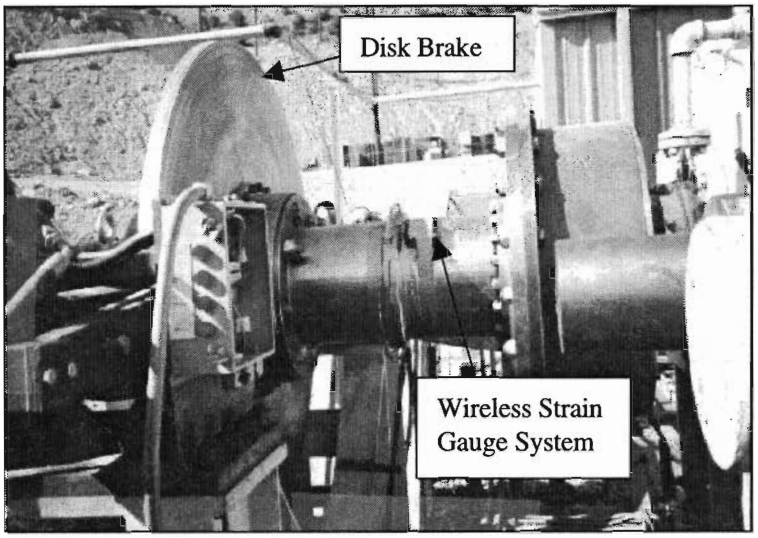

FIGURE 5 Torque measurements on disk brake

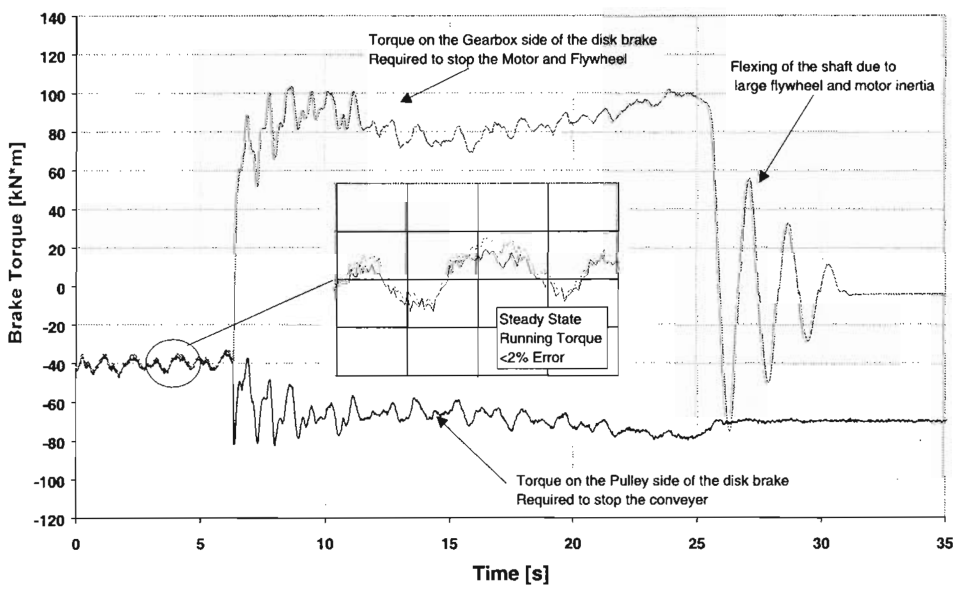

FIGURE 6 Torque measured on each side of disk brake during an emergency stop

rest is used to stop the motor and flywheel (which was required on this conveyor for dynamic control reasons).

The overall error in of the torque measurement is determined by the errors made of the speed measurements (<1%), the torque measurements (<2%), and the parameters of the shaft material (<2%). This results in a maximum overall error of 5%, and on average more likely to be within 2%–3%.

