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Computer Graphics Techniques for Visualising Belt Stress Waves - An Essential Aid in the Understanding of the Stop-Start Behaviour of Long Conveyors

W R B Morrison

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COMPUTER GRAPHICS TECHNIQUES FOR VISUALISING BELT STRESS WAVES - AN ESSENTIAL AID IN THE UNDERSTANDING AND DESIGN OF THE STOP-START BEHAVIOUR OF LONG CONVEYORS

By: Dr W.R.B. Morrison

Director : Winders, Barlow & Morrison Pty Ltd, Brisbane

President: Winders, Barlow & Morrison Inc., Denver

It is now generally recognised that it is essential in the design of long or high inertia conveyors to model the dynamic behaviour of the complete conveyor system, including the elastic behaviour of the belt, to avoid the potentially catastrophic consequences of belt stress waves.

With a finite element dynamic model of a conveyor and appropriate graphics, it is possible to generate three-dimensional plots depicting the stress waves. Such visualisation techniques which provide a complete picture of tension or velocity dynamics for the whole of the belt, have proven extremely helpful in understanding behaviour of the system being modelled.

In addition, these techniques are ideal, in fact essential in some cases, for detecting and correcting problems with the dynamic model. Without this kind of approach it is sometimes possible for incipient numerical instabilities to remain undetected : for the model to provide spurious results even when calibrated.

These presentation techniques have been applied to the investigation of belt stress problems in several conveyors in South Africa, Australia and the USA. Examples illustrating the value of this approach as a problem solving and design aid will be discussed.

COMPUTER GRAPHICS TECHNIQUES for VISUALISING BELT STRESS WAVES

An essential aid in the understanding of the stop-start behaviour of long conveyors

By: Dr. W.R.B. Morrison

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1.0 INTRODUCTION

Elastic stress waves generated in long or high inertia conveyor belts during starting and stopping, and the problems these stress waves can cause for belts, drives and supporting structures are well known.

It is now generally recognized that the design of such conveyors must take account of these stress wave effects if the potentially catastrophic consequences are to be reliably avoided. It is essential therefore to be able to model the dynamic behaviour of the complete conveyor system, and for this to be an integral part of the design process. A number of models of this kind have been developed and the essentials of their representational algorithms have been described in recent conveyor literature (see for example References (1) to (8)).

As with any distributed, interactive system, the dynamic behaviour of a conveyor belt is relatively complex and it is difficult to obtain a clear understanding of the likely behaviour in any given situation, by simply considering the mechanics of the various individual processes which are occurring. Generally there will be transient decaying stress waves propagating in both directions around the belt with partial reflection, partial transmission at drives and the counterweight. At the same time there will be some interaction with the drive and counterweight dynamics producing a total result which is often very difficult to visualise and virtually impossible to predict simplistically.

For similar reasons, it is often difficult to obtain a clear understanding of these processes from observations or measurements on real conveyors.

In situations such as this, dynamic models can provide a very valuable aid in obtaining an understanding of the dynamics of complex belt/drive systems: provided of course the model includes an adequate description of the basic physics of all of the individual processes involved.

The potential of a dynamic model in both of these roles: as a design tool, and especially as an aid to understanding stress wave behaviour, is greatly enhanced if appropriate graphical techniques are employed.

2.0 CONVEYOR STRESS WAVE MODELS

Conveyor stress wave models are generally of two types: those based on the elastic wave equations, References (1), (2), (3), and those which use a finite element representation of the belt, References (5), (4), (7), (8). Of these, the finite element model permits a much more accurate, detailed representation of the system, including non-linear effects.

The results presented in the remainder of this paper are based on a model of this kind, which incorporates various sub-models, the primary features being as follows.

1) Belt

In this sub-model, the belt is represented as a series of interconnected visco-elastic elements. The model includes a description of internal damping, belt friction as a function of tension, speed and load, and the effects of sag.

2) Material

A material sub-model provides a description of the variation in the arrival rate of material on the belt and the translation of the load with the belt.

3) Drives

A sub-model for the drives allows simulation of DC, AC or AC wound rotor motors, with any type of start control, with any kind of coupling (flexible, fluid, delayed fill or scoop), and with or without flywheels. Inertias, and shaft or coupling flexibilities are included, enabling torsional dynamics of the drives to be investigated concurrently.

4) Brakes

Various brake types can be represented, including fully modulated systems with feedback control.

5) Take-up

This sub-model describes take-up behaviour which may be gravity, programmed tension, or fixed.

6) Slip

A slip algorithm checks for slip at drive and brake pulleys and allows modelling to continue after the belt slips.

7) Lift off

Associated with the belt sub-model is another algorithm which detects and signals belt lift off.

Numerical models of the type outlined above are very powerful tools for investigating conveyor dynamics, but their development, verification and use is not without problems. Even in their simplest form, these finite element models are relatively complex and usually generate a large amount of output information. They are, as a result, inherently difficult to check to ensure that they are indeed performing the calculations correctly in every case and providing a faithful representation of the basic physical processes for all configurations.

The graphical techniques discussed below provide a most effective means of visualising the behaviour of the total system, thus greatly simplifying the checking, verification and use of these models.

3.0 REPRESENTATIVE CONVEYORS

To illustrate the presentation techniques and the resulting interpretation that is possible, the dynamic modelling results for two typical conveyors are described.

The first of these, referred to subsequently as Conveyor A, is an existing conveyor, the configuration being shown schematically in Figure 1a. It has a 1350 mm wide belt, about 2 kilometers long from head to tail, with a relatively low lift of about 10 metres. Average capacity is about 3000 tph of loose overburden.

The drive, at the head end, includes two primary and one secondary AC motors, all of 350 kW, driving via delayed-fill fluid couplings. In all cases, the secondary drive starts first, with the primary starting after a delay of 3.0 seconds. Total start time is approximately 60 seconds and maximum belt speed is 5.1 m/sec.

The take-up on this conveyor is a tensioner which preloads the belt to a given initial tension before starting but thereafter remains fixed while the belt is running.

The second conveyor considered, which is referred to here as Conveyor B, is identifical to Conveyor A with the exception that a gravity take-up is used rather than a fixed tensioner. This take-up is located mid way along the return belt, as shown in Figure 1b, this position being selected arbitrarily, the primary objective being to illustrate the associated stress wave behaviour.

The dynamic finite element model used to analyse these conveyors

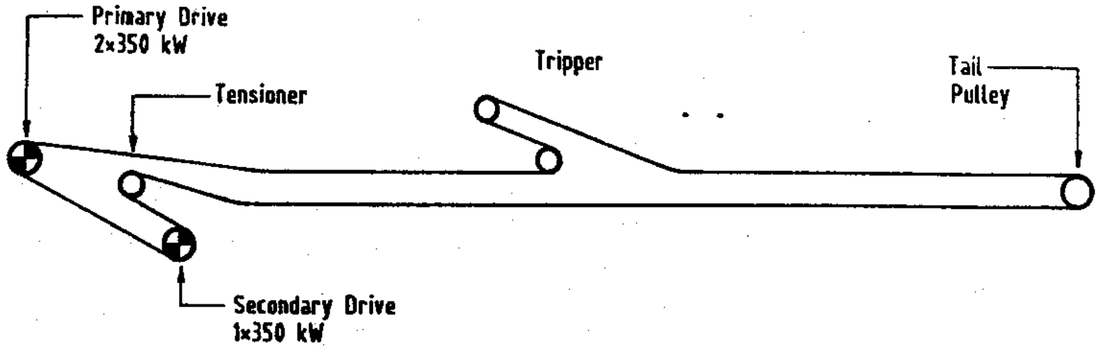

Fig. 1a. Conveyor A Configuration.

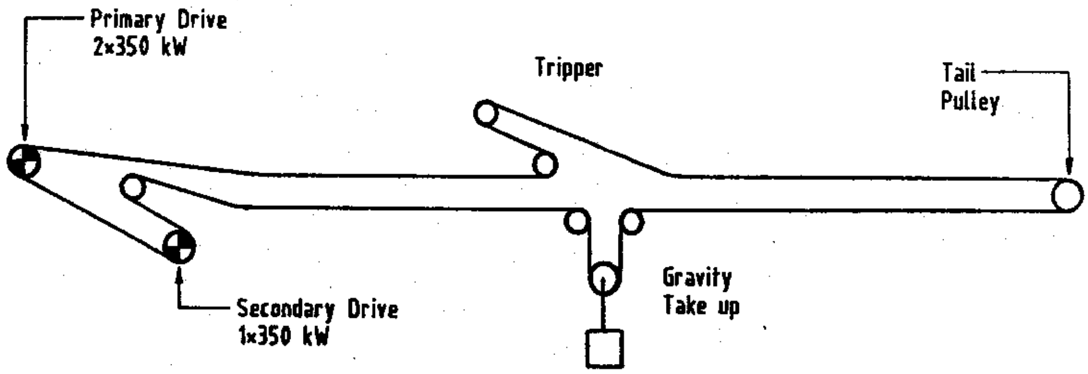

Fig. 1b. Conveyor B Configuration.

has represented the belt as a series of 120 interconnected elements, the average element length being about 35 metres.

