Conveying of granular material using a periodically forced oscillator with dry friction

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Abstract

This paper focuses on the design and testing of a differential motion conveyor using a single linear motor as a drive. Integrating simulation with physical experiment is an important element in the successful design of the conveyor. The experiments and computer simulation explored in this paper are carried out to determine the change in behaviour of the material being conveyed, using various excitation profiles, when the surface properties of the trough bed are changed. The aim is to identify the system parameters where by the material is conveyed most efficiently.

1. Introduction

Traditional vibratory feeders have been designed using eccentric motors [1] and electromagnetic drives to give a shaking motion, ideal for use in sieving and separating. This is not always conducive to simply feeding. A different type of vibratory feeder that uses pure horizontal motion and stiction to move product [2] has shown to hold benefits over traditional conveyors for this type of process. These conveyors work on the principle of slipstick motion. The term slipstick refers to the motion of objects where self-excited vibrations occur due to successive slipping and sticking at a frictional interface [3]. Slipstick is present in a variety of mechanical systems, however, while most seek to lessen its effects differential motion conveyors look to capitalise on them.

Consumer demand for mass produced food and pharmaceuticals is great. In order to meet this demand companies in these industries have needed to increase their factory's outputs. To do this factories are becoming increasingly automated. Manufacturing rates need to be high and the way to meet these rates is through automation and the use of machines capable of a high capacity of throughput.

Conveyors within factories are used to ensure that the machines are fed at the correct rate. They are also used to deal with the increased output at the end of the process. The increased size of modern factories means that efficiently transporting product around the factory is difficult unless conveyors are utilised. Used in the food and pharmaceutical industry, they link machine to machine and process to process allowing the production process to flow and a high production rate to be achieved. Larger physical sizes of product can be moved at once as the limits on mass and size are much larger than those of a human body.

Vibratory conveyors in industry are used to sieve, separate and align product. They are particularly prominent in factories processing wet, heavy or non-uniform product. For example, cereal is formed into flakes from wet pellets. Before the flakes have been formed the pellets are damp and warm. They stick together in clumps making the forming of individual flakes difficult. Vibratory conveyors separate the pellets, preventing them sticking together, and ensure that the flakes can be formed with minimum problems.

New regulations brought in by the health and safety executive regarding noise levels in the work place, specifying that as of 2005 working environments must not exceed 80db [4]. Above this, ear protection must be worn, but all attempts must be made to keep the noise below this, preventing the need for ear protection. These regulations have alerted production managers to the need to replace old machinery with new quieter machinery. This is what has produced the market gap for a low noise vibratory conveyor. The difference in the way differential motion conveyors move product compared to traditional resonance conveyors means that they are quieter in operation.

This project is a Knowledge Transfer Partnership between The University of Northampton and local company Arnott Conveyors Ltd. The research completed will be put to use developing a commercially successful alternative to vibratory conveyors currently on the market while also furthering the use of innovative technology within this industry.

This paper focuses on the design and testing of a differential motion conveyor using a single linear motor as a drive. The aim is to identify the system parameters where by the material is conveyed most efficiently.

2. Simplified Model and Computer Simulation

A simplified rigid body model has been formulated to predict and analyse the behaviour of an object subjected to slipstick motion on a trough of the differential motion conveyor. A number of assumptions are made. The material being conveyed is assumed to be a single particle (in reality, it is a number of non-uniform particles). Thus, as it is a rigid body model it does not take into account the elastic modes of the trough and how they might influence the behaviour of the material being conveyed.

Differential motion conveyors work with a slow forward fast back motion profile. The time taken to move a distance forward is longer than the time taken to move the same distance backwards, giving a net movement of the particles in the forward direction. The conveying surface is displaced horizontally from zero at one speed, and returns at a faster speed. Particles on the conveying surface are subject only to the friction horizontal force which is proportional to the resultant normal force with the coefficient of friction between the particles and the conveying surface representing the constant of proportionality.