Shaft Bending Moments

Excessive bending moments in shafts can cause premature failures of the bearings, pulleys, and couplings, as well as the shafts themselves. Misalignment errors, manufacturing errors, and overconstraint of the drive/gearbox assemblies can result in excessively high bending stresses. Accurate bending measurements are often critical in forensic engineering when determining why a coupling and bearing has failed and can prevent the failure from reoccurring.

The procedure for measuring shaft bending is very similar to torque measurements. For bending, however, the strain gauges are mounted such that only the bending component is measured. Figure 7 shows the bending moments on a primary drive shaft during a fully loaded start. In this case, there have been two sets of bending bridges applied to the shaft. One bridge is located at 0 / 180 degrees (top and bottom) while the other is located at 90 / 270 degrees (right and left sides). If the resulting bending moment is not exactly parallel

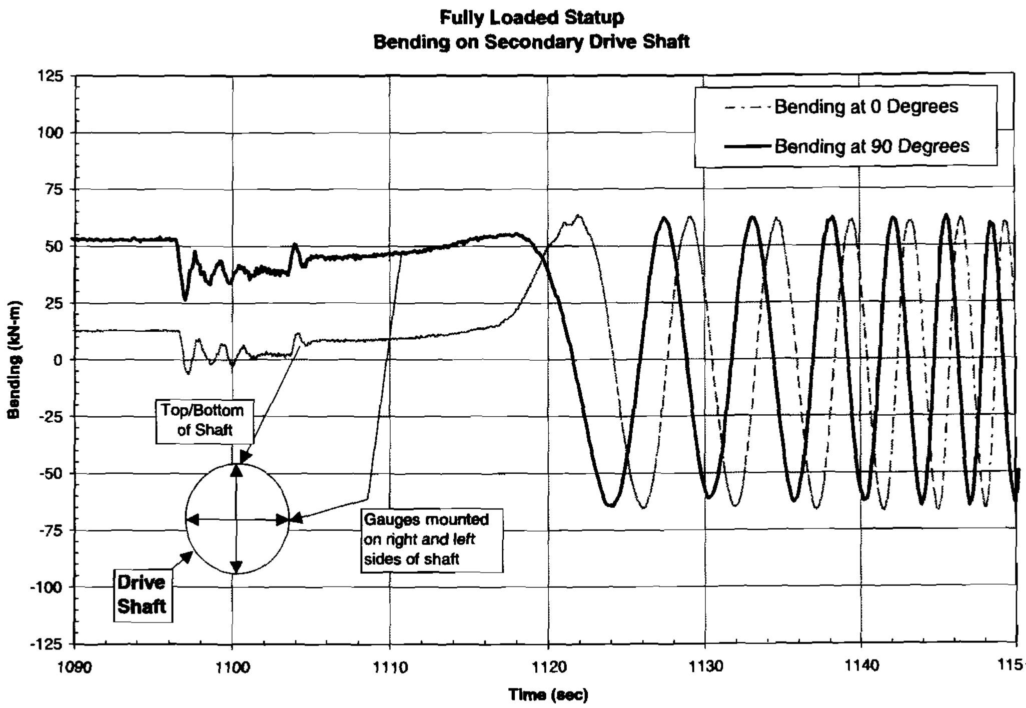

FIGURE 7 Bend measurements taken at 0 and 90 degrees on a pulley drive shaft

with the axis of the shaft, then the magnitude of one of the signals will be slightly greater than the other.

As the conveyor starts, the bending stresses fluctuate due to the shaft's rotation, motor torque, and overhung loads. As the conveyor reaches steady-state operation, the expected cyclic stress curve develops. On this conveyor, the magnitudes of the two bending moments are within 3% of each. These stresses were then used as input parameters for a finite element model of the coupling to determine if the existing design was satisfactory.

Take-up Tension and Holdback Loads

The take-up system is often considered the "heart" of the conveyor. Its type (fixed, winch, or gravity), and tension, governs the conveyor design. Without accurate take-up tension information, the belt safety factors, drive tensions ratios, pulley loads, and other crucial design factors cannot be accurately calculated. The take-up system can also be the root cause of many conveyor problems, especially for fixed take-up systems. If the tensions are too high, belt splices, pulleys, and conveyor structure can be damaged. If there is too little tension, drive slippage and material spillage can occur.