4.0 PRESENTATION OF MODELLING RESULTS

Dynamic behaviour of the elastic stress waves in a conveyor belt can best be described in terms of belt velocities and tensions, which for a situation where there are stress waves, will vary in time and with distance along the belt.

The most common way of presenting this information is to plot the time history of tension or velocity for various points along the length of the conveyor. Typical results using this kind of presentation are given in Figure 2, where velocity behaviour during start-up of Conveyor A is plotted for six locations along the belt, three on the loaded side and three on the return.

While it is clear from this type of presentation that there are velocity variations which are out of phase at the various locations and which are probably the result of stresss waves, it is not possible to be certain of this or to identify separate waves propagating in the two different directions.

An alternative is to plot the velocity along the whole of the belt at a series of different times. However, this method also suffers from the same disadvantages.

5.0 THREE-DIMENSIONAL TENSION/VELOCITY CARPET PLOTS

By far the best method of presenting results of a dynamic conveyor model to visualise stress wave behaviour, is to plot tension or velocity in the form of 3-dimensional carpet plots.

A tension carpet plot, for example, depicts tension on the vertical axis, with time and distance along the conveyor on the horizontal axes. The resulting tension surface can then be

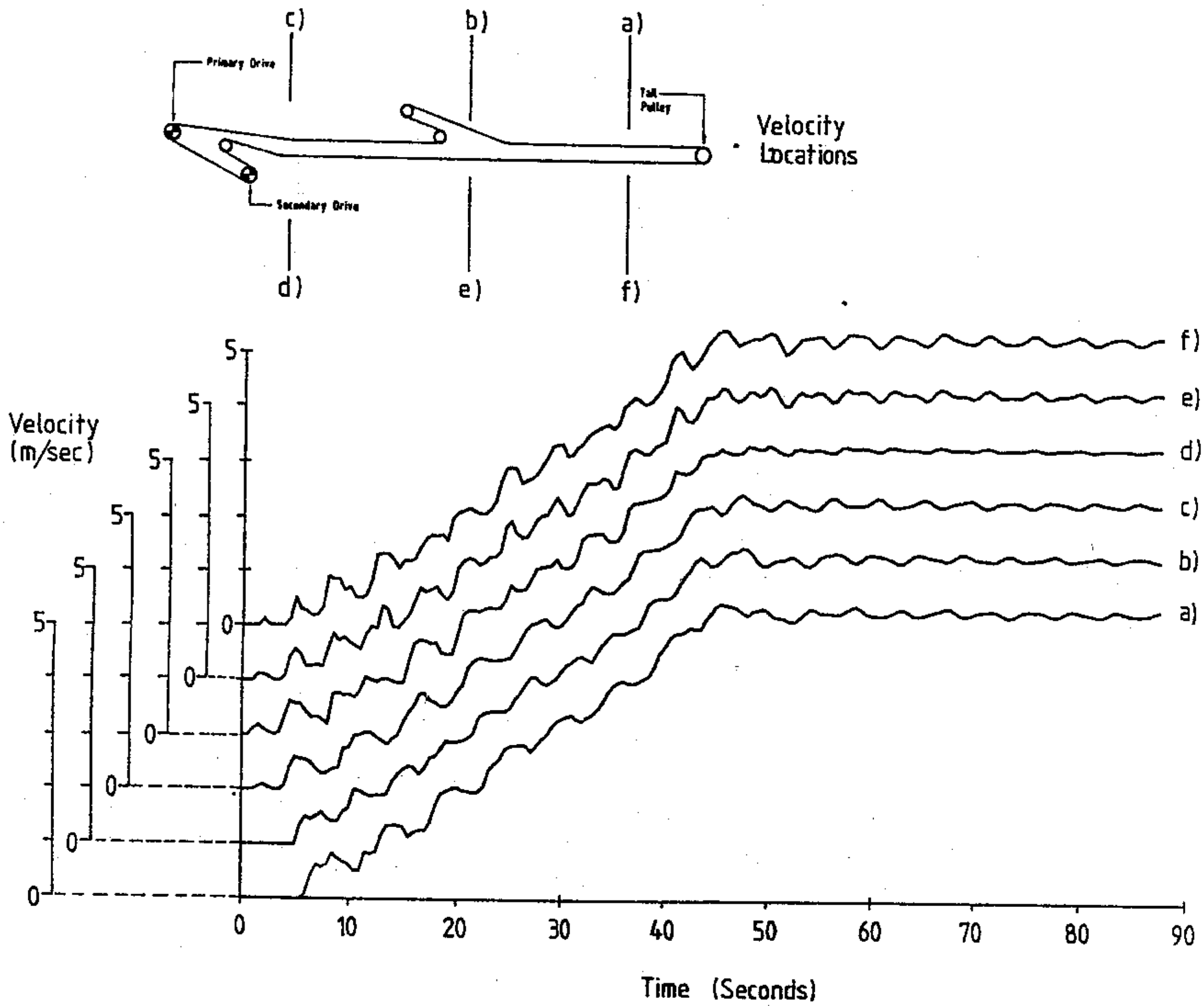

Fig. 2. BELT VELOCITY TIME-HISTORIES - CONVEYOR A START-UP.

presented in isometric, rotated about the co-ordinate axes to show the relief of the surface.

In this kind of plot the complete behaviour of tension or of velocity, over the total simulation time, for the whole of the conveyor, is contained in a single diagram.

More importantly however, when the data are plotted this way, stress waves become clearly visible, allowing a relatively rapid, simple assessment of the behaviour of these waves. By implication, this also allows a rapid assessment of whether the model is representing the belt correctly and producing believable behaviour.

In constructing these plots, the belt is considered 'unfolded' with the total length of belt, (carry and return sides) included in the plot. By choosing the point at which the belt is split and unfolded, and by rotating the plot, it is possible to obtain an orientation in which all of the interesting dynamics information can be clearly seen.

In most cases, it helps clarify the presentation if hidden detail is removed, and this option is generally selected as a matter of course. However, there are situations where retaining hidden detail can assist the visual interpretation, as shown in Figure 15 later.

This plotting technique is illustrated in Figures 3, and 4. The first two of these plots show dynamic tension and velocity for Conveyor A during start-up, accelerating to a steady speed, with the belt loaded to about 250 kg/m. These diagrams are based on the same output data that was used to generate Figure 2, the velocity time histories of Figure 2 being just six cross sections of the full velocity carpet plot.

With the 3- dimensional presentation, it is possible now to visualise stress wave behaviour for this conveyor, and forward and

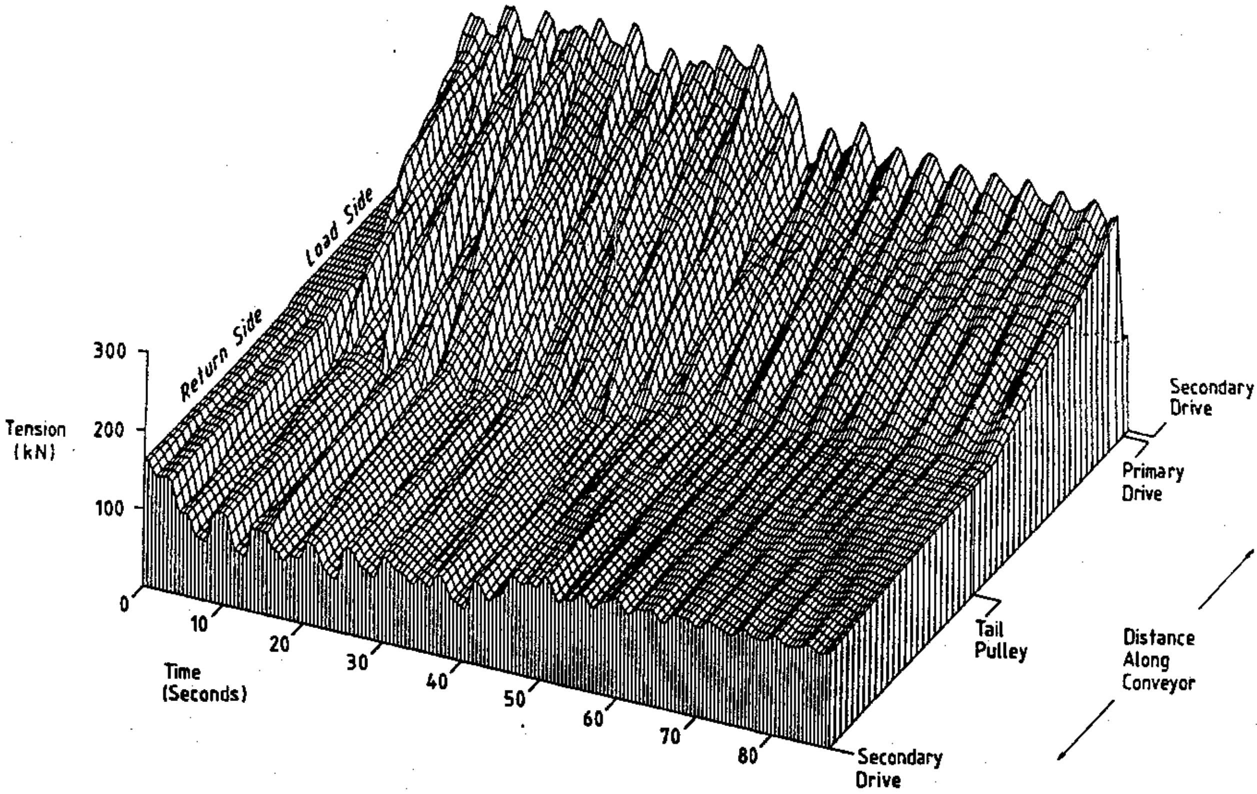

Fig. 3. BELT TENSION CARPET PLOT - CONVEYOR A START-UP.

