DETERMINING DYNAMIC BELT TENSIONS USING VELOCITY MEASUREMENT AND COMPUTER SIMULATION

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1. SUMMARY

Many problems which occur with belt conveyors can be attributed to system dynamics and the associated variations in belt tension. Material spillage, belt and splice failure, belt lift-off in vertical curves and poor tracking are a few examples of situations where knowledge of the dynamic tensions would be of benefit in eliminating a problem. The difficulty is that measuring dynamic tension at arbitrary points along the conveyor is not a simple task. A finite element program developed at The University of Newcastle can accept belt velocity at any number of points along the conveyor as program inputs. Using this feature measured belt velocities can be used to determine the dynamic tensions at any point on the conveyor system. This paper outlines this procedure and discusses some of its applications.

2. NOTATION

a_u	Return idler spacing
B	Belt damping factor
C	Coefficient to approximate secondary resistances
f	Artificial friction coefficient
F_I	Input force
F_O	Output force
F_U	Required peripheral driving force at the driving pulley(s)
F_S	Special resistances (eg. skirts, belt cleaners)
g	Acceleration due to gravity
h	Belt sag
H	Lift of the conveyor between loading and discharge
K	Equivalent belt spring constant
L	Conveyor length (distance between pulley centres)

M	Mass
q_B	Mass of belt per metre
q_G	Mass of material per metre of conveyor
q_{RO}	Rotating mass of carry side idlers per metre of conveyor
q_{RU}	Rotating mass of return side idlers per metre of conveyor
s	Complex frequency variable
T	Tension
V	Velocity
X	Position
δ	Slope angle of the installation

3. INTRODUCTION

While computer simulation of conveyor system performance is widely used as a design tool its application to specific problem solving is not common. Part of the reason for this may be the limitations of the simulation process. To achieve good correlation between measured and predicted results the input data needs to be accurate. This can be achieved with extensive testing of the belting, conveyed material and conveyor components but usually such testing is not practical. Instead, the input data is derived from manufacturers specifications, experience and some trial and error which can lead to inaccuracies in the simulation results. By using input data obtained from field measurements, the characteristics of the belting, conveyed material and conveyor components are automatically passed on to the simulation program. This technique has the advantage of accurate input data without the need for laboratory testing of materials. Computer programs used in the design process utilise various calculation methods, including conventional calculations, to estimate belt tensions at various locations around the conveyor under various operating conditions. Before discussing the use of computer simulation to estimate tensions based on measured velocities it is pertinent to review the types of modelling software currently in use.

3.1 Conventional Conveyor Models

The conventional methods used to determine the effective operating tension of a conveyor have been in use for many years and were originally developed for manual calculations. While these methods are often inadequate for modern conveyor designs they provide an estimate against which the results of subsequent more complex analysis can be checked. As one might expect, the more complex a program becomes the more prone it is to operator error and all results should be critically evaluated as part of the analysis process. The well known conveyor design standards, ISO5048, DIN22101 along with various handbooks produced by manufacturers and associations, use a similar principal to determine the effective tension of the conveyor. Figure 1 shows how the conveyor is modelled as a mass being dragged along a surface, the main force required to move the mass being generated from the friction and change in elevation. The coefficient used to calculate this friction is an artificial number based on experience, a typical value is 0.02.