The take-up tension can easily be measured by using "off the shelf" calibrated load cells. A load cell is a device that uses strain gauges to measure an applied load. Figure 8 shows a load cell installed on a winch-type take-up system. This allowed the maximum, and minimum, belt tensions to be measured in order to verify that the winch was operating within the specified design limits. On a gravity-type system, the acceleration forces of the counterweight and hysteresis of the take-up system can be determined. Additionally, using the take-up tensions in conjunction with the drive torques allows the user to calculate the drive tension ratios and belt safety factors.

Another use for load cells is to measure holdback torque. In many cases it may be physically impossible to mount strain gauges on a shaft between a holdback and belt pulley. In these cases a load cell can be mounted on the holdback arm. Figure 9 show the holdback torque on an inclined conveyor belt during an aborted start. This particular conveyor was equipped with high-speed brakes that were released once the starting command was initiated. As the brakes were released, the load was transferred through the gearboxes and into the holdbacks. As the motor started, the holdback torque was reduced, and eventually went to zero as the conveyor began to move. At peak motor torque, an emergency stop was initiated, resulting in the transfer of the entire motor torque and conveyor loading to the holdbacks.

Belt Velocity

One of the most fundamental of all field measurements is that of belt velocity. Not only is this measurement necessary to confirm that the conveyor is indeed operating at its design speed, but more importantly to verify the starting and stopping dynamics of the conveyor system. Currently, the two most popular methods for determining conveyor velocity are by using either a magnetic pickup sensor or an optical encoder.

Magnetic pickups require a rotating metal plate or gear tooth from which they received a pick signal or "pulse." These devices may have anywhere from 1–32 pulses per revolution. Although the errors produced from these devices may be acceptable at steady-state velocity, their accuracy, and resolution, is severely diminished at low speeds. Since velocity is often used as a feedback signal to the PLC, when starting and stopping the conveyor, these errors may be significant. For example, a magnetic pickup device with only 16 pulses per revolution,