The computer model is designed to give an insight into how the material will behave on the surface of the trough of the conveyor. The aim is to identify the parameters of the system that will have the most influence on its behaviour. This should allow for the design of the most efficient profile and conveying method.

The model is based on the principles of slipstick motion [5]. The system with trough T and material of mass m is illustrated in Figure 1(a) and a free body diagram of the material during operation is illustrated in Figure 1(b).

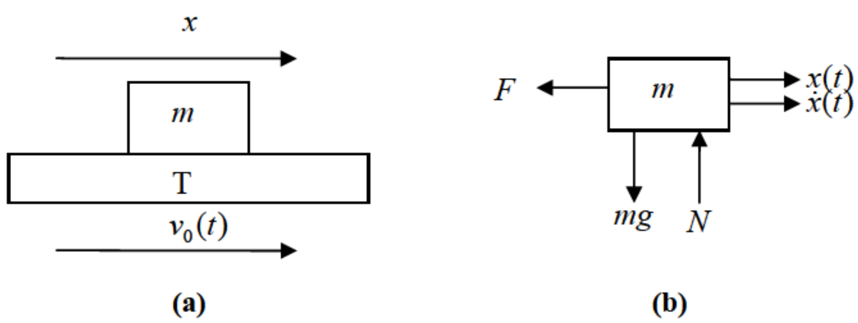


Figure 1: (a) Model of the conveyor trough and material. (b) Free body diagram

The resultant differential equation of motion is given as

$$m\ddot{x} = -F \quad (1)$$

where F is a friction force.

When the trough moves forward the material being conveyed is in contact with the trough and is acting under static friction conditions: $F \le F_S = \mu_S N$, where μ_S is the coefficient of static friction. During this phase of motion the mass m will move with the velocity and acceleration of the trough so that $\dot{x} = v_0$ and $\ddot{x} = \dot{V}_0$.

When the trough moves backward the material loses contact with the surface and is acting under kinetic friction conditions. Thus, $\dot{x} \ne v_0$ and the friction force is then expressed as

$$F = \mu_K N sign(\dot{x} - v_0) \quad (2)$$

where μ_K denotes the coefficient of kinetic friction, N=mg, with g being the acceleration of gravity, represents the normal force, $sign(\xi)$ represents the *signum function,* defined to have the value 1 for $\xi > 0$, -1 for $\xi < 0$, and 0 for for $\xi = 0$. Equation of motion (1) can be solved numerically to determine the motion of the material on the trough surface.

The input driving the simulation is the velocity time profile of the trough, $v_0(t)$. An example of this profile is shown in Figure 2. The velocity profile shown in Figure 2(a) is derived from the displacement profile shown in Figure 2(b). During the forward movement the trough is covering a distance of 0.04 m in 200ms giving a slower velocity while on the backward movement the trough is covering the same distance in 80ms. The resulting backward velocity is higher but in the opposite direction.