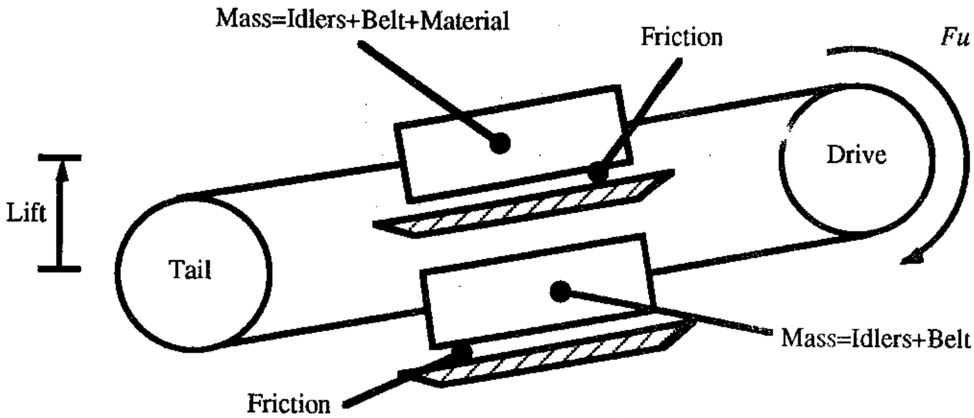

Figure 1 - Conventional conveyor model

Equation 1 is a formula from the design standard ISO5048 and provides a simple manual calculation for the expected effective tension for a belt conveyor. The main drawback of this type of calculation is the lack of information for locations along the conveyors length. The results are for tensions at the drive only and provide no information for other points which might be of interest such as the tension in horizontal or vertical curves. The significant effect on the result of an incorrect value for the artificial friction coefficient and the assumption that it is constant for variations in load, tension and temperature make this calculation a rough estimate of the expected effective tension.

$$F_U = C f L g \left[q_{RO} + q_{RU} + (2 q_B + q_G) \cos\delta \right] + q_G H g + F_S \qquad (1)$$

In order to determine the tensions at points along the conveyor the system can be divided into elements. Using a similar principal to that applied in Equation (1) the belt tension at the node between each element can be estimated. The more elements used, the smoother the "tension profile" of the conveyor will be as shown in Figure 2. Computer programs using this type of analysis are commercially available and normally include estimations of starting and stopping tensions, loading transients and curve analysis. Figure 3 shows how the principal used in conventional calculations is adapted to give the belt tensions at a number of points along the conveyors length.

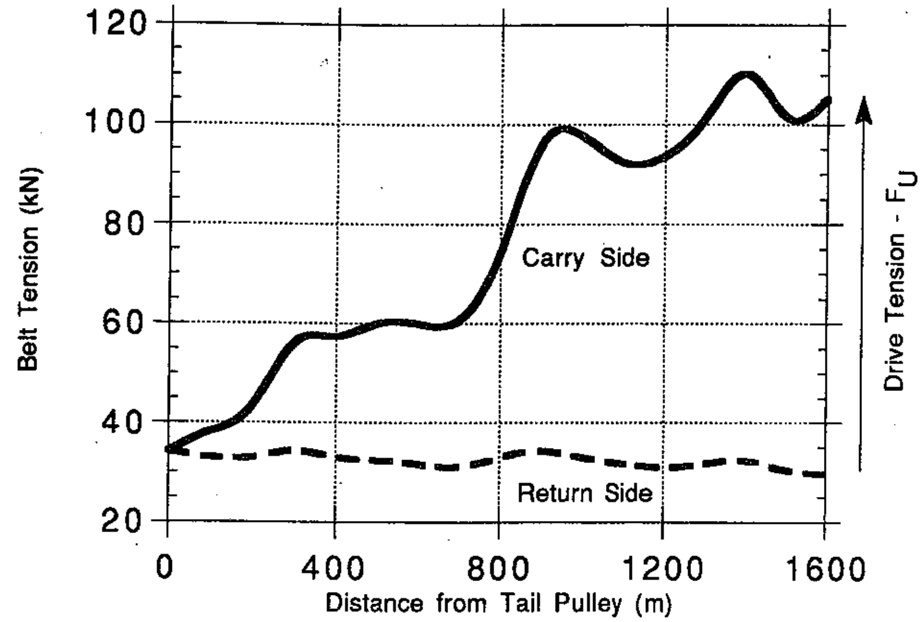

Figure 2 - Steady state tension profile of an overland conveyor

The calculation to obtain the tension at a particular node is given in Equation 2. The calculation is started at a point of known tension, such as the gravity take up, then progresses around the conveyor to points on either side of the drive. Most conveyor system designs would require at least this level of analysis.