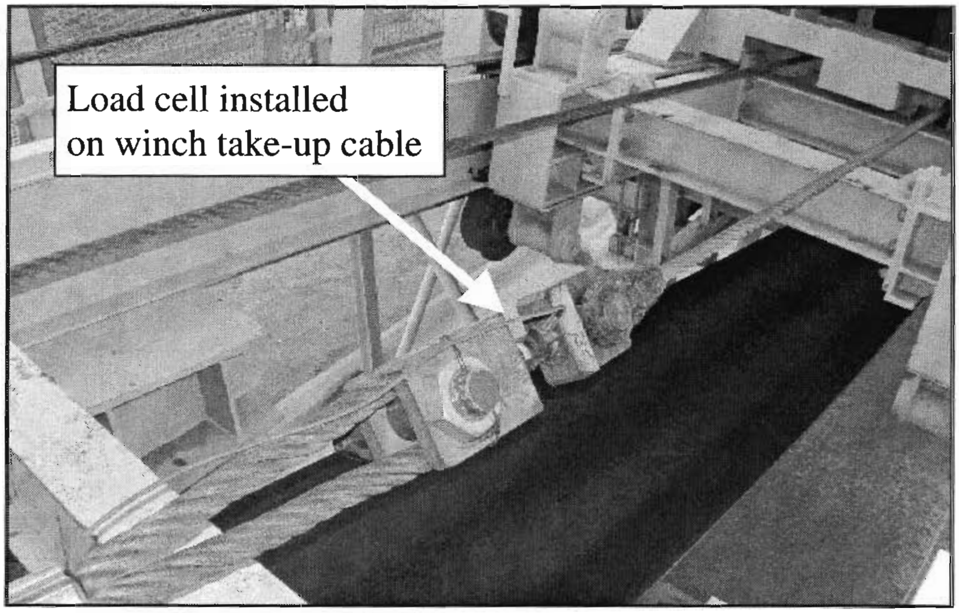

FIGURE 8 Load cell installed on winch take-up system

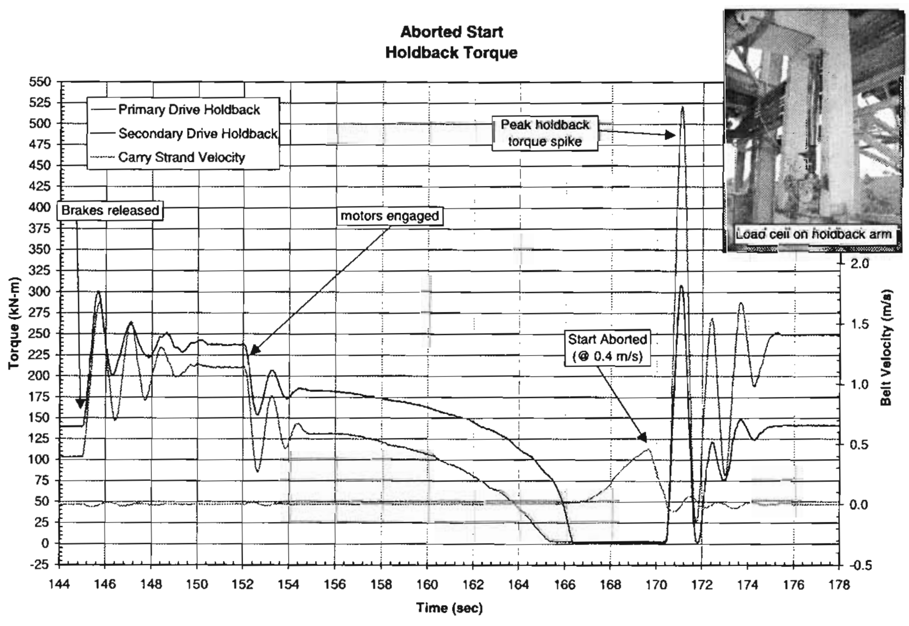

FIGURE 9 Holdback torque measurements taken via load cell mounted on holdback arm

mounted on an 1,800-mm-diameter pulley rotating at 5.6 rad/s (belt speed is 1 m/s) will only produce 1 pulse every 350 ms. Optical encoders, on the other hand, use an etched glass disk, which is rotated through a photo-electric diode. These devices normally contain over 2,000 pulses per revolution. For the example above, an optical encoder and corresponding tachometer mounted on the same system would produce 1 pulse every 3 ms. Furthermore, unlike magnetic pickups, optical encoders output a dual quadrature signal. This allows higher noise rejection, increased accuracy at low speeds, and the ability to infer the rotational direction.

A typical optical encoder setup is shown in Figure 10. An optical encoder and wheel assembly is mounted on a movable aluminum arm and fixed to the structure. The apparatus can be mounted on either the carry or return side of the belt, or on a bend or tail pulley. In this case, two velocity encoder units are used to measure possible belt slippage. One unit is mounted on the belt, and measures the actual (angular) belt speed. The other unit

