Vibratory conveyor with elliptical oscillation is quiet and fast

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Abstract:

The article concerns invention of a vibratory conveyor driven by two unbalance motors which are arranged to generate an elliptical oscillation of a linear or spiral conveyor track. The elliptical oscillation increases the conveyor speed, reduces noise, reduces energy consumption, reduces wear of the conveyor track and extends the service life as compared to linear oscillation. The basic principles of vibratory conveying technology are explained with a focus on the issue of vibratory bowl feeders designed to feed billets in forging lines.

Keywords: vibratory conveyor, vibratory bowl feeder, spiral elevator, elliptical oscillation

1 Introduction

Vibratory conveyors and feeders are used in many industries for horizontal and vertical transport, sorting and orienting of parts of various shapes and sizes including bulk material. Vibratory feeders can arrange parts from a loose stockpile into a single row so that the parts come out of the feeder equally oriented one after the other and can be processed by an automated production line. Thanks to this capability they are often installed in forges to automatically feed billets into forging lines [1]. Their advantages include simplicity, mechanical robustness and the ability to convey a wide range of shapes and sizes. In many forging lines they successfully replace manual work and ensure reliable and quiet feeding.

Beside completely trouble-free applications there are also known cases in practice where the vibratory feeder under certain conditions does not feed reliably, does not achieve the required conveyor speed or exhibits extremely high noise levels. The causes of these problems are explained below and a new vibratory conveyor design developed by ROBOTERM is presented which eliminates the existing problems. Fig. 1 shows the vibratory bowl feeder for feeding billets into forging lines on which the benefits of the new solution are demonstrated.

Fig. 1 - Vibratory bowl feeder for automatic feeding of billets into forging lines

2 The principle of vibratory conveyors

There are many different designs but the common basis of all vibratory conveyors is a conveyor body with a conveyor track that performs periodic oscillations. The conveyor track can be linear for horizontal conveying or spiral for vertical conveying. The oscillations can be excited by different types of drive [2]. Electromagnets or various unbalanced rotor drives which include in particular unbalance motors are most commonly used to excite vibrations in practice.

Vibrations are characterized by the shape of the oscillation, its amplitude and frequency. The various modes of oscillation of vibratory conveyors are investigated in detail in [3]. A plane harmonic oscillation can be straight, circular or elliptical. The oscillation can be decomposed into a horizontal and a vertical component. If the components are in the same phase the resulting oscillation is straight and the ratio of the components determines its inclination. If the components are phase shifted the resulting oscillation is elliptical or circular.

For the acceleration a, the amplitude y and the angular frequency ω of the harmonic oscillation relation (1) is valid which can be applied to both the horizontal and vertical components of the oscillation.

$$a = -\omega^2 \cdot y \qquad (1)$$

From the horizontal and vertical acceleration components the inertial and frictional forces can be calculated which specify the character of the material movement. At low accelerations the material lies on the track and does not move. If the inertial forces exceed the frictional force the material starts to slide along the track. If the vertical component of the acceleration of the track exceeds the gravitational acceleration the material begins to jump. The actual motion of the material can be complex and mathematically difficult to describe. Parts or particles of bulk material can slide, jump, roll, swing and bounce off the track and each other in different ways.

The character of the oscillation and material movement varies according to the application. Higher frequencies usually electromagnetically excited are used for conveying light parts and fine bulk material. The gravitational acceleration is exceeded and the particles perform short jumps (called microjumps). Lower frequencies and drives with unbalanced rotors are more often used for transporting heavy parts. In this case exceeding the gravitational acceleration is undesirable as the vibrating machine becomes extremely noisy when heavy parts are bouncing. The material only slide with both forward and reverse slide usually occurring during one period of oscillation. At low accelerations the sliding phase is short and is followed by adhesion of the material to the track. At higher accelerations the material is permanently sliding and only the direction of sliding changes from forward to reverse and vice versa. A higher feed rate is achieved with permanent sliding than with partial sliding.

