THEORY OF VIBRATORY TECHNOLOGY

Revised and Augmented Edition

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FOREWORD

Vibratory technology today is associated with new, progressive scientific and production development methods. The use of vibratory technology leads to radical improvements in traditional production processes and mechanisms. The successes in the development of vibratory technology are largely predetermined by the implementation of the applied theory of vibration and vibration rheology.

The need for a further increase in the effectiveness of vibratory technology and the expansion of its application creates, on the one hand, a great demand for further study of vibratory processes in the course of various production processes with the purpose of establishing new physical effects. On the other hand, increasing the power of vibratory machines and the growth of their specific loading, dictated by the need to intensify production, strengthens the links between the machine, load, and the drive, leading to the necessity of considering them as a single load-machine-drive unit with strong interaction between the constituent subsystems. Such systems exhibit special effects that are not characteristic of traditional lightly loaded vibratory machines.

The presented methods of systemic consideration of load-machine-drive vibratory systems enabled the formulation of useful approaches to the utilization of resonance phenomena in the processed medium, which opened the possibility of a radical increase of power intensity of vibratory production processes, reduction of nonproductive energy losses, and an increase of productivity of the equipment.

In light of current demands for further development of vibratory technology, the authors devote considerable attention to the development of the theory of vibratory processes on the basis of phenomenological vibration rheology and the computational techniques for analysis of vibratory machines under load, taking into account the characteristics of the drive. Special attention is given to the development of methods of optimum development and identification of phenomenological models of various production processes.

New applications of vibratory technology and new approaches in traditional spheres of its application are considered in this book. Significant attention is given to the systematization and classification of vibratory machines, which, in the opinion of the authors, identifies the fundamental features of different modifications of each type of machinery, illustrates trends for further development, and indicates directions of their improvement.

Development of reliable methods of analysis of the process parameters and the characteristics of vibratory machines enables the development of application principles for multicriterial optimal design methods. This is illustrated by the numerous examples of characteristic vibratory machines.

The authors express the hope that the reader will find the book interesting and that it will prove useful in practical activities.

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CHAPTER

ONE

PHYSICAL PRINCIPLES OF VIBRATORY TECHNOLOGY

1.1 FUNDAMENTAL TYPES OF PROCESSES REALIZED WITH THE USE OF VIBRATION. VIBRATION REGIMES

At the present time a wide range of different processes are being realized with the application of vibration in which vibration plays various roles. Therefore, it is difficult to construct a rigorous functional classification. However, if the main operation executed in the given process is adopted as the classification index, then the following main categories of operations realized with the application of vibration can be identified: conveyance, processing of disperse systems with the purpose of maintaining or increasing efficiency of one or another production process, cutting, and crushing.

Vibratory conveyance serves not only conveying purposes, but also constitutes the basis for several technological processes. The main types of vibratory conveying operations are conveyance along horizontal or slightly elevated (tilted) surfaces, lifting along a spiral load-carrying element or in devices of special construction, vibratory loading and discharge from containers, bunkering. The second field of application of vibration - processing of disperse systems with the purpose of technological treatment - is the most versatile. This includes, first of all, formation of a vibratory boiling layer to accelerate mass-transfer processes in which various types of chemical and physico-chemical reactions occur. Such processes include catalytic and solid-phase reactions, combustion, extraction, dissolution and leaching, reclamation of metals from ores, and many others. Realized in vibration-processed disperse systems also are mixing, classification and separation, compaction of poured mixtures and concretes, crystalization, pressure processing, hardening, drying, dewatering, granulation, washing, centrifuging, and other operations. Vibration is fairly widely used in the processes of cutting and crushing: these are vibration turning and drilling, abrasive forming, breaking and grinding, crushing of soil and rocks.

Since the efficiency of the given processes is dependent on the regime of oscillations of the working element of the machine, various types of vibrations are used in practice: harmonic and semi-harmonic rectilinear, two-component, and three-dimensional. The trajectory of motion is generally shaped by translational and torsional vibrations of the working elements. Parameters of trajectories and modes of vibrations of the working elements of vibratory machines are constantly being developed and improved. In many processing operations superposition of vibrations to the working element can increase the specific energy intensity and efficiency of the process. The range of frequencies used in modern machines starts with low-frequency mechanical oscillations (infrasound) and reaches high-frequency ultrasound. Large amplitudes correspond to low frequencies and lesser ones to high frequencies.