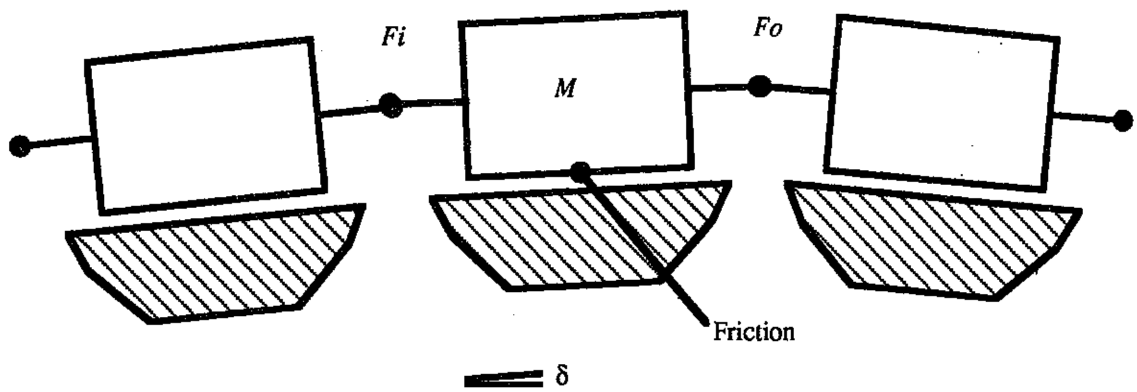

Figure 3 - Conventional conveyor element

$$F_o = F_i + f\,M\,g\cos\delta + M\,g\sin\delta \qquad (2)$$

3.1 Dynamic Conveyor Models

For this type of analysis the elastic characteristics of the belt are included in the model. Most programs of this type use finite element analysis [1][2], although other methods such as velocity wave modelling [3] have been applied successfully to many conveyor installations. Dynamic analysis can generate data on almost all aspects of the conveyor operation including starting and stopping tensions and velocities, take up movement, load sharing between drives, drive and brake drum slip etc. The details of these programs are generally confidential and there is little published information available on their operation and theoretical background. The discussion here will centre around a finite element program developed at the University of Newcastle.

DYNAMIC CONVEYOR BELT ELEMENT

There are a multitude of configurations used to model the visco-elastic properties of each conveyor belt element. The element shown in Figure 5 is one of the simplest models and provides a good illustration of the basic principals involved in dynamic calculations. As with steady state analysis the belt is divided into a series of masses, but rather than being connected by a rigid element the connection is an elastic element. For steady state analysis the tension between any two masses is purely a function of the upstream tension and the forces applied to the upstream mass. When the properties of the belt are included, the position of a particular mass and therefore the belt tension at any moment in time is dependent not only on the forces applied to that mass but also on the position of the mass relative to the masses on either side.

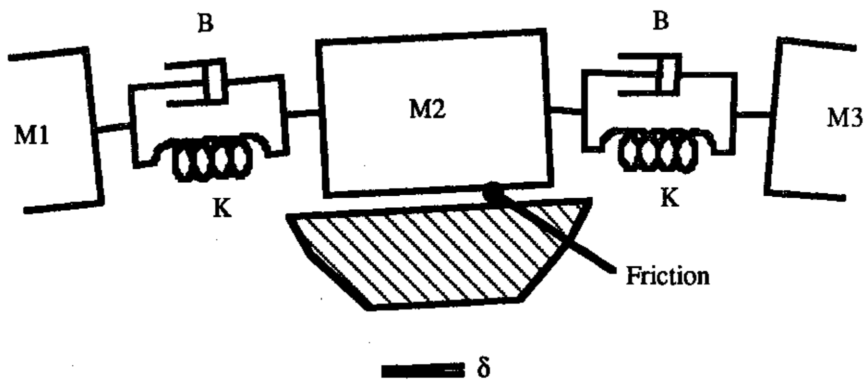

Figure 5 - Simple dynamic belt element

Equation 3 describes the position of mass 2 in complex frequency notation. The element used in this example makes the transfer function fairly simple and has the advantage of producing results which can be correlated with steady state analysis. More complex elements are used where simulation of individual component parameters is required.