3 Unbalance motor driven vibratory conveyors

This article focuses on vibratory conveyors driven by unbalance motors which are electric motors with an unbalanced rotor designed to excite vibration. Unbalance motors are attached to a flexibly mounted body with a conveyor track and excite its vibration. Usually adjustable weights are placed on the rotor of the unbalance motor to set the magnitude of the excitation force. The greater the excitation force, the greater the amplitude of the oscillation and its acceleration. For example a six-pole asynchronous vibration motor has an excitation frequency of 20 Hz at a supply frequency of 60 Hz and a synchronous speed of 1200 rpm.

3.1 Linear vibratory conveyor

The conveyor track is in the shape of a trough or tube and is elastically mounted. One or more unbalance motors are attached to the track. For conveyors with one unbalance motor the rotor axis is horizontal and perpendicular to the direction of conveying. If the unbalance motor is located in the center of gravity of the conveyor it will excite circular oscillations of the track. For conveyors with two unbalance motors (Fig. 2) the motors are placed symmetrically usually on the sides. The unbalance motors synchronize spontaneously when switched on so that the components of the centrifugal force acting sideways cancel each other out. If the total excitation force passes through the center of gravity of the conveyor each point of the track performs equal oscillations consisting of vertical and longitudinal oscillations. If the vertical and longitudinal oscillations are in the same phase the resulting oscillation is a straight oblique oscillation. If the excitation force takes place outside the center of gravity of the conveyor an excitation torque is generated, the track performs swinging oscillations and a different oscillation shape can be observed at different points along the track.

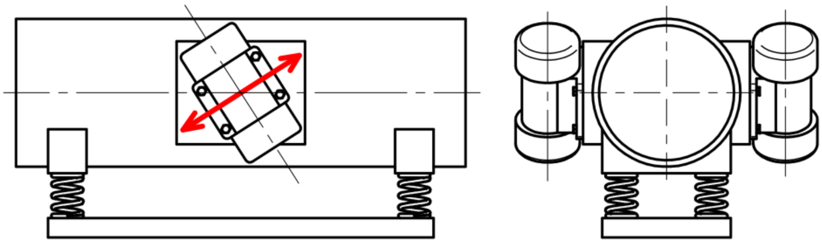

Fig. 2 - Linear vibratory conveyor

3.2 Spiral vibratory conveyor

These include vibratory bowl feeders (Fig. 3) which are mainly used for automatic feeding and spiral elevators which are used for vertical material transport. In vibratory bowl feeders the spiral track rises along the inner wall of a flexibly mounted bowl while in spiral elevators the spiral track rises along the outer wall of a flexibly mounted column. The unbalance motors are placed axially symmetrically and synchronize spontaneously when switched on so that the components of the centrifugal force acting radially to the vertical axis cancel each other out. The vertical and tangential components of the acting forces excite vertical and torsional oscillations of the conveyor track. If the vertical and torsional oscillations are in the same phase the track oscillates along the helix and a straight oblique oscillation can be observed at each point.

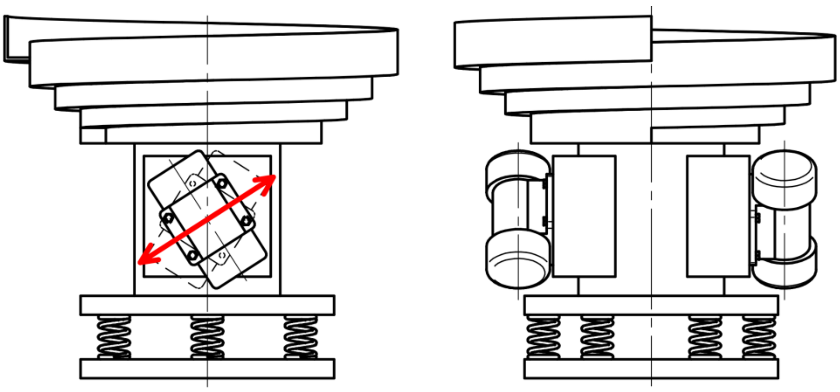

Fig. 3 – Spiral vibratory conveyor

4 Conveyor speed

This chapter discusses the causes of insufficient conveyor speed problems in vibratory conveyors driven by unbalance motors that do not significantly exceed gravitational acceleration in operation. The conveyor speed of a particular vibratory conveyor can vary over a wide range because it is strongly influenced by multiple factors that can change in operation.