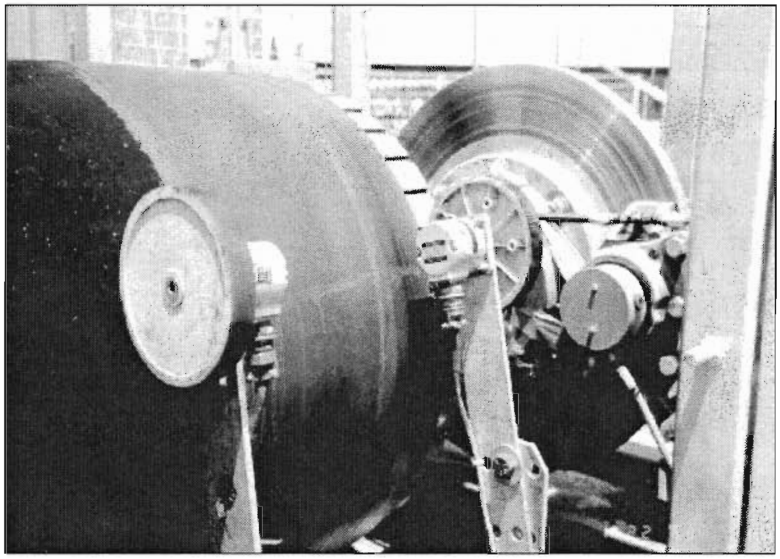

FIGURE 10 Two encoders mounted on a brake pulley to observe potential belt slip

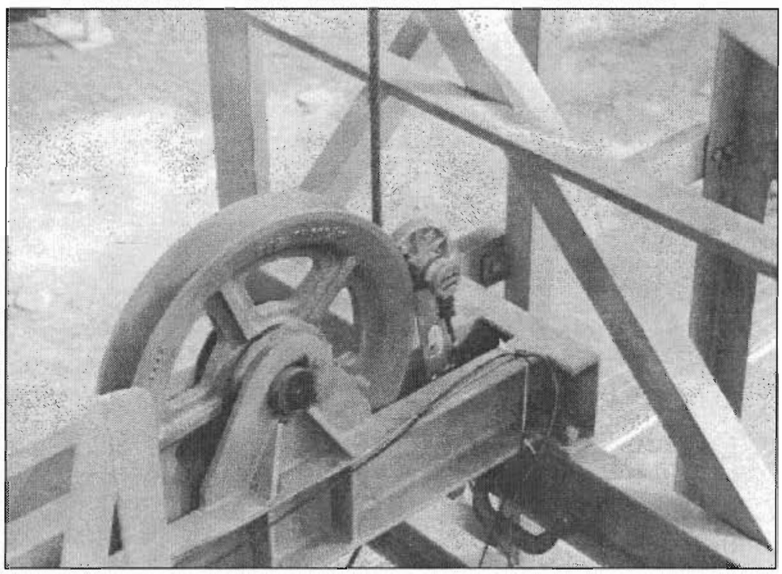

FIGURE 11 Take-up displacement—Optical encoder mounted on take-up sheave

is mounted on the pulley lagging to measure the (angular) pulley speed. Any velocity difference between these two, taking into account the difference in radii, is an indication of belt slip.

Take-up Displacement

Take-up displacement is measured with the same equipment used for measuring conveyor velocity. In this case, however, the dual quadrature signal is summed together to provide an equivalent displacement instead of velocity. A typical displacement apparatus mounted on a take-up sheave is shown in Figure 11. The accuracy of the assembly is approximately ±5 mm over a 1,000-mm displacement range. This is less than 0.5% and well within the desired precision.

Belt Side Travel

Belt side travel measurements are important to conveyors with horizontal curves. In horizontal curve areas, both the carry and return side idlers are banked towards the inside of the curve. As the conveyor is loaded, the belt tensions increase, which causes the belt to "pull" towards the inside of the horizontal curve. As the belt moves inwards, it is also forced upward by the banking angle of the idlers. Gravity counteracts this movement and holds the belt in position. When the belt is empty, the tensions are generally lower and the belt moves to the outside position. Steady-state and dynamic (starting/stopping) measurements are important in order to verify that the installed banking angles are