$$X_2 = (X_1 + X_3)\frac{Bs+K}{M_2 s^2 + 2Bs + 2K} + F_2 \frac{1}{M_2 s^2 + 2Bs + 2K} \qquad (3)$$

where : X_1,X_2 and X_3 are the position of masses M1,M2 and M3 respectively and F_2 is the sum of the other forces acting on the mass (eg. gravity, friction).

The transfer function described in Equation 3 is transformed into a discrete equivalent which can then be used to simulate behaviour of the element in a computer program.

DYNAMIC ANALYSIS RESULTS

Presentation of the results of dynamic analysis is an important part of the overall process. The volume of data produced by this type of program is large and interpretation of result tables or conventional graphs is time consuming. Morrison described the use of three-dimensional plots to assist in visualising dynamic belt tensions and velocities in 1988 [1]. Since that time this type of presentation has become common for dynamic analysis programs. As Morrison pointed out, this type of simulation is prone to digital instability if the sampling frequency is too low. By plotting all the results on one graph in three-dimensions any unstable areas can be quickly identified.

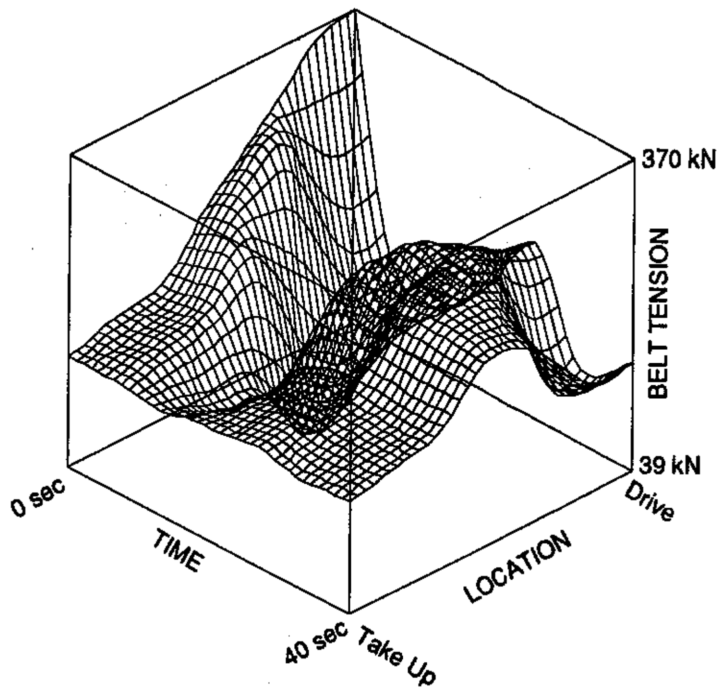

Figure 6 - Three dimensional plot of conveyor stopping tensions

The other major advantage of three-dimensional presentation is the ease with which the maximum and minimum values can be determined. Figure 6 shows the dynamic tensions for a conveyor during a braked stop. An orthogonal view of the plot, shown in Figure 7, allows the minimum tension value to be identified. Conventional graphs can then be used to obtain detailed information for that particular point on the conveyor, as shown in Figure 8, or for other information such as take up movement, see Figure 9.