4.1 The influence of friction

Based on a mathematical model, experiments and observations carried out by ROBOTERM, it was found that the friction between the material and the conveyor track has a very significant effect on the conveyor speed. Friction can be a critical factor that determines the direction of material movement which is especially valid for a rising conveyor track. Using a physical model of a linear vibrating conveyor with a horizontal track and circular oscillation it was observed that objects made of different materials move not only at different speeds but also in some cases in opposite directions. For vertical transport on a spiral track it is generally true that materials with higher friction reach higher speeds. It has been observed on vibratory bowl feeders with a straight oscillation designed to feed forging lines that rusted steel billets reach high feeding speed (up to 100 mm/s) while smooth billets move much slower. Especially if the surface of the billets is greasy or wet undesirable backward movement can sometimes be observed.

4.2 The influence of shape

Higher speeds are achieved by elongated shaped parts that lie well on the track. Lower speeds are achieved by shapes that can wobble or roll. The frictional force acts mostly at the point of contact underneath the conveyed part and exerts a moment against its center of gravity that can cause the part to tilt or roll. The parts may thus oscillate by swinging motion instead of sliding. When conveying cylindrical steel billets on a spiral track it can be observed that billets with a large length/diameter ratio reach higher speeds. A wobbling can be observed in case of short cylindrical billets. Wobbling and swinging is also found in barrel shaped billets which are sometimes produced by shearing a round steel bar.

4.3 The influence of filling weight

Another factor affecting the conveyor speed is the weight of the vibrating masses which in vibratory bowl feeders changes during operation as the weight of bowl charge changes. Ignoring the effect of the suspension, the constant excitation force of the unbalance motors causes larger amplitude of oscillation and a greater acceleration in an empty bowl than in a full bowl. In practice the effect of the suspension cannot be neglected as the oscillation can be strongly influenced by resonance. Unbalance motor driven conveyors generally operate above resonance which means that the excitation frequency of the unbalance motors is higher than the natural frequency of the elastically mounted body with the conveyor track. When starting or stopping the unbalance motors a transition over the natural frequency can be observed during which there is a short-term increase in amplitude. The natural angular frequency ω_0 of an elastically mounted body depends on the stiffness k of its mounting and the mass m of the body according to relation (2).

$$\omega_0 = \sqrt{\frac{k}{m}} \qquad (2)$$

The elastically mounted body of a vibrating conveyor can oscillate in different ways in space and has multiple natural frequencies. The conveyor speed is most affected by the natural frequency of vertical oscillations which is usually higher than the natural frequency of longitudinal or torsional oscillations and more closely matches the excitation frequency of vibratory motors. It follows from relation (2) that if the mass of the vibrating charge decreases as the bowl is emptied the natural frequency increases and approaches the excitation frequency. This is followed primarily by an increase in the vertical component of the oscillation and hence the vertical component of the acceleration. For linearly oscillating vibratory bowl feeders it can be observed that an empty bowl has a steeper inclination of oscillation than a full bowl. Therefore an empty bowl may have poorer conveying capacity and a higher noise level. The full vibratory bowl is characterized by a gentler inclination of oscillation and smaller oscillation amplitude in both vertical and horizontal directions. The smaller oscillation of the full bowl is due to the larger distance from the resonance and the larger filling weight at constant excitation force. A too small oscillation also causes a reduction in conveyor speed. This implies that there is an optimum weight of filling for the maximum conveyor speed. The effect of the filling weight on the conveyor speed can be reduced by controlling the speed of the unbalance motors which is discussed in Chapter 5.

4.4 The influence of suspension stiffness

According to relation (2) the natural frequency can also be affected by the stiffness. The stiffness of the suspension can vary during operation if the vibratory conveyor body is mounted on rubber springs which unlike steel springs do not have a constant stiffness and exhibit hysteresis. The stiffness of rubber springs is greatly affected by temperature. It has been observed in practice that low temperature increased the stiffness of rubber springs, brought the vibratory feeder closer to the resonance of vertical vibrations and reduced the conveyor speed. Aging of the rubber can have a similar effect because it also increases its stiffness. Optimally the spring stiffness should be adjustable to compensate for the effect of the filling weight and to keep the natural frequency constant. This can be achieved with air springs and pressure regulation.