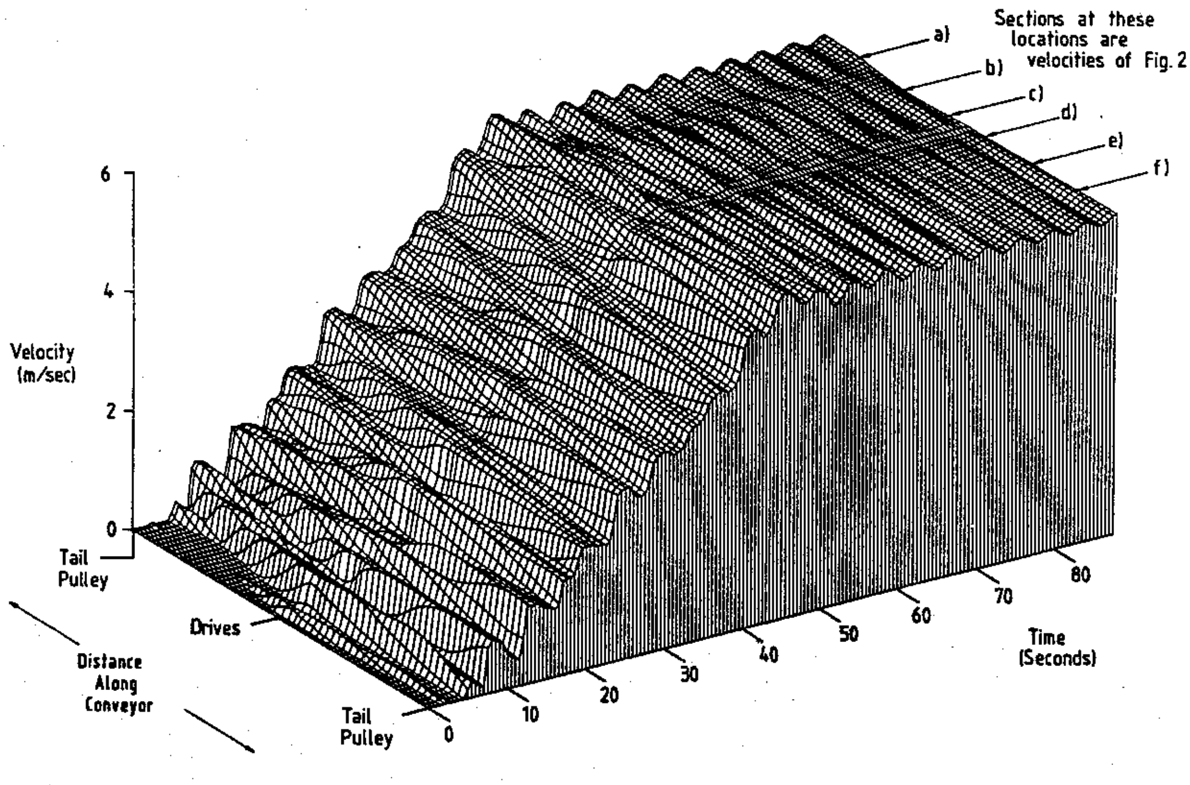

Fig. 4. BELT VELOCITY CARPET PLOT - CONVEYOR A START-UP.

rearward propagating waves and their interaction are clearly evident.

Figure 5, is a 3-dimensional velocity plot for the same conveyor, illustrating typical stopping behaviour and the associated stress waves.

6.0 PROPAGATION OF STRESS WAVES

Stress wave behaviour as shown in figures 3, 4 and 5, when viewed over the whole of the start-up period, can be relatively complex because of the constantly changing input and the number of interacting waves that are present. It is difficult as a result to separate the various individual phenomena which are occurring.

For this reason, the first few seconds of the start sequence of Conveyor A have been replotted in Figures 6 and 7, to enable the wave propagation characteristics to be more clearly seen. During the early part of the start up, it is possible to distinguish individual stress waves before the process of interaction and reflection complicate the overall behaviour. As a further aid to the interpretation, corresponding drive motor torques and speeds are also shown in Figure 8.

To demonstrate the interaction which occurs at a gravity take-up, the comparative information during the first few seconds of starting Conveyor B has also been plotted in Figures 9 and 10, with drive parameters, counterweight movement and tensions given in Figure 11.

In all of these plots the conveyor has been split so that the drive is shown located approximately at the centre of the distance axis with the tail pulley close to one end.

From these diagrams it is possible to identify or check various properties of the stress waves and characteristics of their

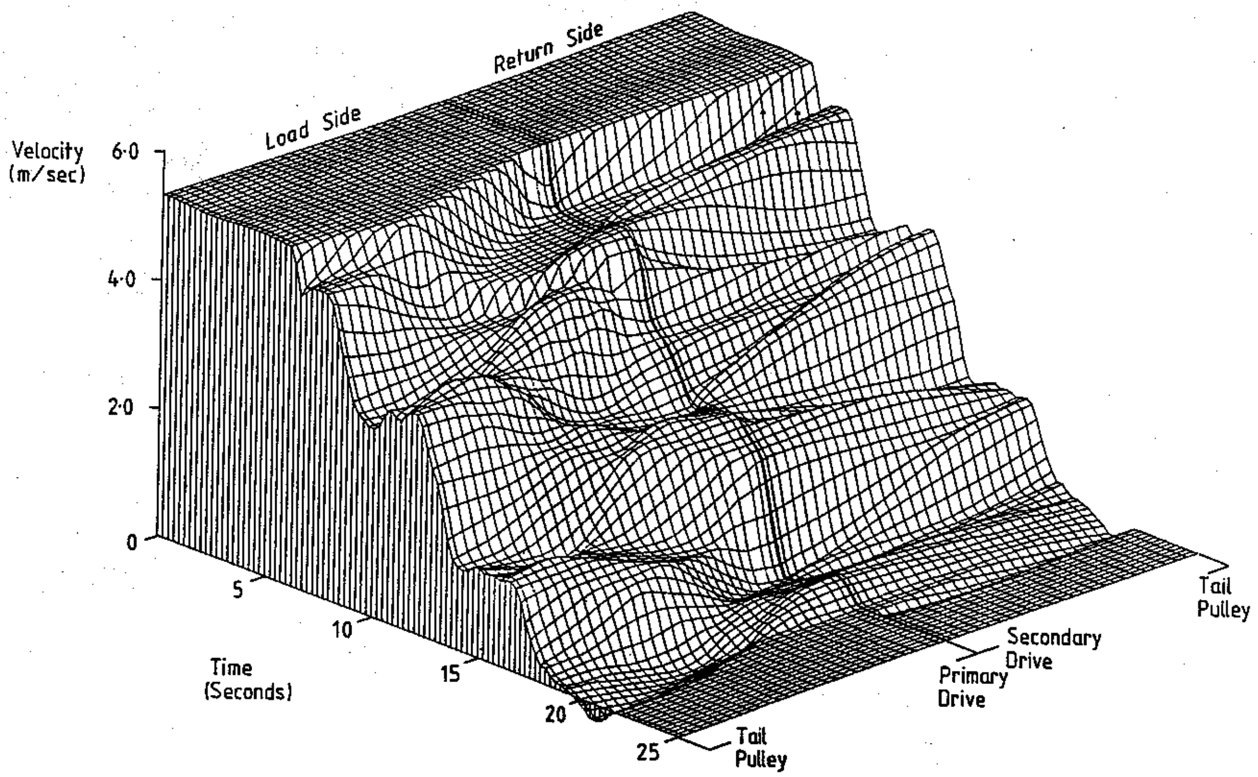

Fig. 5. BELT VELOCITY CARPET PLOT - CONVEYOR A BRAKING.