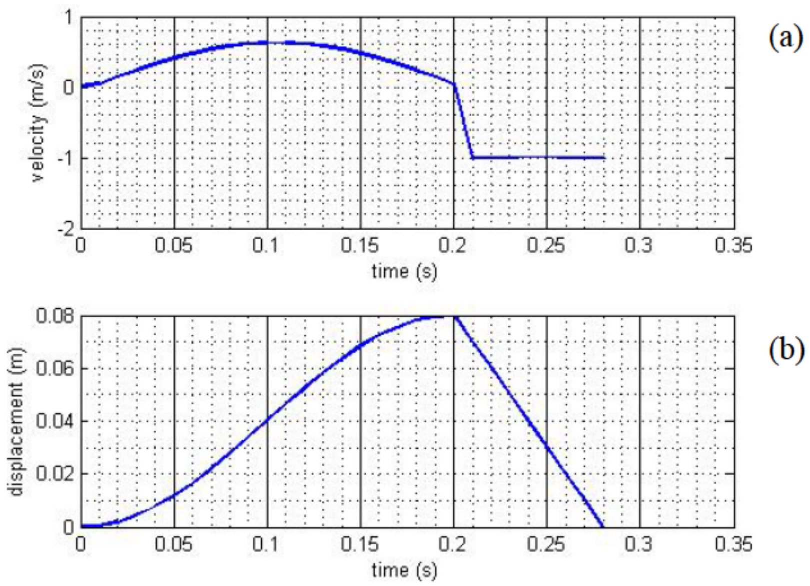
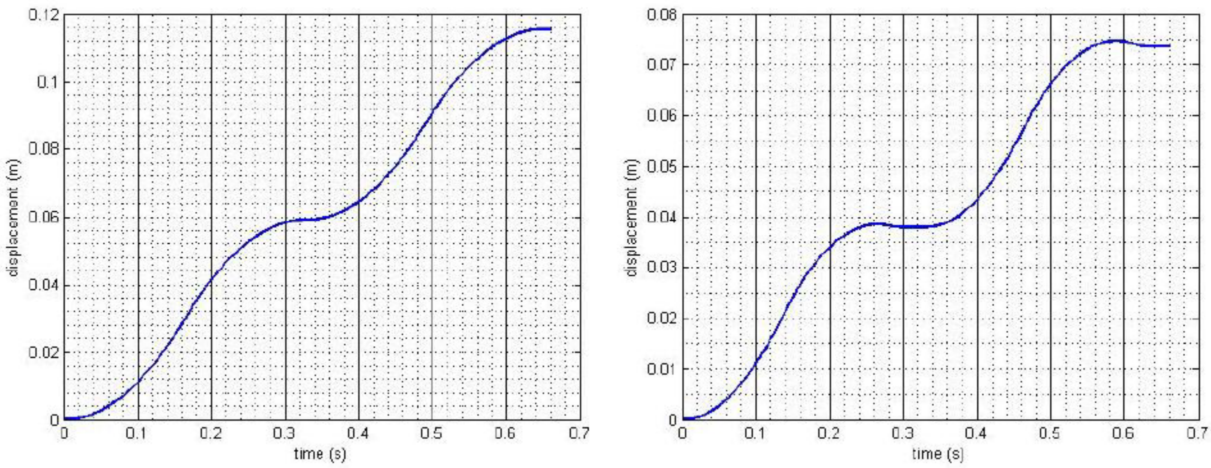


Figure 2(a): Velocity time profile, v_0. (b) Displacement time profile

By changing the parameters of $v_0(t)$ the factors that influence the behaviour of the material most can be observed. The results of the simulation conducted with the velocity profiles corresponding to forward stroke lengths of 0.04 m and 0.08 m, time 0.28s, a static friction coefficient of 0.7 and a kinetic friction coefficient of 0.5 are presented in Figure 3(a) and 3(b), respectively. The results consist of the velocity, $\dot{x}(t)$, and displacement, *x(t),* of the material being conveyed.



(a) (b)

Figure 3(a): Displacement when stroke length is 0.08m.

(b) Displacement when stroke length is 0.04m

Operating over the same time period, a larger stroke length will produce a faster conveying speed than a shorter stroke length. This is shown in Figure 3 where a 0.08m stroke length produces an overall displacement of material of just over 0.1m and a 0.04m stroke length produces an overall displacement of just under 0.08m in the same time period. A decrease in the time taken to cover the stroke length will also produce a faster conveying speed. The quicker the trough is moved backwards the quicker the material will lose contact with the surface minimising any backward movement of the material and so increasing the net forward movement.

The simulation can also highlight the role that friction coefficients have to play in the flow rate. Generally, lowering the friction coefficient will increase the flow rate. This statement only becomes untrue when the friction coefficients are so low that the material behaves under kinetic friction conditions on both the forward and backward movement of the trough. If this is the case the net forward movement of the material is reduced.