1.2 VIBRATORY CONVEYANCE

Due to influences of many factors, the process of conveyance by vibration of massive loads is very complicated. Of main interest when determining the efficiency of the regimes of conveying processing machines is the study of physical characteristics of the process and establishment of the dependence of conveyance speed, process energy-intensity, degree of speed transmission to the transported medium, intensity of its mixing, creating the state of vibratory boiling, on parameters of the oscillation regime. These parameters are the shape of the trajectory, frequencies, amplitudes, phase shift angle between the harmonic components of two-component oscillations, angle of vibration and inclination of the load-carrying element. Of no lesser significance is the study of the effect of the properties of the transported medium, degree of filling of the working element and the operation conditions on the enumerated performance parameters of vibratory conveyance/processing.

Let us consider the main correlations between the speed of vibratory conveyance under rectilinear harmonic oscillations on parameters of the working regime of the vibratory machine, such as vibration amplitude and frequency and also the angles of vibration and inclination of the working element.

The dependence of the conveyance speed of a reference of piled up product (sand) with a coefficient of transportability $k=1$, layer thickness of up to 50 mm for a horizontal arrangement of the vibratory machine and angle of vibration of 20° on frequency at various vibration amplitudes is presented in Figure 1.1a. For each constant value of amplitude the dependence is, to a certain extent, of parabolic character. Then at higher frequencies the curves become gently sloping and with further increase of frequency, they can pass through an extremum. Moreover, with increasing vibration amplitude the curves become straight and acquire a larger inclination.

As the graphs show, the larger the oscillation amplitude, the lower the frequencies at which the extreme values of the speed of conveyance are reached. It can also be noted that with increasing amplitude the value of the extremal speed of conveying increases. By comparing the shape of the curves of the speed - frequency dependence with the character of the vibratory conveyance regime (continuous, intermittent), it can be noticed that with increasing oscillation frequency in the

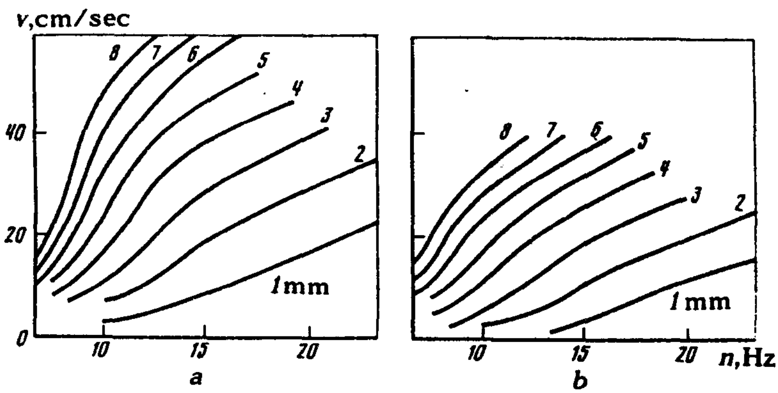

Figure 1.1 Conveyance speed vs. the regime parameter under rectilinear harmonic oscillations *a)* sand; *b)* small-lump piled-up load.

region of continuous (no loss of contact) vibratory conveyance regimes, a slow but more or less uniform increase in speed takes place. Upon transition to a jolting regime, frequency increase entails more intensive growth of conveying speed. However, the latter takes place only within a limited range of frequencies which is narrower the greater the oscillation amplitude. Further increase of oscillation frequency at first causes only an insignificant increase of speed and then even a decrease in speed occurs. In this case, an unstable conveying process is observed which is caused by physical reasons associated with the violation of the energy transfer conditions from the working element to the transported medium.

For each amplitude value there exists a maximum speed obtained at a frequency which is lower the greater the oscillation amplitude. Thus, in order to attain maximum speeds, one must operate at a possibly larger amplitude adopting such frequencies and vibration angles which enable obtaining the required speed of vibration conveyance.