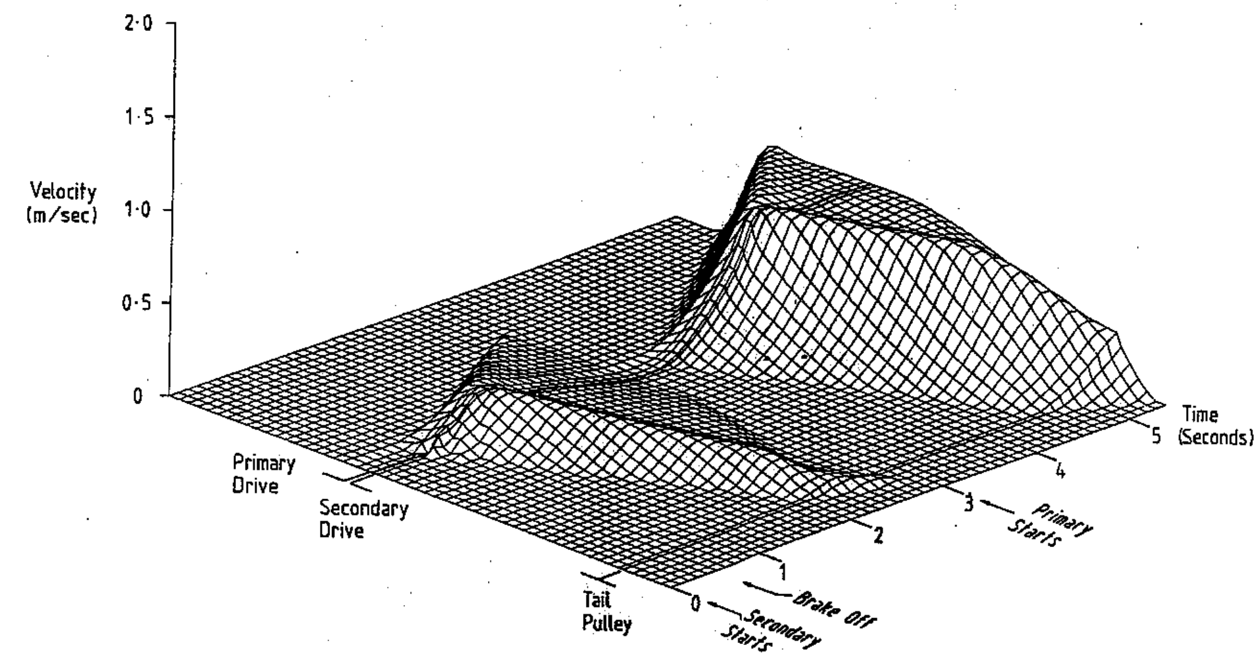

Fig. 6. VELOCITY WAVES DURING START INITIATION - CONVEYOR A.

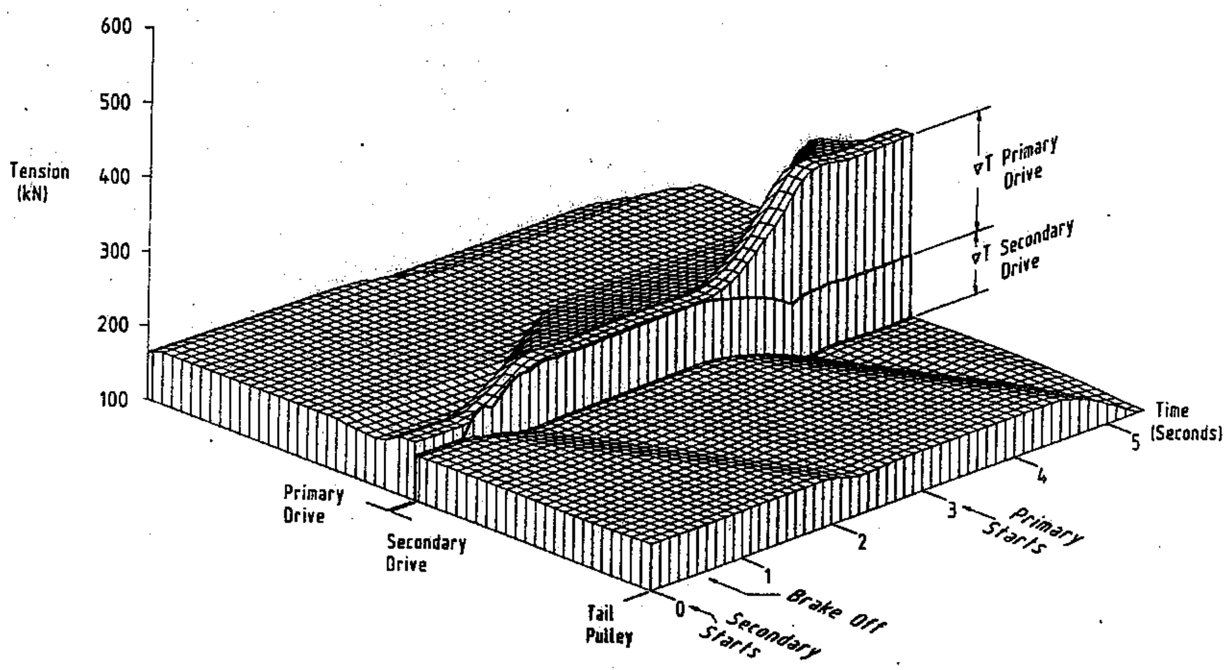

Fig. 7. TENSION WAVES DURING START INITIATION - CONVEYOR A.

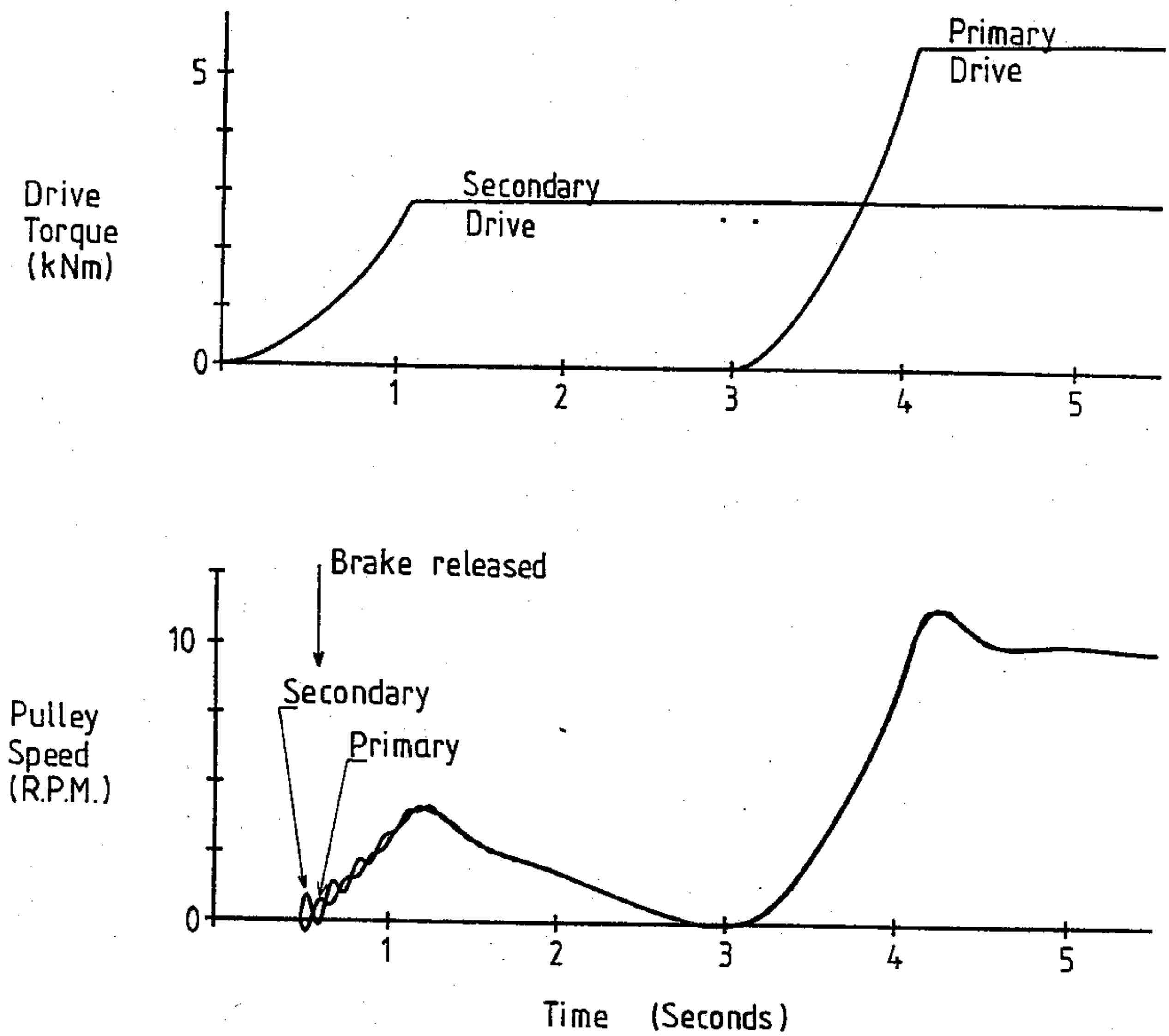

Fig. 8. DRIVE BEHAVIOUR DURING START INITIATION CONVEYOR A

behaviour, in particular the following.

6.1 PROPAGATION VELOCITY AND ATTENUATION

Referring to Figures 6 and 7 it can be seen that the initial start-up of the secondary and primary drives results in two distinct disturbances which propagate in the belt.