4.5 Possibilities to increase conveyor speed

If the feeder speed is not sufficient it can be increased by increasing the amplitude and frequency of the oscillations. The amplitude of the oscillation can be increased by adjusting a greater unbalance of the unbalance motor, the frequency can be increased by increasing their speed if they are powered by a frequency converter. However, both of these parameters increase the acceleration according to relation (1) and can lead to material jumping and excessive noise. Conveyor speed can therefore be limited by the maximum acceptable noise level. The Fig. 4 shows the measured noise level of a VZ 1800 vibratory bowl feeder filled with 1161 kg of steel billets as a function of the vertical acceleration component *a* given in multiples of the gravitational acceleration g. The acceptable noise level depends on the ambient noise level. In an industrial forge the noise of the surrounding machinery can overpower a vibratory feeder operating at 1.2 g.

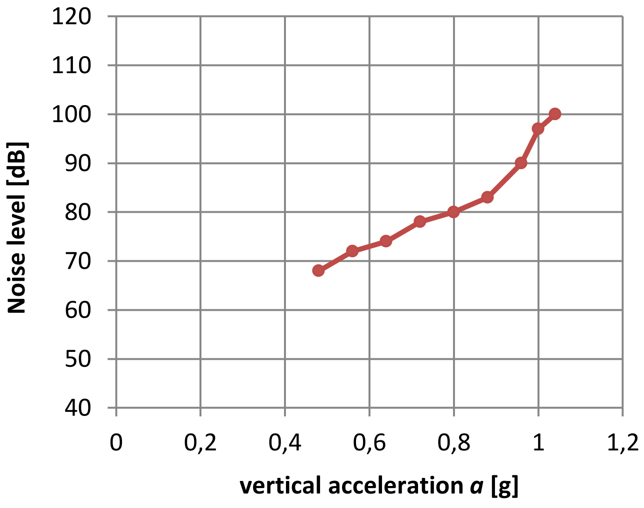

Fig. 4 - Dependence of noise on the vertical component of acceleration *a*

Since the acceleration according to relation (1) increases with the square of the frequency it is more advantageous to increase the amplitude and slightly decrease the frequency in order to maintain the acceleration. But too low a frequency will bring the running closer to the resonance of the vertical oscillations and again increase the acceleration, reduce the conveyor speed and increase the noise. This fact can be seen from the Fig. 5 where a minimum of vertical acceleration *a* can be observed for an empty VZ 1800 vibratory feeder at an exciting frequency *f* around 11 Hz. The resonance therefore determines the lower speed limit of the unbalance motors. The resonance can be postponed further away from the exciting frequency by reducing the natural frequency which can be achieved e.g. by reducing the number of springs or increasing the weight of the elastically mounted body but at the cost of greater stress on the springs or a reduction in the load capacity of the vibration machine. Another possibility to achieve higher speed is to optimize the shape of the oscillation by changing the position of the unbalance motors which is the subject of Chapter 6.

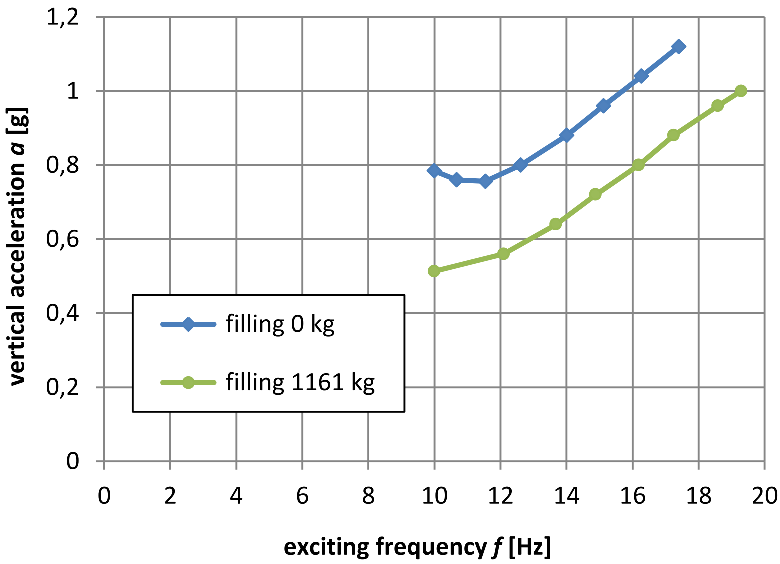

Fig. 5 – Dependence of the vertical acceleration component *a* on the exciting frequency *f*