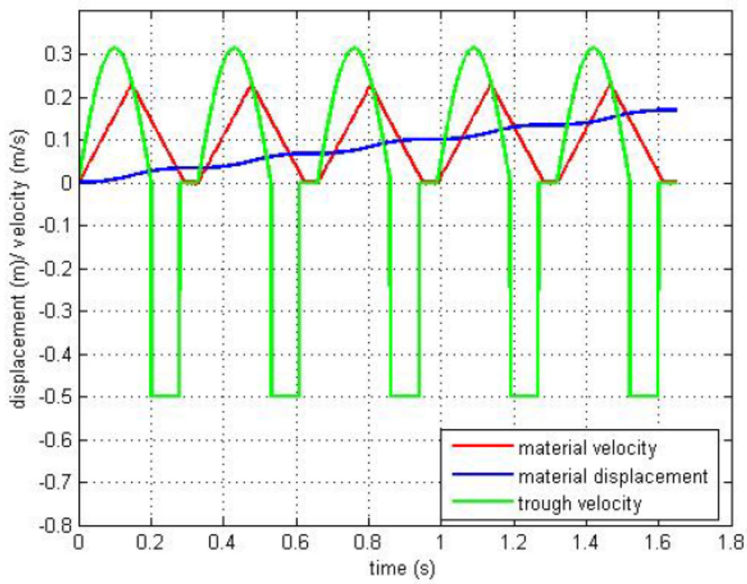


Figure 4: Displacement/ velocity time plot for low friction material

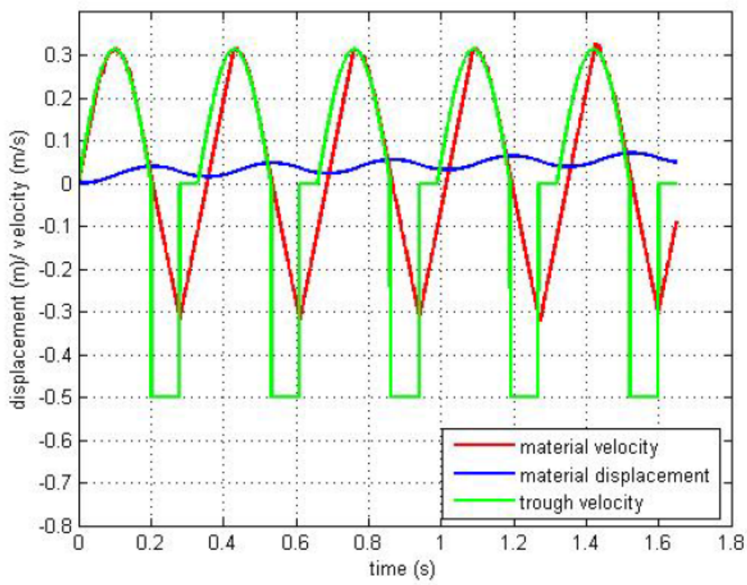


Figure 5: Displacement/ velocity time plot for high friction material

Shown in Figure 4 and Figure 5 are, the velocity of the material being conveyed (red), the displacement of the material being conveyed (blue) and the velocity of the trough (green). Comparing the low friction material (μ_s =0.21, μ_k =0.16) in Figure 4 to the high friction material (μ_s =0.5, μ_k =0.43) in Figure 5, the effects friction coefficients have on the displacement characteristics of the material are evident. In the same period of time the low friction material covers a distance of 0.17m while the high friction material covers a distance of 0.055m. Under low friction conditions the product loses contact with the trough almost instantaneously at the transition between the forward and backward movement (see Figure 4). High friction conditions mean the material being conveyed will stay in contact with the trough at the beginning of the back stroke (see Figure 5). This will prevent the material from travelling the full length of the stroke for each movement and will slow down the flow rate.

What is shown from the simulation is that the material displacement and conveying efficiency of the system depend on a range of parameters. Within the profile, the stroke length, time durations and frequency are the most influential. The most critical external influence is the friction coefficients between the trough and the material. While these can not be altered it is important to take them into consideration when designing the trough.