When the secondary drive first starts, the drive pulley rotates, pulling belt in from the loaded side (and rotating the primary drive pulley in the process) and feeding it out to the return side. A velocity wave propagates along the loaded side, stretching the belt progressively, reaching a point about half way along the loaded part of the belt before friction dissipates the wave. On the return side, the wave propagates along the total unloaded length, around the tail pulley and back a short distance along the loaded belt before it too is dissipated.
Corresponding tension waves also propagate away from the drive pulley: as a positive wave (increase in tension) along the loaded side of the belt, and as a negative wave (reduction in tension) along the return side.

Immediately after this initial disturbance has decayed, the whole belt remains stationary momentarily, all velocities returning to zero. At this point, part of the belt has been stretched, part relaxed but no general movement occurs since the torque available in insufficient to overcome total belt friction. When the primary drive starts, further stress waves propagate upstream and downstream from the drive and the whole belt now begins to accelerate.

The speed of propagation of these waves is indicated by the slope of the disturbance fronts on the 3-dimensional plots. It is clearly higher along the return side of the belt than along the loaded side, as it should be. Further, the rate at which the disturbance energy is dissipated is also higher for the loaded belt, primarily because of the higher friction between belt and idlers.

Values of the propagation velocity for the loaded and unloaded belt, as determined from the tension/velocity plots are listed below, together with theoretical values calculated according to the procedures of Harrison (3). The agreement is acceptable, the slightly lower velocities obtained from the dynamic model reflecting the inclusion of nonlinearities in the model.

Table 1 - Stress Wave Propagation Velocities

	Belt Empty	Belt Loaded
From Model	730m/sec	2200m/sec
Calculated as per Harrison (3)	800m/sec	2210m/sec

6.2 REFLECTION/TRANSMISSION AT GRAVITY TAKE-UP

Behaviour of tension and velocity disturbances arriving at a gravity take-up can be seen from the 3-dimensional velocity and tension plots of Figures 9 and 10, which are for Conveyor B. The only difference between this and Conveyor A is the gravity take-up, so that the differences between the corresponding velocity and tension carpet plots are attributable solely to the effect of the gravity take-up.

The most significant features are most clearly seen in the velocity plot, and particularly for the initial velocity disturbance generated when the secondary drive first starts. For clarity, this part of the velocity plot is reproduced in Figure 12 to larger scale.

Initially, the disturbance approaching the take-up along the return

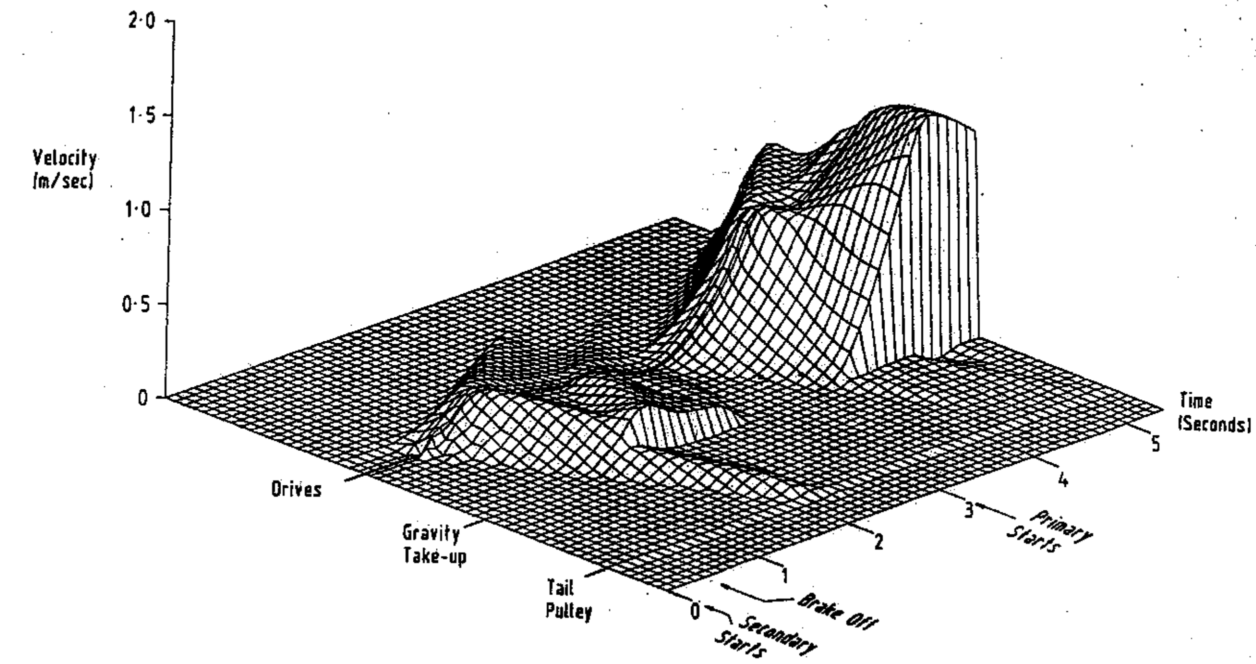

Fig. 9. VELOCITY WAVES DURING START INITIATION - CONVEYOR B.

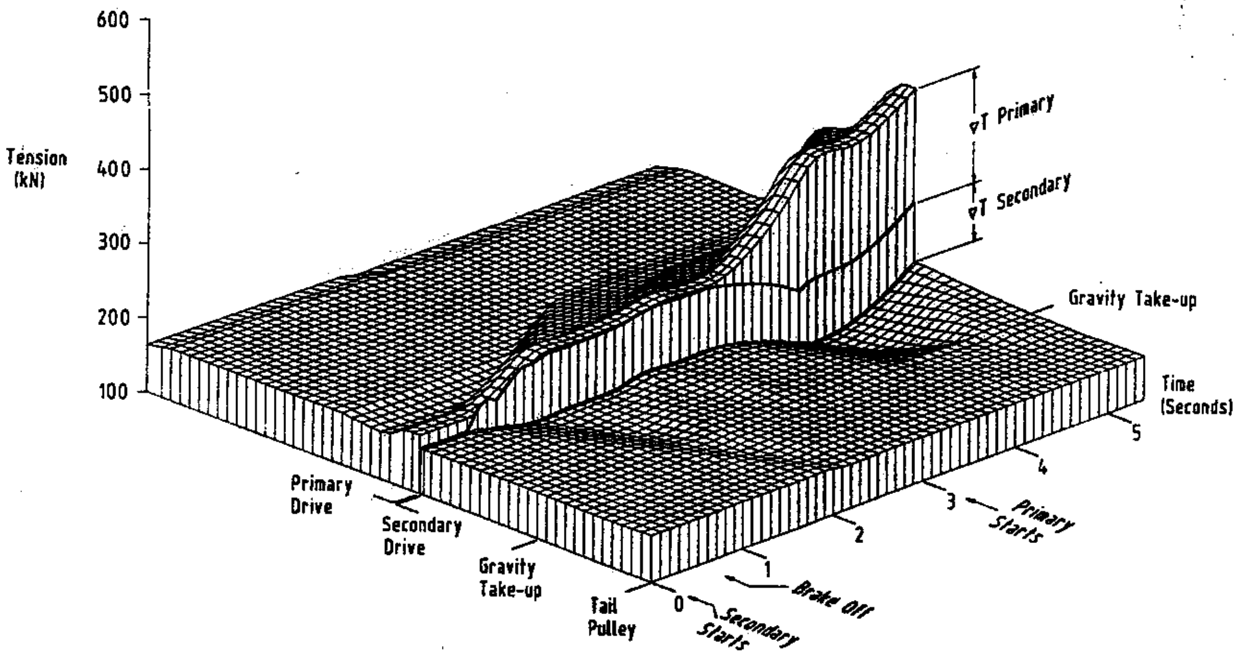

Fig. 10. TENSION WAVES DURING START INITIATION - CONVEYOR B.