Analysis of experimental data indicates that to determine the speed of motion of a product of interest, the speed obtained from the graph for sand should be multiplied by the coefficient of transportability for the product.

Figure 1.1*b* shows the dependence of the conveying speed for a small-lump load.

For different loads at the same regimes magnitude of the conveying speed is different. When difficult to transport loads are moved, a sharper decrease in speed takes place beyond the extremal value.

Vibration angle has a considerable effect on the speed of vibratory conveyance. Figure 1.2*a* shows the dependence of the speed of vibration conveying of a 40 mm layer of sand on the vibration angle at acceleration amplitudes of vibrations of the load-carrying element from 2.4 to 6.35 *g*, and Fig. 1.2*b* shows the dependence for rocks up to 50 mm chunk size at $K = 7.8 \div 14.5$. As can be seen, the correlation between the speed of motion on the vibration angle is very complex, its character is largely determined by the properties and thickness of the layer of the transported load, in particular by the vibration of the load-carrying element. Under limited oscillation intensity of the latter, the speed rises with increasing vibration angle. For easily transportable loads at small layer thickness this tendency is retained in a narrower range of accelerations than for loads that are difficult to transport and are moved in a thick layer. Under medium vibration intensity an opposite

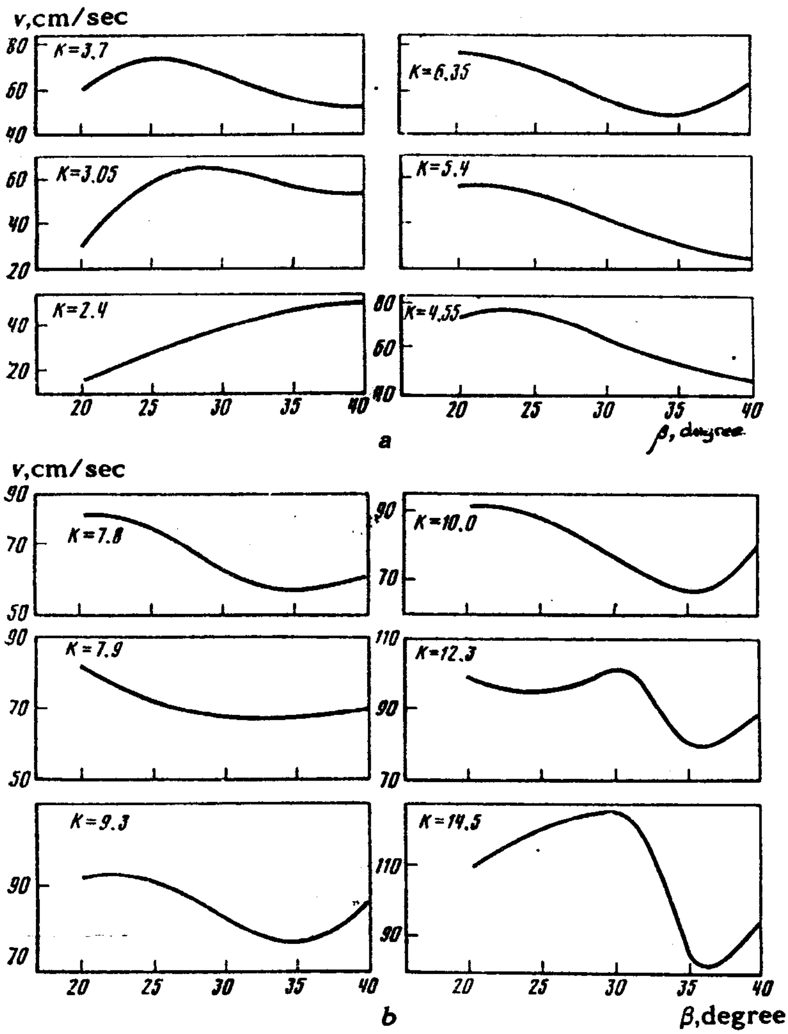

Figure 1.2 Conveyance speed of piled-up loads vs. vibration angle under various accelerations of the load-carrying element. *a)* sand; *b)* rock of chunk size up to 50 mm.

tendency is observed - when the vibration angle is increased the speed of vibration motion decreases. In the region of high-intensity regimes increasing the vibration angle leads first to a decrease of the speed then to its increase again, although the absolute maximum speed is attained nonetheless at lesser vibration angles.