5 Unbalance motor speed control

Speed control is particularly advantageous for vibratory feeders whose charge weight varies during operation. With a full feeder the amplitude and acceleration will decrease so it is advantageous to increase the speed of the unbalance motors. Conversely with a small charge weight it is advantageous to reduce the speed to avoid material bounce large noise generation. If the vibratory feeder is equipped with a frequency converter and an accelerometer that measures the vertical component of acceleration the speed of the unbalance motors can be controlled automatically. The speed control then maintains a constant vertical acceleration of the oscillation allowing maximum feeding speed with minimum noise with both full and empty feeder. The condition for functional speed control is that the vertical acceleration increases with frequency. This means that the control cannot work with too low a frequency near the resonance where this dependence becomes invalid (Fig. 5).

If the vibratory feeder is equipped with an accelerometer the actual weight of the charge can be continuously calculated from the measured acceleration and the known speed of the unbalance motors. The control software can then alert the operator to refill if the current fill weight drops below a set minimum limit. Automatic refilling of the feeder in fully automatic operations can be controlled in the same way.

6 Elliptical oscillation

A harmonic plane oscillation is defined by three variables: the vertical amplitude, the horizontal amplitude and the phase shift between them. Until now vibratory conveyors with two unbalance motors have mainly used straight oblique oscillation which is a special case of general oscillation and is characterized by zero phase shift. Existing research on optimizing the oscillation shape [3, 4] shows that an elliptical oscillation is more efficient. Elliptic oscillation also occurs in practice [5, 6, 7, 8] but rarely because these methods of achieving elliptic oscillation are in general more complicated.

It is more practical to define oscillation in terms of total amplitude, inclination and ellipticity. The total amplitude is determined by the unbalance of the unbalance motor. The inclination and ellipticity are determined by the position of the unbalance motor axis, which can be defined by two angles. The inclination of the unbalance motor axis seen in Fig. 2 a Fig. 3 determines the inclination of the oscillation and is commonly optimized in practice. The lean angle of the unbalance motor axis seen in Fig. 6 a Fig. 7 determines the ellipticity and is zero in current practice. The invention is based on the non-zero lean angle of the unbalance motor axis and is described in detail in the patent application [9]. The lean of the unbalance motor can be applied to both linear and spiral vibratory conveyors and can excite an elliptical oscillation in both cases.

6.1 Excitation of elliptical oscillations of a linear conveyor

To excite an elliptical oscillation of a vibratory conveyor with a linear track the unbalance motors must be symmetrically arranged and their axes must form intersecting lines (Fig. 6). The lean of the unbalance motor can be achieved by tilting the bearing plates to which the unbalance motor is bolted by its flange. It is advisable to position the unbalance motors so that the connecting line of their centers passes through or near the center of gravity of the conveyor. This ensures that the resulting excitation force passes through the center of gravity of the conveyor and does not excite a moment that would cause swinging oscillations.