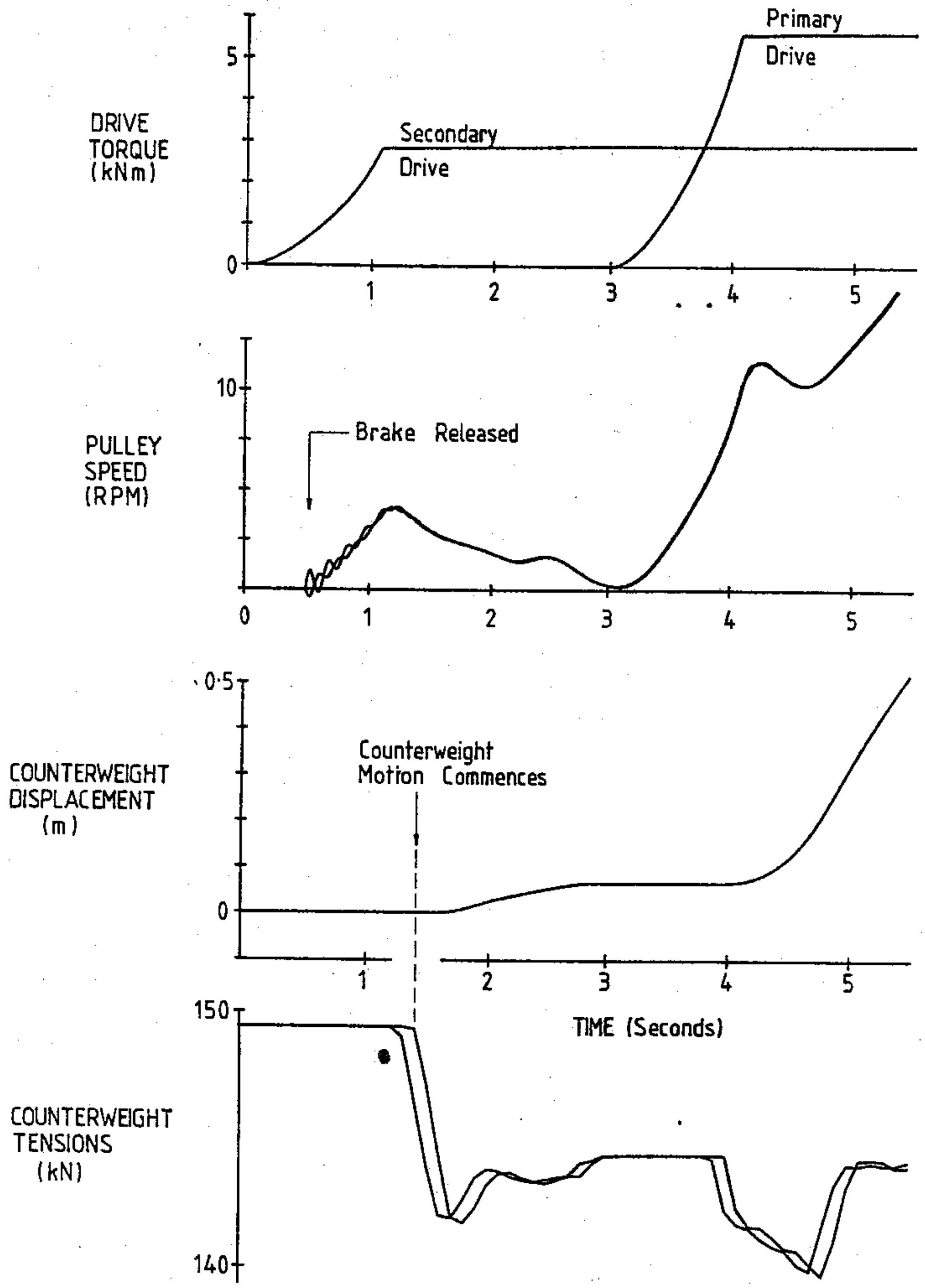

Fig. 11. DRIVE AND COUNTERWEIGHT BEHAVIOUR DURING START INITIATION - CONVEYOR B.

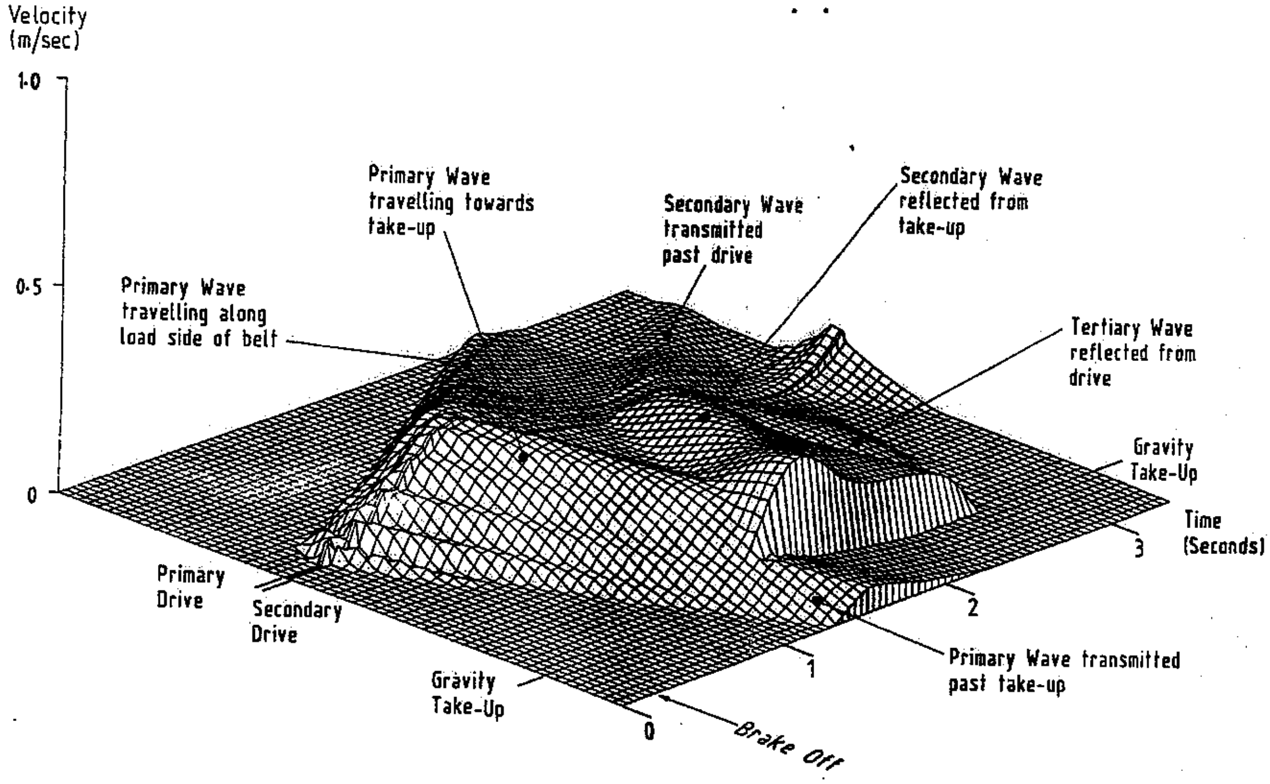

Fig. 12. DETAIL OF INITIAL VELOCITY WAVES FOLLOWING SECONDARY DRIVE START - CONVEYOR A.

side of the belt, propagates past the take-up without any significant reflection, and continues along the return side of the belt. However, about 0.2 to 0.3 seconds after the disturbance first arrives, the wave is almost totally reflected, resulting in a wave propagating back towards the drive, and a substantially higher peak velocity than occurred for the same wave in the system without the take-up (Conveyor A).

The reason why the wave is initially transmitted and then reflected is related to friction in the take-up. When the wave first arrives, tension differentials at the counterweight pulley are insufficient to overcome friction: the counterweight remains stationary and the take-up pulley rotates, allowing the velocity disturbance to propagate past the take-up. Once the counterweight begins to move, however, the upstream and downstream tensions are maintained relatively constant and velocity disturbances are primarily reflected.

Even when the counterweight is moving, tension and velocity disturbances arriving at the take-up are not completely reflected. Because of the intertia of the counterweight, a small part of the approaching disturbance is generally transmitted, as can be seen most clearly towards the rear of the velocity plot of Figure 6, after the arrival of the first stress wave following starting of the primary drive.

6.3 REFLECTION/TRANSMISSION AT DRIVES

The results plotted in Figures 6 to 11 are not particularly suited to examining reflection and transmission behaviour at the drives, since these are cases where the drives are the primary source of disturbances propagating in the belt.

Nevertheless, the tension and particularly the velocity carpet plots of Figures 9, 10 and 12 do illustrate the mechanisms involved, where the velocity disturbance reflected from the take-up, returns to the drive. It is evident from this that only a small proportion of the wave is reflected and that most of the disturbance energy passes the drive pulley, propagating down the loaded side of the belt until dissipated.

In elastic wave equation models, it is generally assumed that the drive is perfectly relective. Here is obviously a case where the drive is not.

The reason why the velocity disturbance should be transmitted rather than reflected, in this case, is related to the characteristics of the fluid coupling. At low fill level and high slip, the coupling torque is low, and the coupling appears relatively flexible to the approaching disturbance: the drive pulley rotates with the velocity disturbance (transferring belt to the loaded side).

Later in the start-up cycle, when fill levels are higher, the couplings are much stiffer and approaching disturbances are predominantly reflected.

For most drives, near maximum torque, the assumption of full reflection is probably reasonable. However the example quoted above, does illustrate the point that this assumption is not universally valid and that it is always better to use a model which does not rely on this assumption, but rather correctly simulates the basic physics under all conditions.

6.4 STANDING WAVES

The modelling results, presented as velocity/tension carpet plots, also demonstrate the formation of standing waves in the belt.