3. Physical Prototype

The majority of differential motion conveyors use eccentric motion drives coupled with pivoting legs to achieve the desired slow forward fast backward motion. This means that the trough follows an arc rather than a purely horizontal path. The design of the drive means that the control of the conveyor is limited. In order to change the parameters of stroke length, time and frequency that were discussed previously the conveyor must be stopped and the eccentric weights within the motor physically moved.

Linear motors have been used in this project to overcome these problems and ensure that the level of control of the conveyor is increased and the trough follows a purely horizontal path. Figure 6 illustrates how the linear motor is connected to the controller and peripheral devices while Figure 7 shows the physical prototype.

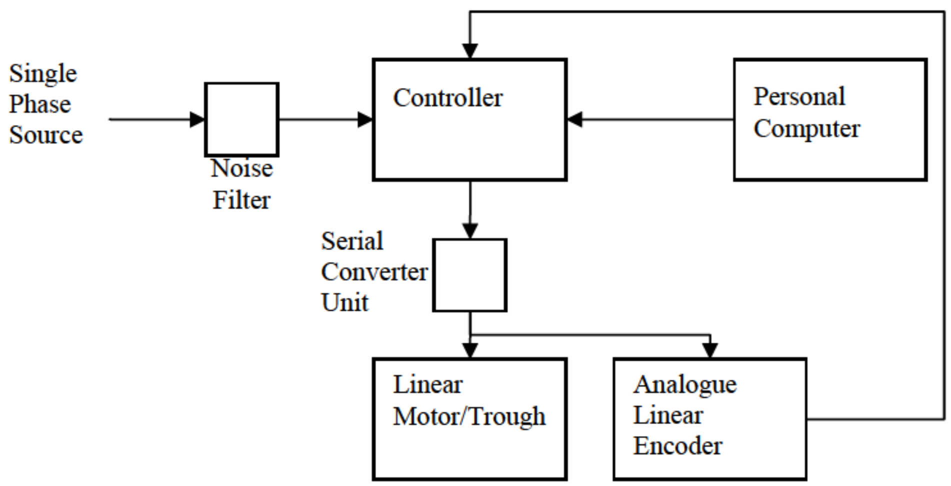


Figure 6: Block diagram of prototype

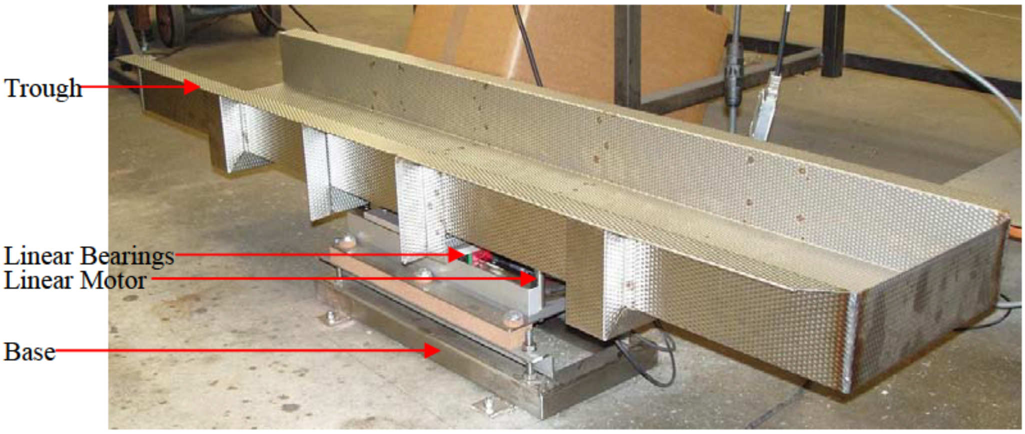


Figure 7: Physical prototype with linear motor

The prototype consists of an OMRON linear motor (peak force of 600N, rated force 280N) fixed to an aluminium base that can be adjusted to change the angle the motor sits at relative to the floor. The magnetic track of the motor is stationary on the base and the coil moves on linear bearings. The trough is attached to the coil of the motor by way of a bolted flange. This ensures that the motion of the motor is directly translated to the trough without any mechanical linkages. The linear motor is controlled by an XtraDrive servo drive. The linear encoder running in parallel with the linear motor provides a feedback loop into the controller. A personal computer is connected by a serial converter to the servo drive which in turn is connected to the linear motor. Alterations are made to the profile on the personal computer before being transferred to the linear motor.