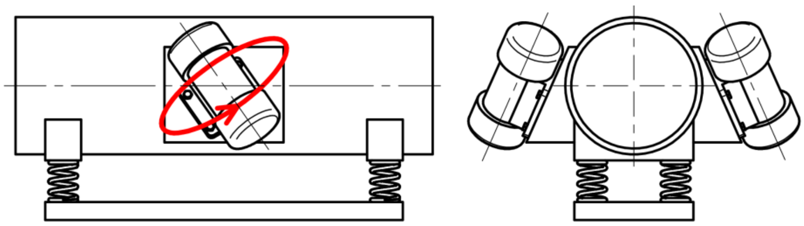

Fig. 6 – Linear vibratory conveyor with tilted unbalance motors

6.2 Excitation of elliptical oscillations of a spiral conveyor

On a spiral conveyor the unbalance motors are placed axially symmetrically and their axes form skew lines. The axes of the unbalance motors have a non-zero angle with the plane perpendicular to the connecting line of the unbalance motor centers which causes an elliptical oscillation. This positioning of the unbalance motors can be achieved by tilting the bearing plates to which the motors are bolted (Fig. 7) or by moving the unbalance motors sideways on the vertical bearing plates (Fig. 8). The relative positions of the unbalance motors in Fig. 7 and Fig. 8 are equivalent. If insufficient conveyor speed is a problem with the vibratory conveyor in operation it is advantageous to induce an elliptical oscillation by moving the unbalance motors as this can be done without demanding structural modifications.

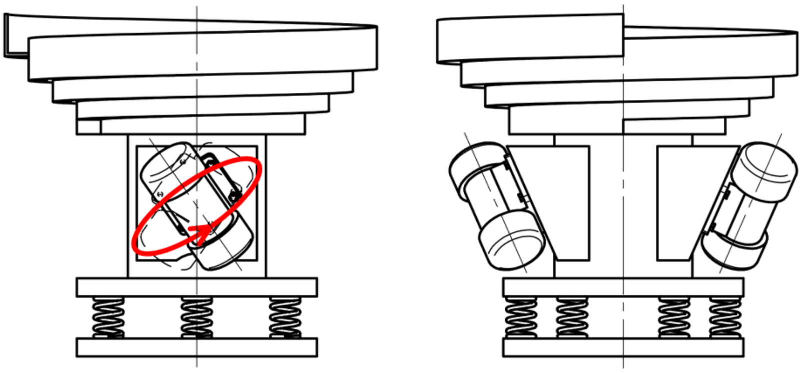

Fig. 7 – Spiral vibratory conveyor with tilted unbalance motors

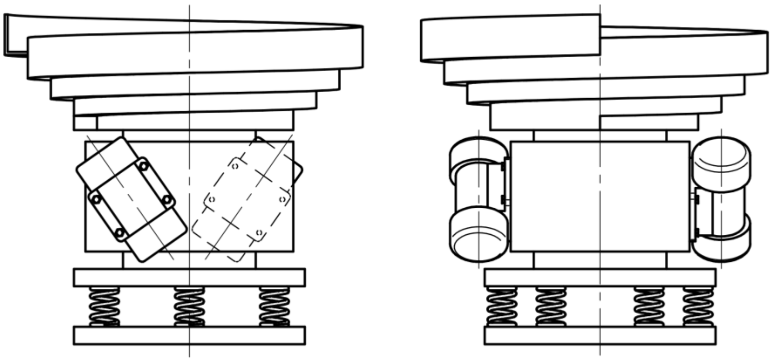

Fig. 8 – Spiral vibratory conveyor with displaced unbalance motors

6.3 Increase in conveyor speed

The ellipticity of the oscillation is another parameter that can be optimized to achieve higher conveyor speed. At the ROBOTERM company measurements were carried out on a VZ 1800 vibratory bowl feeder to evaluate the effect of the ellipticity of the oscillation on the conveyor speed. Two positions of unbalance motors with different displacements on the vertical bearing plate as shown in Fig. 8 were tested. For each position both directions of rotation of the unbalance motors and thus both directions of the elliptical oscillation were measured. Changing the direction of rotation has the same effect as moving the unbalance motors to the opposite side or tilting the unbalance motors at the opposite lean angle. In total four variants of the elliptical oscillation were tested. The vertical amplitude and therefore the vertical acceleration was always the same. For each variant of oscillation the conveyor speed of different billets was measured. The results of the measurements are shown in Fig. 9.