This phenomenon can be seen in the velocity plot of Figure 4, after the start sequence has finished and the belt has reached its maximum speed. For greater clarity, this part of the diagram is

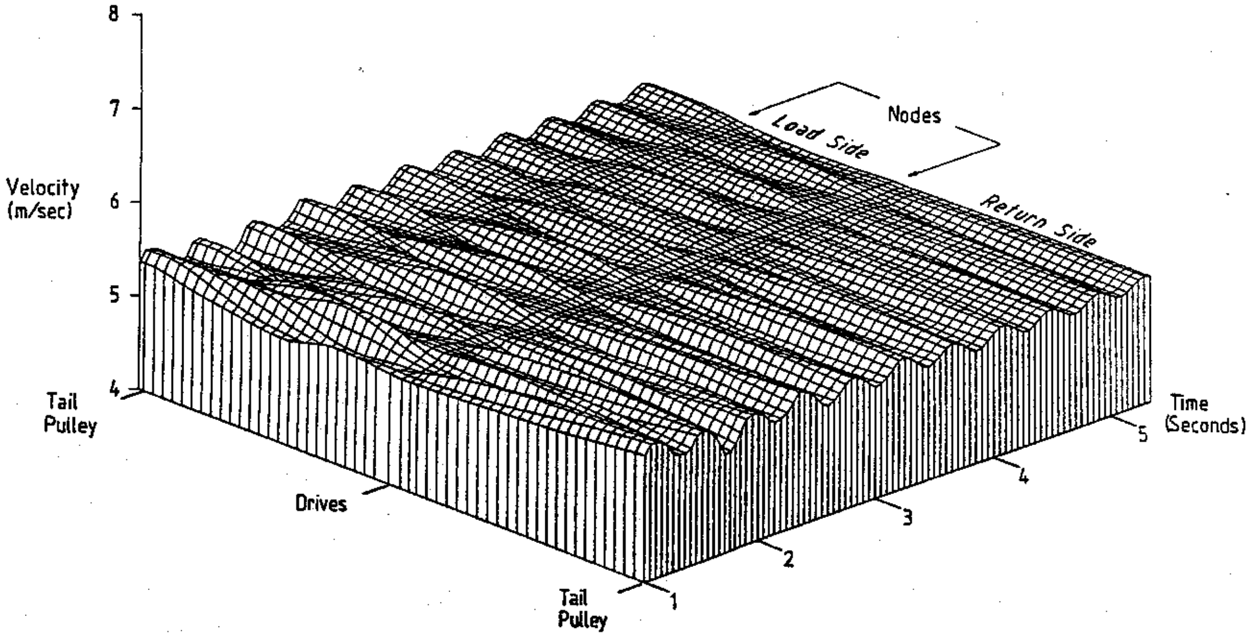

Fig. 13. STANDING WAVES AFTER ACCELERATION TO STEADY SPEED.

replotted in Figure 13 to larger scale.

For this particular conveyor configuration, a standing wave pattern is developed with two nodes, one at the drives (which now are primarily reflective) and the other at a point about two thirds of the distance along the loaded side of the belt. The location of this second nodal point is such that the wave propagation times from the drives are the same for waves approaching via the return belt or the loaded belt.

These standing waves decay in time, the rate of decay depending substantially upon the internal damping in the belt.

7.0 TRANSPORT OF MATERIAL ON THE BELT

The three-dimensional graphical presentation used for velocity and tension is also very useful for illustrating the movement of material on the belt in cases where the loading rate is varying or intermittent.

Dynamic modelling of situations where the loading on the belt varies along its length and in time is relatively difficult, requiring special techniques to avoid 'numerical' dispersion of the material. Without these special procedures, the material load is very quickly spread uniformly along the belt.

For this reason alone, it is important to check the behaviour of the model to ensure that it is in fact simulating the transport of the material load as it should. The correct result is very simple and obvious, and the quality of the modelling is easy to verify.

As an example of the use of these graphical techniques for checking material transport, the load behaviour for Conveyor A is given in figure 14. The condition simulated is the case where the loading rate varies from zero to a steady 1270 kg/second and then back to zero after a period of 60 seconds. This results in a

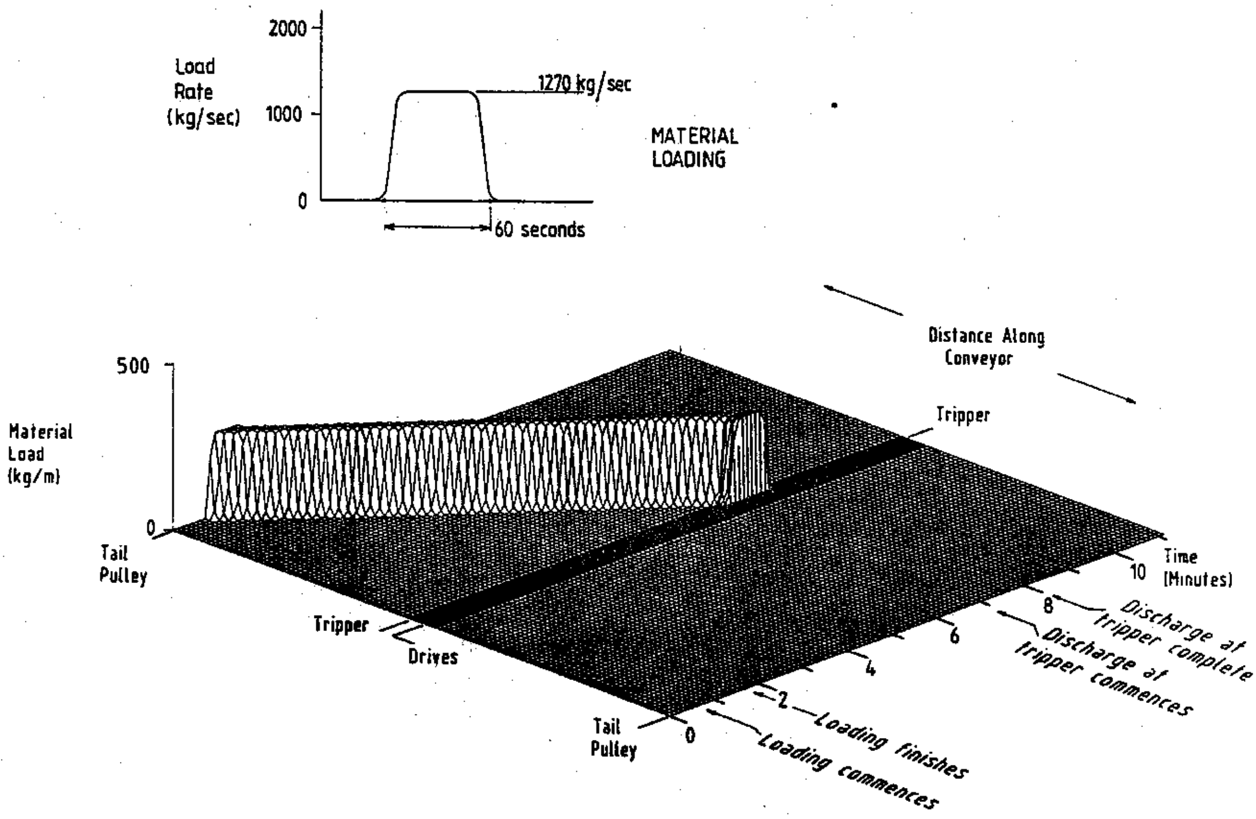

Fig. 14. TRANSPORT OF A BLOCK OF MATERIAL ALONG LOAD SIDE OF BELT.
(Belt at Steady Speed)

uniform block of material about 300m long being added to the belt. Transport of this block along the load side of the belt and its discharge at the tripper is illustrated in the Figure.

8.0 NUMERICAL INSTABILITIES

A major potential problem with any numerical model, and conveyor dynamic models are no exception, is the problem of numerical instability. The three-dimensional plotting technique described above has also proven extremely useful in identifying and correcting problems of this kind.

Numerical instabilities generally occur when the solution time step is too long. The model solution (velocities, tensions and other calculated variables in the case of conveyor models) will usually oscillate and diverge and when this happens the modelling results may bear no relationship whatever to real behaviour: in which case the results are of no practical use.

In the case of complex, non-linear models, it is not possible to calculate the time step required to guarantee stability and it is therefore usual for the selection of time step to be based on a process of trail and error.

Sometimes the onset of unstable behaviour is clearly obvious in the whole of the model output, but there are other times when this is not the case. There is a real danger therefore that an instability may remain undetected and that modelling results may be used and interpreted when in fact they are spurious.

This problem can and does arise with models that are nonlinear. Such models can be conditionally stable, the instability growing and decaying in time or being limited to one specific area of the model. In such cases, the instability can pass undetected unless the entire model output is examined.

This problem, as applied to conveyor dynamic models, is illustrated in Figures 15 and 16, which show the velocity carpet plots for Conveyor A for the first few seconds of the start cycle. Each of the plots of Figure 15 is simulating the same event, the only difference being the solution time step, which is shortest for Figure 15a and progressively longer for each of Figures 15b and 15c.

These results show the progressive development of a numerical instability, in this case initiating near the drive. For the shortest time step, the model is stable. At increased time step (Figure 15b) the model becomes incipiently unstable, the instability growing or decaying, as conditions at the drive vary. Increasing the time step further (Figure 15c) leads to earlier initiation of the instability, and an increase in magnitude with velocities ultimately diverging.

It is instructive to note however that in these cases the effects of the instability are apparently limited to a relatively narrow zone adjacent to the drive. Moreover, where the model is incipiently unstable, once the instability has decayed, there is nothing in the model output which would indicate that the model had been unstable. Unless the whole of the model output is monitored, the unstable condition and the fact that the results may be erroneous could well remain undetected.