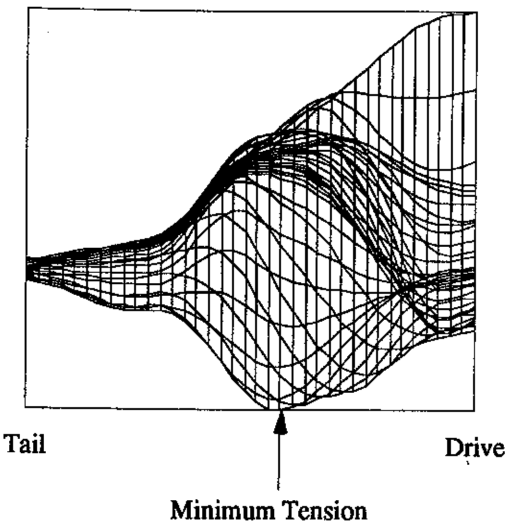

Figure 7 - Front view of the plot shown in figure 6

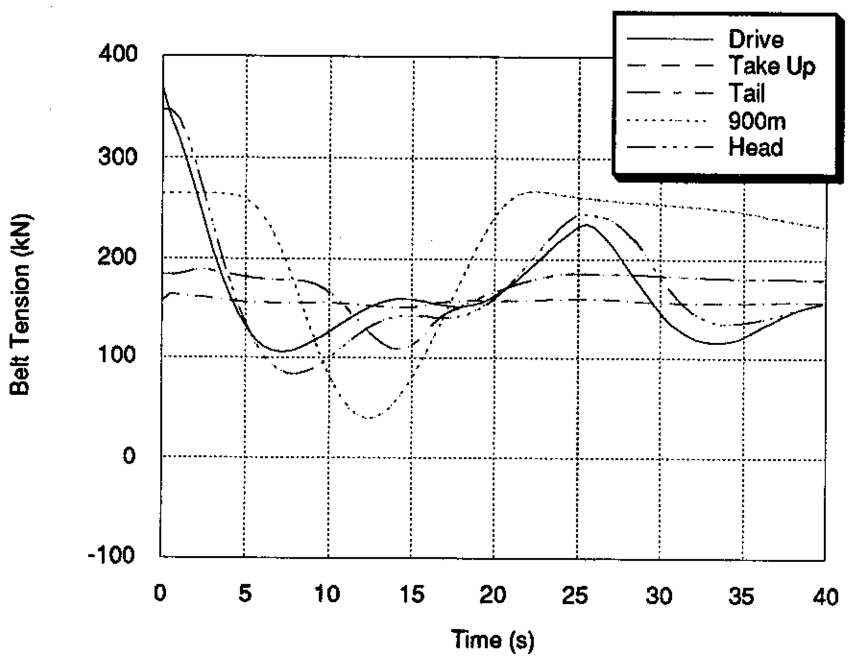

Figure 8 - Conventional graph of the data in figure 6 including the minimum tension 900m from the tail pulley