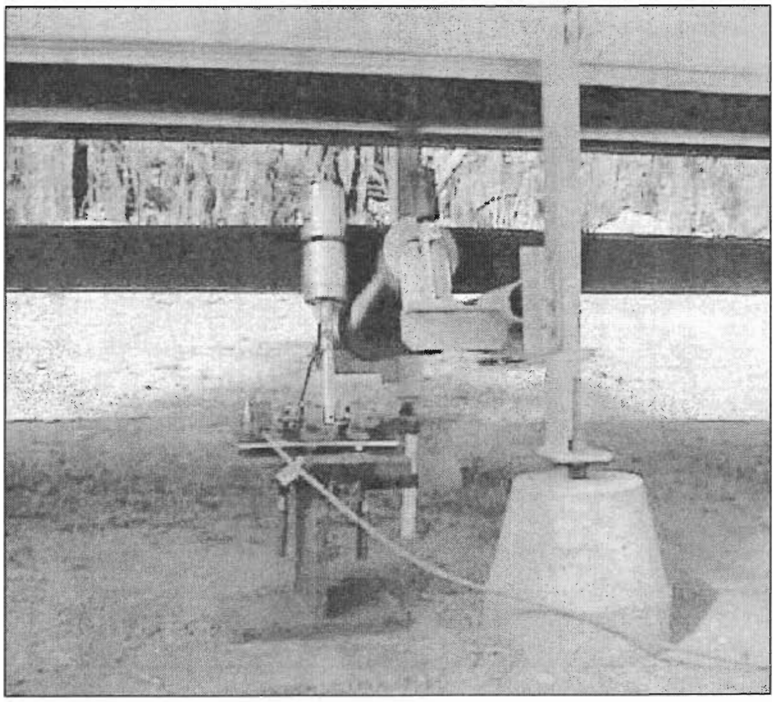

FIGURE 12 Typical side travel measurement setup

adequate, and to verify theoretical models for future conveyor designs. Figure 12 shows a typical side travel measurement setup. Optical encoders are mounted at the pivot point of a movable arm with a side guide roller on one end. The rotation of the optical encoder can be multiplied by the length of the moveable arm to determine the position of the belt.

Side travel measurements are also important in validating the conveyor's factory construction and field splice alignment. Factory and field construction defects are highly repeatable and measurable.

Figure 13 shows the results of side travel measurements taken on a long overland conveyor system. Both the carry and return sides were equipped with side travel measurement devices.

Acoustic Measurements

Acoustic measurements can be of vital importance when designing overland conveyors. In many cases, the conveyor system may travel through, or near, a populated area. It is often extremely useful (and in many cases required) to be able to accurately predict the amount of noise a particular conveyor system will generate. This, however, can also be extremely difficult to theoretically predict. Noise generation is a function of belt speeds, material type and tonnage, idler arrangement, hood cover design, and the structure itself. Fortunately, this is one of the easier measurements to record. A high-quality sound meter can be purchased and usually comes with a calibration device. Measurements can then be made on a variety of conveyor systems, with the data stored in a common database. This database can then be referenced for future conveyor designs. Figure 14 shows the results of various acoustic measurements on an overland conveyor. This particular conveyor has variable frequency drives that allows the system to run at a range of belt speeds. Sound measurements were recorded at preset distances from the conveyor.

Other Measurements

Although the above list encompasses some of the major measurement equipment used in the conveyor industry, there are still several other items worth mentioning. Weight scale readings, temperature measurements, and an assortment of PLC control signals are but a few of the additional items that must be recorded in order to get a complete and accurate representation of the conveyor system. This information is then combined with other measurements in order to understand the complete operational behavior of the system, and the cause and effect relationships between components.

CONDITION MONITORING EQUIPMENT

There is often a plethora of condition monitoring equipment permanently installed on belt conveyor systems: belt rip detection, motor protection, belt displacement switches, chute pluggage sensors, and the list goes on. Many of the systems described herein are already built into conveyor systems (load cells, velocity encoders, position sensors).

One of the more unique types of condition monitoring equipments is a revolutionary new belt-scanning device, tradenamed CBT Belt C.A.T. Scanning System. It can be used to monitor, and accurately predict, the condition of steel cord belt splices. It is a noncontact device, which operates while the belt is running. The device can detect cable breaks and is sensitive enough to pick up even the most minor damage to cords and individual wire strands. Figure 15 shows a typical data measurement and the actual belt upon inspecting the damaged area.