If an instability persists, as shown in Figure 16, the entire model output will usually be effected, at least to some extent. However, as this diagram illustrates, except near the source of the instability, the model results can remain reasonably coherent and retain an appearance of plausibility. Velocity or tension disturbances which could be interpreted as belt stress waves might in these circumstances simply be the result of a numerical instability.

Provided the total model output is scanned, as is possible using

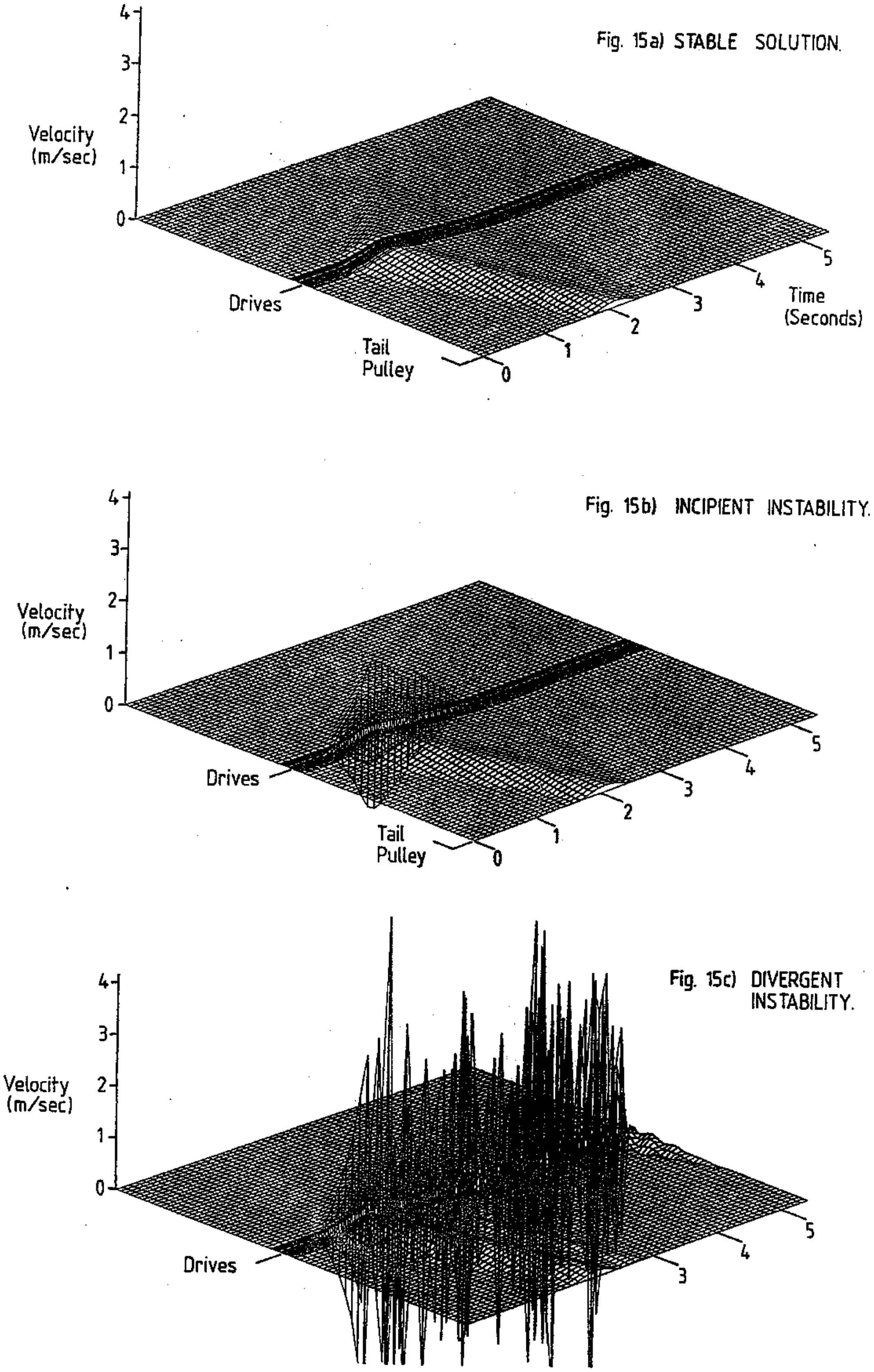

Fig. 15. NUMERICAL INSTABILITIES

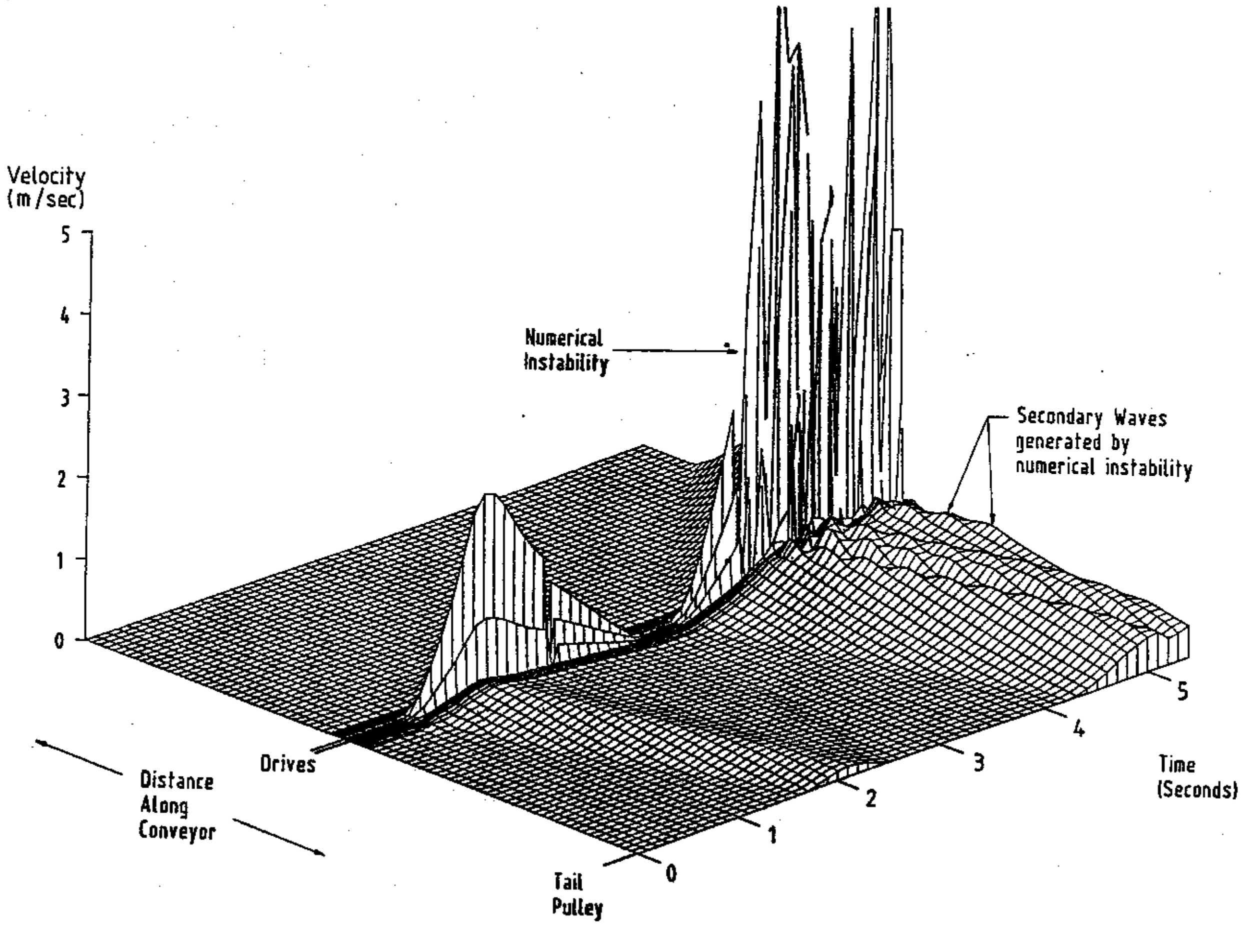

Fig. 16. SECONDARY WAVES GENERATED BY NUMERICAL INSTABILITY

3-dimensional plotting, the chances of an instability occurring without being detected are extremely small. Further, if there is an instability which is not detected with this kind of presentation, then its effects can safely be ignored.

9.0 CONCLUSION

With a finite element dynamic model of a conveyor and appropriate graphics, it is possible to generate three-dimensional plots depicting the behaviour of belt stress waves.

These visualisation techniques, which provide a complete picture of the tension or velocity dynamics for the whole of the belt, have proven extremely useful as an aid in understanding behaviour of a conveyor system during the design process.

In addition, these techniques are ideal, in fact essential in some cases, for detecting and correcting problems with dynamic models. Without this approach, it is sometimes possible for incipient numerical instabilities to remain undetected: for a model to provide believable but spurious results, even when calibrated.

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