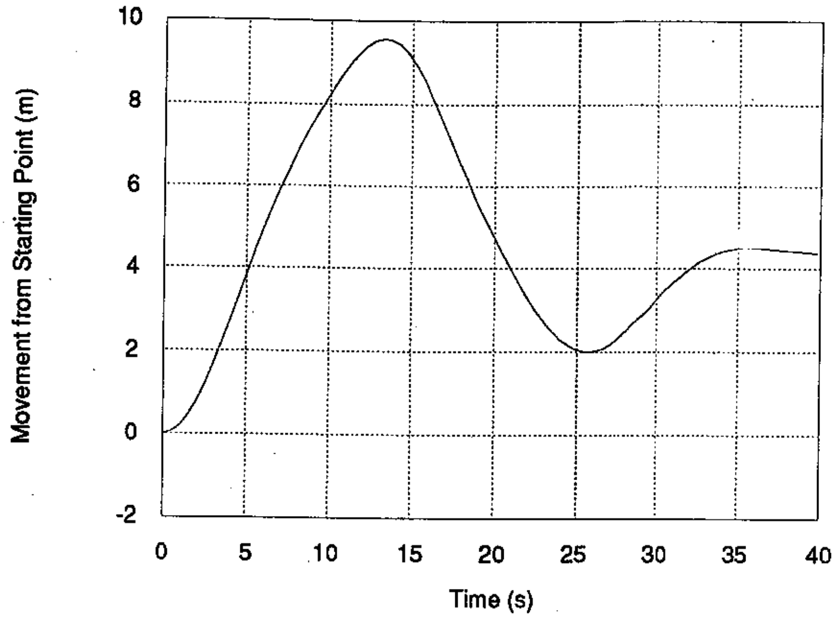

Figure 9 - Graph showing take up movement during a braked stop

4. DETERMINING TENSION FROM VELOCITY MEASUREMENTS

The adaptation of the simple dynamic belt element for the conversion of measured values of velocity to belt tensions is not a difficult task. Figure 10 shows the element in a form more suitable for consideration of belt tensions. Equation (4) gives the tension between the mass nodes M1 and M2 based on the position of each node in complex frequency notation. The equivalent formula using velocity is given in Equation (5).

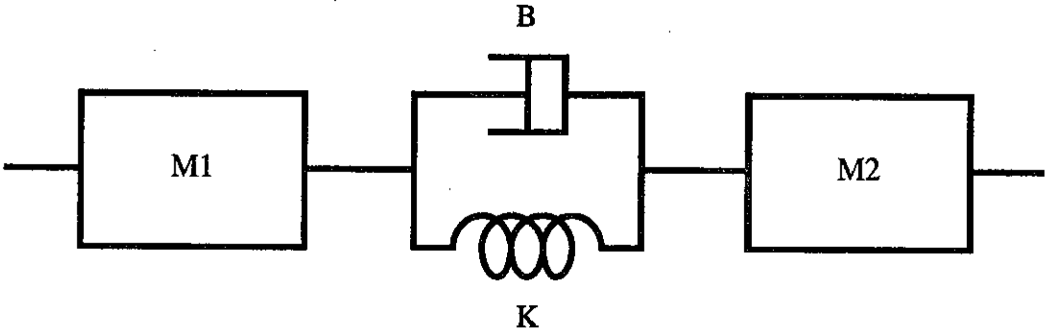

Figure 10 - Dynamic tension element

$$T = (X_2 - X_1)(Bs + K) \tag{4}$$

$$T = (V_2 - V_1)\frac{(Bs + K)}{s} \tag{5}$$

where : X_1 and X_2 are the positions of M1 and M2.
V_1 and V_2 are the velocities of M1 and M2.

In this case the equations are shown for determining tension between two adjacent nodes. Since this procedure can be employed as part of a simulation of the entire conveyor as many or as few elements as necessary can be applied to any situation. It is quite feasible to measure V_1 and V_2 at the drive where the conveyor is easily accessible and use these values to determine the dynamic tension at the tail which may be underground and difficult to reach with instrumentation. By using the finite element program to fill in the gaps between the point of velocity measurement and the desired location of the tension measurement tensions can be determined at any point along the conveyor quickly and easily.

As stated earlier the tensions in the belt could be determined purely by simulation without the need to use measurements of velocity. It is important, however, to bear in mind the limitations of finite element simulation. In any software package of this type a number of assumptions and estimates are made when determining the program input parameters. Belt modulus, belt damping factor, stress wave velocity, variations in idler friction, rubber hardness, material properties and so on all reduce the accuracy of the final results from the computer program. By using field measurements as inputs to the program, many of these uncertainties are reduced or eliminated, particularly if the velocity measurement is carried out close to where the tensions are to be determined. Another application of this technique is to use the velocity data to evaluate the behaviour of some of the input parameters used by conveyor simulation programs.

5. FIELD TESTING

5.1 Experimental Set Up

To evaluate the success of this procedure an experiment was conducted using a test conveyor system located on campus at the University. The test conveyor system consists of two 60m conveyors operating in a closed loop to allow the testing of conveyor performance with material loading. The conveyors are 600mm wide with facilities for monitoring belt tensions, drive power and belt velocity throughout the system. For this experiment, velocity was measured on the return strand of the conveyor at two points, one adjacent to the head pulley, the other at the tail. Between these two locations a sensor was used to monitor the sag of the belt between idlers which was later converted to belt tension.