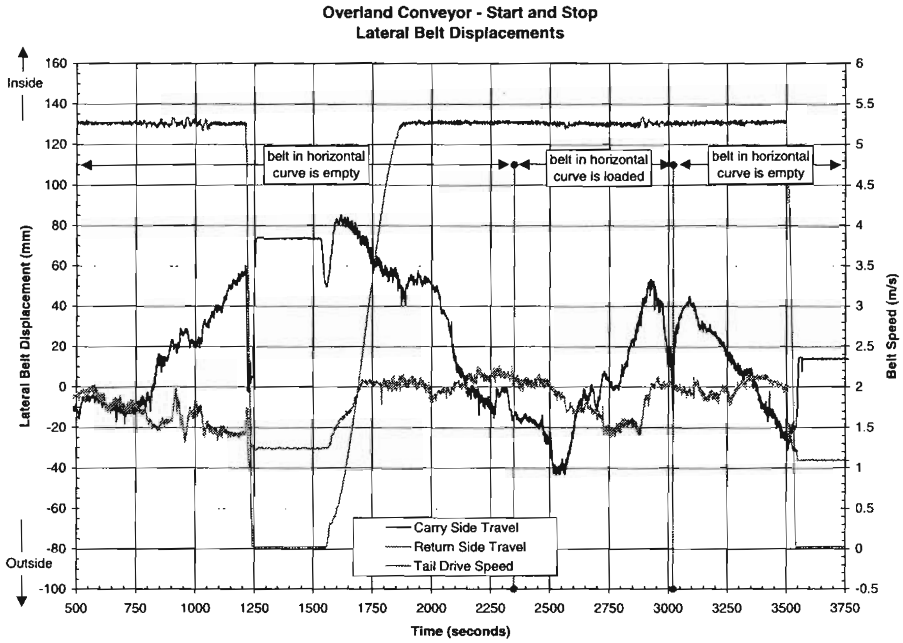

FIGURE 13 Side travel measurements on a long overland conveyor

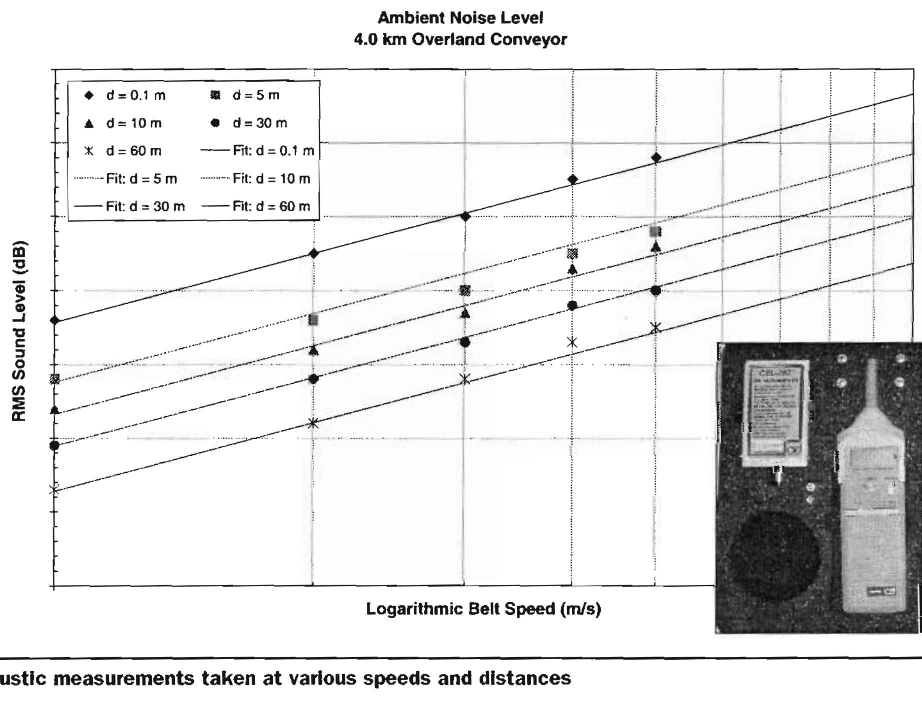

FIGURE 14 Acoustic measurements taken at various speeds and distances

Vibration measurements, on gearboxes and pulley bearings, are another unique type of condition monitoring equipment that is used on conveyor systems. The measurements are taken at specified locations at given time intervals (typically on a bi-weekly or monthly basis). The exact amplitude and frequency of the vibration measurements are not nearly as important as the initial "fingerprint" of the combined data itself. In theory, as the equipment begins to fail, a change will occur in the amplitude and/or the vibration frequency of the measurement. Current measurements can be compared to historical data taken at the same location to indicate if a future failure is probable.