Hence, it follows that to increase the speed of vibratory conveyance at high-intensity regimes the vibration angle ought to be decreased and, conversely, in calm (low-intensity) regimes the angle ought to be increased. In order to attain higher speeds with deteriorating load transportability and increasing layer thickness the vibration angle must be increased.

Investigations indicate that with increasing angle of inclination the speed of conveyance is rising; furthermore, for slow regimes a more intensive increase of speed is observed. Decreasing the vibration angle also has favorable effect. However, increasing the angle of inclination does not ensure a sharp increase of speed. Upon conveying upwards along an elevation, the speed drops very significantly.

Thus, although vibration conveyance at an inclination increases the translational speed, it does not however significantly exceed, as a rule, the amplitude values of vibratory speed of the carrying element. To increase conveyance speeds under motion at an inclination, one must increase the vibration amplitude, and decrease the vibration angle and vibratory frequency.

The effect of layer thickness on the vibratory conveyance speed is very important. Experiments show that when investigating vibratory conveyance parameters, one must consider not the load itself as such but rather its thickness which is an intrinsic characteristic of transportability. In the majority of cases the layer thickness acts in the same way - it lowers the speed of vibratory conveyance. The only exception is transported media (loads) with round particles, for example potatos, when the lowest speed is developing while transporting a monolayer. This is explained by the fact that due to the round shape the individual particles in a monolayer are rolling; sliding friction is substituted by rolling friction which disturbs the transfer of energy from the carrying element to the transported load. When operating in high-intensity regimes, stability of conveyance is increasing with increasing layer thickness.

A somewhat different effect is exerted by the layer thickness on the output of the vibratory conveying machine.

Thus, despite the decrease of speed of motion with increasing layer thickness, the output of the plant is increased. This is explained by the fact that with increasing thickness, the cross-sectional area of the load layer is increasing, up to a certain limit, faster than the decrease of conveying speed. However, this tendency is gradually changing. At some point the increase of the cross-sectional area of the load layer begins to be fully compensated by the decrease of the conveyance speed, thus stabilizing the output. Further increase of the layer thickness can lead to a decrease of the output. It is established that for each type of load at a given configuration of the carrying element, there is an ultimately attainable output.

The presented experimental data are characterizing effects on the conveyance speed of amplitude and frequency of vibrations, vibration angle, and angle of inclination of the carrying element of the vibratory plant under rectilinear harmonic oscillations. Let us analyze a correlation between the speed of load conveyance, and vibratory velocity, and acceleration of the carrying element.

The dependence of the speed of vibratory conveyance of 50 mm thick sand layer on a horizontal vibratory conveyer and at vibration angle of 20° on the amplitude of vibratory velocity of the carrying element is depicted in Fig. 1.3a. The experimental points plotted on the graph pertain to frequencies 4.2 - 23.4 Hz and amplitudes 0.55 - 25.0 mm. The region where the experimental points are located is shaded. The points corresponding to the same vibration frequency are joined by the lines. It is evident that various conveyance speeds correspond to a single vibratory velocity of the carrying element.

Analysis of experimental data indicates that the conveyance speed at invariable vibratory velocity of the carrying element is changing within a certain range with the change of frequency. The greater the frequency, the higher the speed of conveyance at a given constant vibratory velocity of the carrying element. This can be explained by the fact that the efficiency of the process of velocity transfer to the load in specific regimes is increasing with increasing vibratory acceleration of the carrying element.