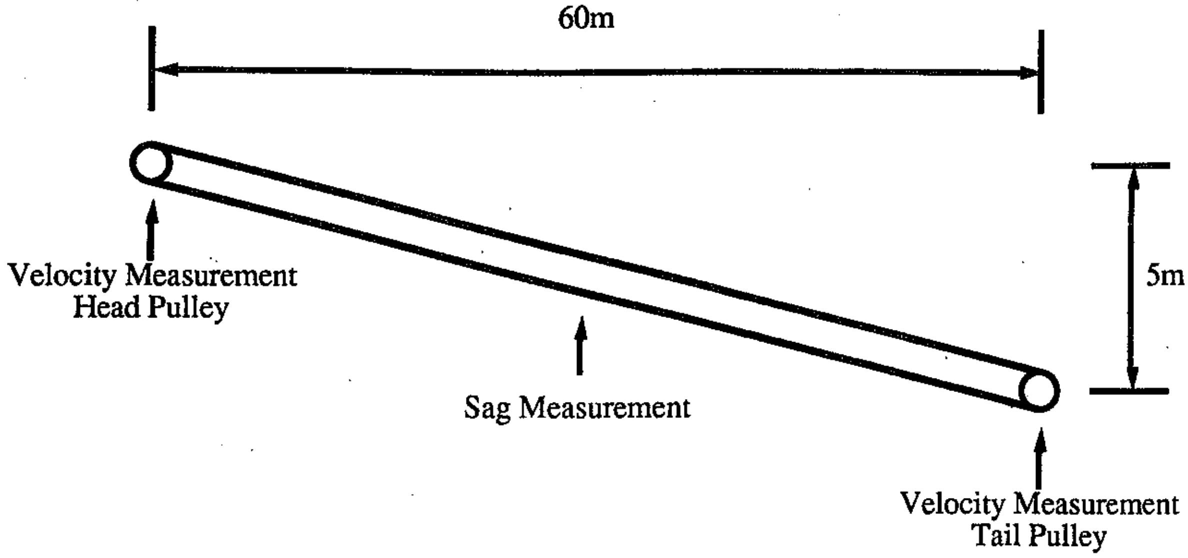

Figure 11 - Experimental set up

5.2 Using Sag to Monitor Tension

One method of measuring belt tension is to measure the sag of the belt between idlers. The relationship between belt sag and belt tension used for this measurement is described by Equation (6).

$$T = \frac{a_u q_B g}{8\left(h/a_u\right)} \qquad (6)$$

This is a simplified relationship based on the sag of a rope between two points and is used in conventional design procedures to determine minimum belt tension requirements. The simplification is justified in this case because the sag measurement was conducted on the return side of a conveyor with flat idlers where the belt will approximate the behaviour of a rope. If applied to the carry side of the belt, the mass of the material must be taken into account and the effect of the belt troughing on the distribution of tensions and subsequently the sag of the belt is difficult to estimate.

5.3 Results

Figure 12 shows the measured values for belt velocity taken at the head and tail pulleys. These values were supplied to the finite element simulation program to compute the estimated value for belt tension shown in Figure 13. The measurements of belt sag were used to calculate the belt tension at the same point giving the measured results in figure 13.