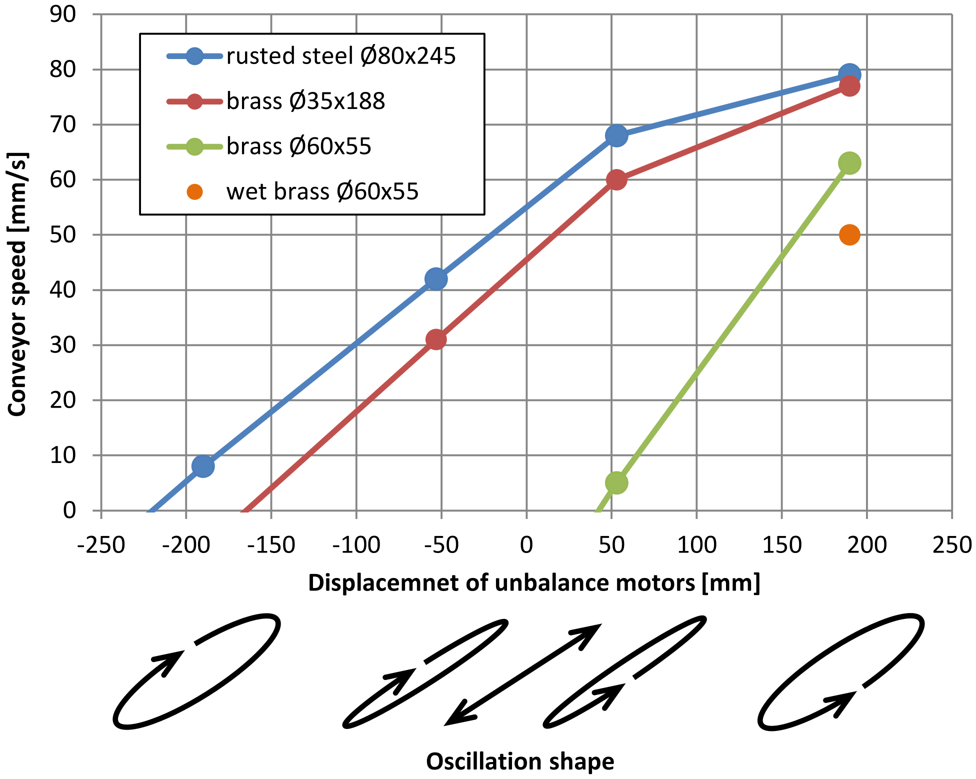

Fig. 9 - Dependence of the conveyor speed on the ellipticity of the oscillation

Measurements have shown that the elliptical oscillation in the correct direction significantly increases the conveyor speed. With elliptical oscillation high conveyor speeds have also been achieved for low-friction materials that do not move forward or move backward on vibratory conveyors with a straight oscillation and rising track. In critical cases the ellipticity of the oscillation is the decisive factor for the correct operation of the vibratory conveyor.

With the correct direction of the elliptical oscillation the track in the lowest point of oscillation moves in the conveying direction. There is a maximum vertical acceleration at the lowest point and the material is most pressed against the track. At this point the track exerts the greatest force on the material and can impart the greatest forward acceleration. Therefore it is desirable for the track to move forward at the lowest point. If the material is to move for example to the right the oscillation must be counterclockwise. The direction of rotation of the unbalance motor is the same as the direction of oscillation when viewed in the direction of the connecting line of the unbalance motor centers.

The measurements also confirm the influence of friction and the shape. Steel cylindrical billets with a rusted surface with a diameter of 80 mm and a length of 245 mm have a high friction and in all cases move forward. The brass billets have a smooth surface and less friction so they move more slowly. The brass billets with a diameter of 60 mm and a length of 55 mm are very unfavorable for feeding as they have a small length/diameter ratio and exhibit wobbling and swinging. With straight oscillation they could not be fed successfully. With elliptical oscillation high conveying speeds were achieved even in wet conditions.

6.4 Extension of service life

As the material moves along the conveyor track a frictional force is generated which causes wear on the track and the material. After a certain period of operation the track wears so much that it requires repair. Due to the higher conveyor speed the elliptical oscillation conveys the same amount of material in less time which extends the life of the entire conveyor. The effect of the elliptical oscillation on the wear of the track was calculated in a mathematical model of a vibratory bowl feeder set to a track slope of 2.7°, a vertical acceleration of 1 g, an inclination of the unbalance motors of 30° and a speed of 1000 rpm. At this setting the material is permanently sliding. It was compared the wear of the track when transporting the same amount of material with a straight oscillation and with an elliptical oscillation with a tilting of the unbalance motor of 10°. It was found that the effect of elliptical oscillation on wear is strongly dependent on friction similar to its effect on conveyor speed. With a friction coefficient of 0.3 a 1.6-fold extension of the track life was calculated and with a friction coefficient of 0.2 it was 3.3-fold extension of the life.