4. Experimental Tests

4.1 Comparisons of Simulation Results and Experimental Results

The simulation was designed to run from a user defined profile generated in MATLAB. However, the linear motor allows for data to be taken from it and entered into the simulation as the driving velocity profile $v_0(t)$. Comparisons can then be made between the simulation and the physical prototype. Figure 7 shows $v_0(t)$ as generated by the linear motor.

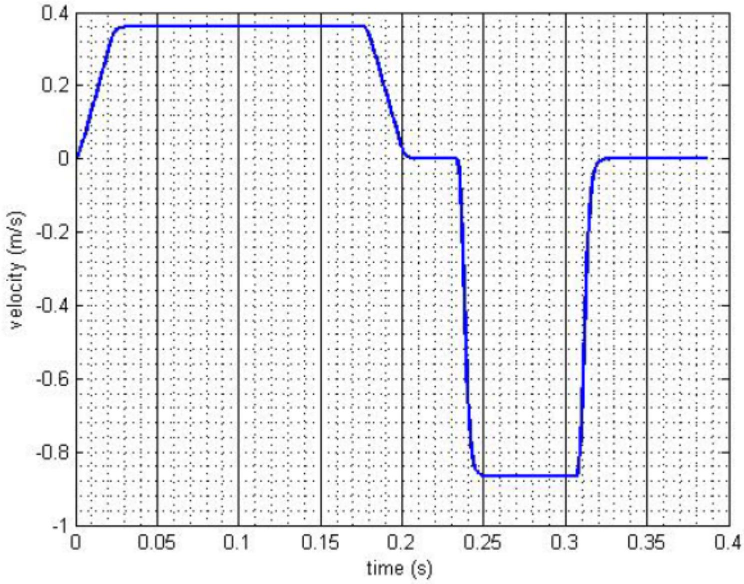


Figure 8: Linear motor velocity time profile

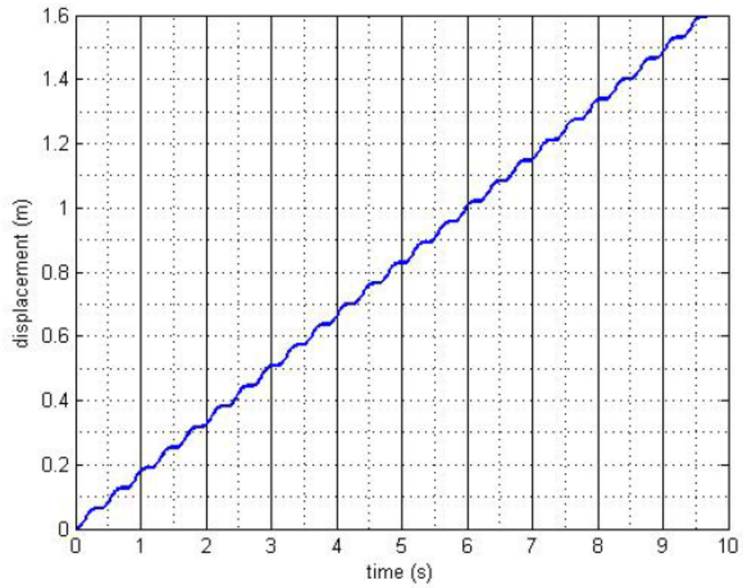


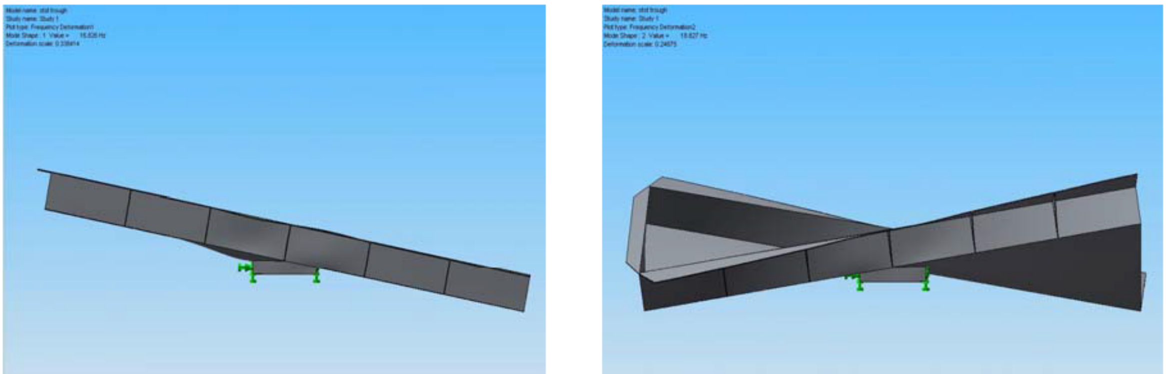
Figure 9: Displacement of material, $v_0(t)$ generated from linear motor

Using the velocity time profile shown in Figure 8, the simulation predicts that the material *(*cereal, μ_s *=0.33,* μ_k *=0.27)* will take 9 seconds to cover the 1.5 m length of the trough (see Figure 9). The same experiment was carried out on the physical prototype. The results are shown in Table 2. It takes 12.4 seconds for the material on the physical prototype to cover the same distance.

The most accurate representation of the simulation that can be set up on the physical prototype is to convey a single piece of material. The assumption made in the model that the material is a single particle is therefore correct and the behaviour observed when multiple particles are conveyed is disregarded. A single M16 stainless steel nut *(μ_s =0.4, μ_k =0.3)* was used for this test. The simulation predicted the nut would cover the length of the conveyor in 10 seconds. In reality the nut was conveyed the length of the trough in 10.39 seconds.

The assumptions made in the model effect the accuracy of the simulation. When used to predict the behaviour of a single particle the simulation is relatively accurate. When used for predicting the behaviour of multiple particles it becomes less accurate, predicting a faster rate of displacement than in reality. Used in this scenario, the simulation can predict the most influential factors but cannot give an exact representation of how the material is going to behave. The difference is not so marked as to prevent the simulation being useful but the reduced speed of the prototype must be taken into account.

The simulation is a rigid body model and thus overlooks the elastic modes of the system. These were investigated through FEM modelling and the two most influential modes are illustrated in Figure 10. These modes are not activated by the trough's motion as it operates at below 5 Hz and the first mode occurs above 10 Hz



(a) (b)

Figure 10: (a) 1st Elastic mode of trough (b) 2nd Elastic mode of trough

4.2 Profile Tests

Tests to convey granular material (cereal) were conducted in order to assess the performance of the conveyor. Table 1 describes the different profiles that were used in the tests, where profile 1 is based on FMC Corporations displacement time profile [6]. The linear motor allows for the displacement and the time in which the displacement is covered to be altered.