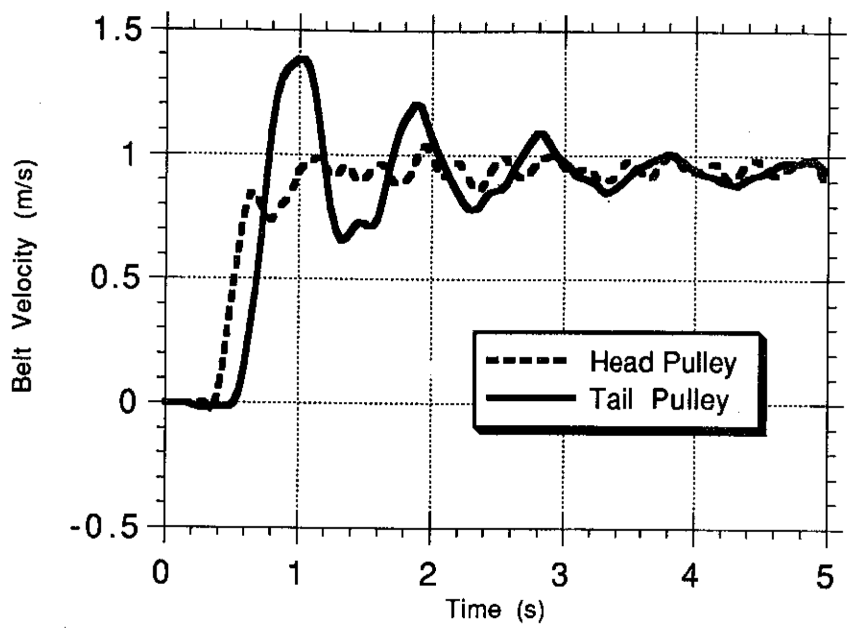

Figure 12 - Belt velocity , measured values

Figure 13 shows good correlation between the estimated values for tension and the values calculated from measured belt sag. The only input parameters for the program used for this calculation were the belt spring constant (*K*) and the belt damping factor (*B*) both of which were calculated using data from the manufacturers specifications.

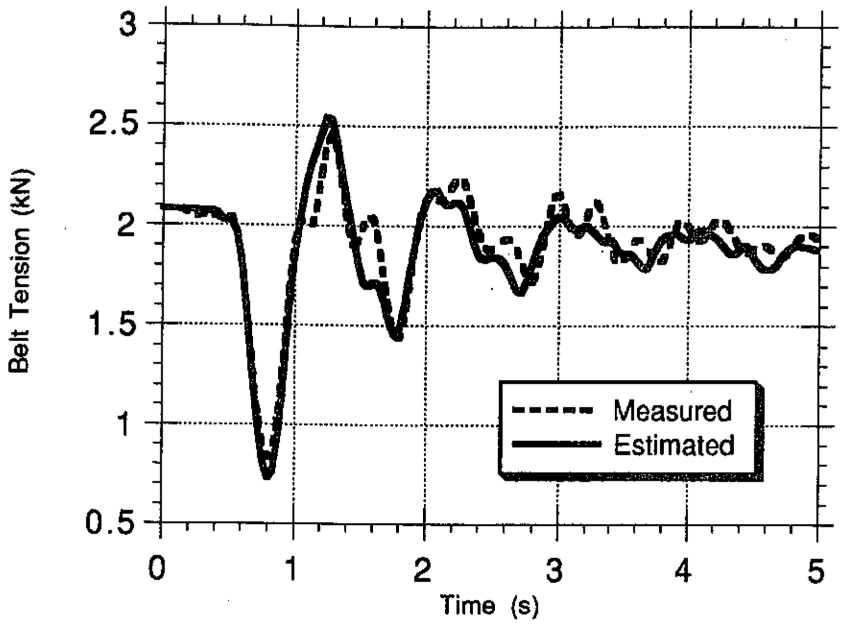

Figure 13 - Belt tension , computed from measured sag and estimated by simulation

6. CONCLUSION

A method for determining dynamic belt tensions based on measured values of belt velocity has been presented. This procedure will find applications in the performance evaluation and solving of specific problems on existing conveyor installations. The concept of being able to measure velocity at an easily accessible point of the conveyor and use this data to determine the belt tensions anywhere in the system will overcome many of the difficulties encountered when using instrumentation on conveyor belts.

In addition to this, the technique outlined in this paper provides an opportunity for continued research into the behaviour of many of the variables used for computer simulation. Data on conveyor system characteristics while operating under normal conditions is difficult to obtain, particularly data on the visco-elastic properties of the belt itself. It is hoped that by using measured velocities and The University of Newcastle Conveyor Simulation Program a study can be conducted into the characteristics of a number of conveyor system parameters which have not previously been evaluated in the field. This research will lead to improved results from simulation software used for conveyor system design.

7. REFERENCES

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