The elliptical oscillation also extends the life of the other parts of the vibratory conveyor. The body of the conveyor is made of a weldment which is subjected to strong dynamic stresses and suffers from material fatigue. Fatigue cracks can cause unexpected downtime. The bearings of the unbalance motors are heavily stressed by the centrifugal force from the unbalanced rotor. Due to the better transport properties of the elliptical oscillation the vibratory conveyor can be operated with less acceleration which not only reduces the dynamic stress on the entire conveyor but also on the foundation and surrounding structures.

6.5 Consumption reduction

Because elliptic oscillation reduces frictional losses it can transport material up to many times more efficiently than straight oscillation. The efficiency is increased and the power consumption is reduced in the same proportion as the service life is extended since the friction losses are directly related to wear. Elliptical oscillation can bring interesting savings especially for vibratory conveyors with high feeding capacities.

6.6 Optimal elliptical oscillation

The vertical amplitude of the oscillation is already limited by the acceptable noise of the conveyor so it is advisable to keep it constant during optimization. It remains to optimize two parameters of the oscillation, e.g. inclination and ellipticity. The measurement has shown that even a slight ellipticity improves the transport properties of the vibratory conveyor. However, the measurement only investigated the effect of ellipticity at a constant oscillation inclination, which was optimized for a straight vibrating conveyor and in practice ranges from 25° to 45° from the horizon. With an elliptical oscillation a smaller oscillation inclination is better as evidenced by mathematical models and previous research work [3, 4].

The optimum oscillation parameters vary with the application and depend mainly on the friction and the slope of the track. The mathematical models show that for the sliding principle of vibratory conveying the optimum oscillation inclination is in the range of 0° to 15° and the optimum phase shift is in the range of 45° to 90°. The greater is the horizontal amplitude of the oscillation, the greater is the conveyor speed. Vibratory conveyors with large horizontal amplitude and a phase shift approaching 90° can achieve very high speeds. The maximum conveyor speed of an elliptical oscillation is limited mainly by the maximum horizontal amplitude and by design constraints which do not allow the horizontal amplitude to be increased arbitrarily.

7 Conclusion

The newly developed and patented design of the vibratory conveyor with two unbalance motors and elliptical oscillation fundamentally improves the characteristics of vibratory technology and expands its application possibilities. The elliptical oscillation makes it possible to completely eliminate the problems of insufficient conveyor speed and high noise level which have so far been considered the main disadvantages of unbalance motor driven vibratory conveyors. The elliptical oscillation can be used to increase the capacity of the production line if it is currently limited by the vibratory feeder or conveyor. In cases where the performance of a straight oscillating conveyor is sufficient the elliptical oscillation will allow operation with less unbalance, significantly lower noise levels and less dynamic stress. The elliptical oscillation significantly increases the efficiency of the vibratory conveyor, reduces wear and tear on the conveyor track and extends its service life up to several times. This is a great benefit as repairs of a worn track tend to be costly and require extended downtime. Better efficiency also translates into lower consumption which can lead to interesting savings for conveyors with large transport capacities. In the case of vertical material conveying the elliptical oscillation allows the conveyor to be designed with a steeper track slope resulting in smaller dimensions and lower production costs.

A significant advantage of the invention is that it is based on a simple change in the position of the unbalance motors and therefore can be applied to various types of newly designed and already manufactured vibratory conveyors without demanding structural modifications or without increasing production costs. The risks arising from a slight change in the oscillation shape of a proven product are minimal as the important parameters of the vibratory machine remain unchanged. Vibratory conveyors driven by unbalance motors have a wide range of applications and are often an essential element for production automation. Due to the ease of application the invention can contribute to increasing productivity, reducing costs and mitigating the environmental footprint in many areas of industry.

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