In the author's experience, these vibration measurements are somewhat hit-or-miss. In some cases, vibration monitoring has classically shown the failure history of bearings. Bearings that appear to be failing may be monitored daily until a plant shutdown can occur and they

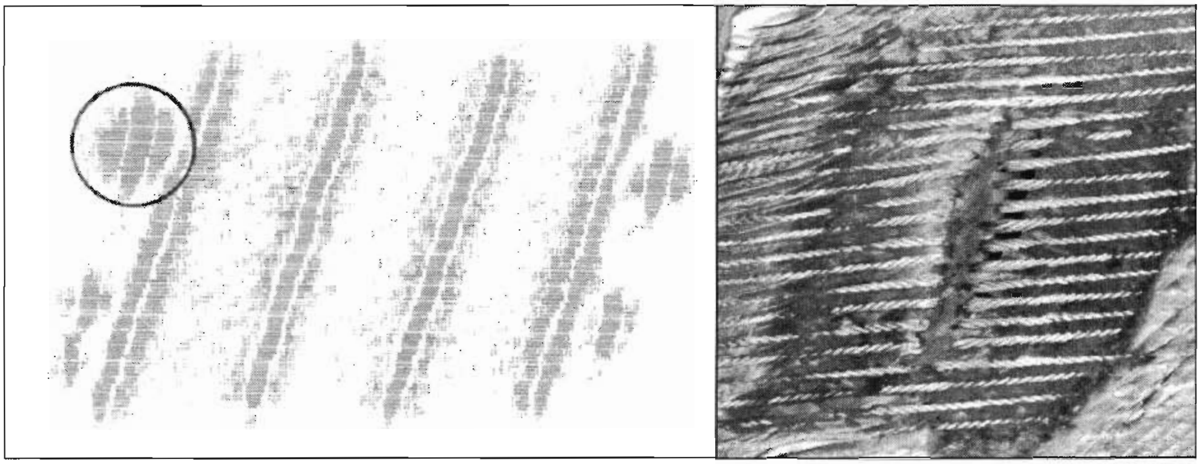

FIGURE 15 CBT Belt C.AT. Scanning System—field measurements and actual belt damage

can be replaced. In other cases, however, gearboxes have been opened revealing a complete failure of the input and other gears, even though vibration monitoring had not shown any signs of failure.

Vibration measurements can also be used for wide variety of other reasons. Belt flap is one area where vibration measurements can be taken in order to pinpoint the precise tension and frequency range of a problem.

CONCLUSION

Accurate field measurements are essential to understanding the operational behavior and long-term performance of belt conveyor systems. By performing the basic field measurements on a conveyor, the system can be given a "clean bill of health" right from the start. In many cases, problems that may cause future failure of critical components can be detected and corrected during commissioning. Fields measurements are also invaluable for forensic engineering and validating theoretical models. This paper has discussed some of the most commonly used data measurements and techniques, as well as some of the most sophisticated and advanced equipment. When available, the accuracy of the measurements has been presented with real field measurements supporting the results.

REFERENCES

CEMA. 1997. *Belt Conveyors for Bulk Materials*. Fifth ed.

Lodewijks and Kruse. 1998. The Power of Field Measurements–Part I; *Bulk Solids Handling*. 18:3:415–427.

Nordell, L.K. 1996. The Power of Rubber–Part I. *Bulk Solids Handling*. 16:333–340.

Pierce, Jim. 1998. Examples from Recent Scanning of Steel Cord Belting Utilizing the New CBT Belt C.A.T. Scanning System. *Bulk Solids Handling*. 18:3:469–473.