MOTION PROFILE	DESCRIPTION
1	Displacement = 40mm, Forward Movement Time = 200ms, Backward Movement Time = 80ms, No Delay
2	Displacement = 40mm, Forward Movement Time = 200ms, Backward Movement Time = 80ms, Delay = 100ms
3	Displacement = 40mm, Forward Movement Time = 200ms, Backward Movement Time = 80ms, Delay = 50ms
4	Displacement = 40mm, Forward Movement Time = 200ms, Backward Movement Time = 80ms, Delay = 25ms

Table 1: Test Profiles

Running the motor under the conditions of profile 1 (see Figure 8) highlighted the material behaviour that was not accounted for in the simplified model and could not be evident from the simulation. The product on the bare trough tends to spread out before moving and does not cover the complete stroke length. The material continues to act under kinetic friction at the beginning of the forward movement preventing it from covering the complete distance. Heavier materials display a faster conveying speed than lighter materials because they come to rest quicker, therefore travelling a greater proportion of the distance. In order to ensure that the lighter products travel the whole stroke length they must come to rest before the start of the following stroke. This is achieved by inserting a delay between the end of the backward movement and the start of the following movement. The length of the delay is dependant on the product being moved. If the delay is too short the product will display slip as discussed above, if it is too long the product will be at rest longer than necessary and the conveying speed will be decreased rather than increased. The motion profiles described in Table 1 were used throughout the prototype experiments.

The motion profile is altered each time by inserting a delay of various lengths. The success of the profile is gauged on the time taken for the material to cover the full 1.5 m length of the trough.

MOTION PROFILE	TIME TAKEN TO CONVEY MATERIAL (s)
1	12.4
2	11.93
3	10.56
4	10.78

Table 2: Profile Tests.

Table 2 shows the difference the addition of a delay makes to the displacement rate. Time is measured as how long it takes for the material being conveyed to travel 1.5m. The 25ms delay in profile 4 is not long enough to allow the product to come to rest, while 100ms in profile 2 sees the product is at rest for longer than necessary. For the product used in this experiment profile 3, 50ms delay time, is the most successful.

This experiment was only carried out using a small amount of product in the trough. With the trough full of product (3 inches deep) the way in which the product moves is different. The interactions between particles are different compared to when there is only a small amount of product. The particles at the back push the particles at the front forward and off the end of the trough as well as preventing the particles from spreading out.

The results from the simulation and the prototype are combined to give the optimum running conditions for the conveyor. To run the conveyor at its most efficient the profile should be adapted for the material which is being conveyed on it. However, it is not possible to specify a profile for all materials that are likely to be conveyed. The best way to overcome this is to design a basic profile for different categories of product that can be adapted by the final user to suit the exact grade of material being conveyed.

4.3 Friction Tests

The simulation demonstrated that the friction between the trough surface and the material being conveyed influenced the conveying speed (see Figures 3 and 4). A similar test was run on the physical prototype. The surface of the trough was changed to display varying friction coefficients from low friction carbon fibre reinforced plastic ($\mu_s=0.3$) to high friction rough sandpaper ($\mu_s=0.73$). The test was run using cereal as the material being conveyed. The results are shown in Table 3.

MOTION PROFILE	SURFACE	TIME (s)
1	CFRP μ_S=0.3	12.4
1	SILICONE RUBBER μ_S =0.45	+25
1	SMOOTH SANDPAPER μ_S =0.56	+25
1	ROUGH SANDPAPER μ_S =0.73	+25

Table 3: Surface Friction Tests

Only the Carbon Fibre Reinforced Plastic (CFRP) surface allows the trough to be cleared in less than 25 seconds. The higher friction surfaces prevent the particles from sliding along the trough. They stay in contact with the trough on both the backward motion and the forward motion. Therefore, the net movement of the particles is small.

5. Summary and Conclusions

This paper has discussed the key factors influencing the conveying of granular material using a differential motion conveyor with a periodically forced trough. A computer simulation has been conducted and a physical prototype with linear motor discussed.

It has been shown that there is an optimum profile to follow in order for conveying to be as efficient as possible. Different products behave differently and therefore need different profiles. If the wrong profile is used it can lead to the product slipping or resting and the resulting conveying speed being decreased.

Future work will include developing a more accurate simulation model to predict the behaviour of the material on the trough. The model should accommodate the interactions between the particles in the conveying material. It could then be used to pre-empt what profile should be used without the need for physical testing. However, some more effort would have to be put into providing accurate material properties for the product to be conveyed.

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