The dependence of the speed of vibratory conveyance on the amplitude of vibratory acceleration of the carrying element, plotted from the same experimental data, is depicted in Fig. 1.3*b*, which shows that oscillation acceleration of the carrying

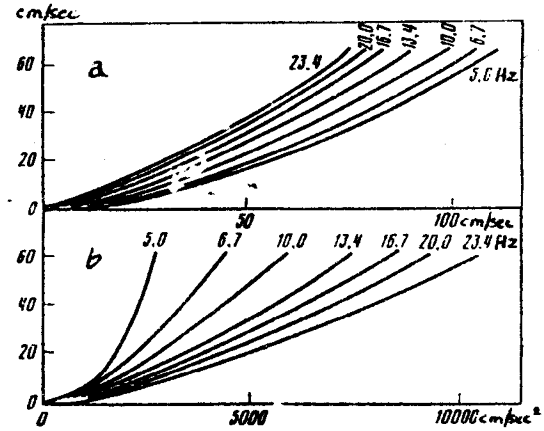

Figure 1.3 Conveyance speed of sand vs. parameters of rectilinear harmonic vibrations *a)* velocity amplitude; *b)* acceleration amplitude.

element, just as vibratory velocity, does not uniquely determine the conveyance speed. The conveyance speed can vary within very wide limits at the same value of acceleration. A second parameter for the determination of the conveyance speed is vibration frequency of the carrying element. In the case under consideration, an effect opposite to the one which occurred for the dependence on the vibratory velocity of the carrying element is observed, namely, with increasing frequency the conveyance speed decreases. This is due to the fact that at a constant value of acceleration amplitude of the carrying element, velocity amplitude of its motion decreases with increasing frequency and, conversely, it rises with decreasing frequency. Hence, it follows that in order to increase the conveyance speed of the vibratory installation which is operated with a specified vibratory acceleration of the carrying element, it should operate at low frequencies and with increasing vibration amplitudes.

This allows one to conclude that neither vibratory velocity nor acceleration taken separately singularly determines the speed of vibratory conveyance. The vibration frequency of the load-carrying element affects magnitude of this speed. This is due to the fact that the conveyance speed is determined by two principal factors: vibratory velocity of the carrying element, and efficiency of the process of velocity transfer to the load. Since the vibratory velocity of the carrying element is proportional to the first power of the frequency, and the coefficient of velocity transfer is proportional to the second power of frequency, it can be assumed that their combined effect is proportional to the vibration frequency raised to an intermediate power. Indeed, the effect of frequency is diverse: if in the first case (see Fig. 1.3*a*) the speed of conveyance is increasing with increasing frequency, then in the second case (see Fig. 1.3*b*) this speed is decreasing. This allows one to presume that one can find some generalized parameter $A\omega^n$ which would uniquely determine the speed for the specified conditions of vibratory conveyance. The sought result for the presented experimental data was achieved at the exponent equal to 1.25. This parameter of the regime for a given load in the considered conditions of vibratory conveyance uniquely determines magnitude of the speed.

Experimental data show that the speed of the load motion in vibratory conveying machines is less than the velocity amplitude of the carrying element and is lower than the velocity component in the direction of motion.

The efficiency of the process of velocity transfer from the carrying element to the transported load is usually estimated by the value of the coefficient of velocity transfer which is defined as the ratio of the mean speed of load motion to the amplitude value of velocity of the carrying element. Figure 1.4 shows values of the coefficient of velocity transfer which were computed from experimental data obtained during the vibratory conveyance of 50 mm sand layer at a vibration angle of 20° (curve *1*) and 10 mm layer of crushed ore of 0 - 6 mm size and vibration angle of 22° (curve *2*). It is evident that the coefficient of velocity transfer rises with increasing vibratory acceleration of the carrying element, and approaching some stant value of 0.70 - 0.80 at large acceleration magnitudes. ore intensive oscillations, i.e., with increasing amplitude of acceleration, a decrease in the coefficient of velocity transfer takes place. Therefore, in order to increase the efficiency of the process of velocity transfer from the carrying element to the transported load, one must increase intensity of oscillations of the load-carrying element up to the limits ensuring stable regimes of vibratory conveyance.

The required conveyance speed can be obtained with various combinations of parameters of the operating regime of the plant, namely, amplitudes, frequencies, and the angle of vibration. The problem is to select such a combination which would ensure the optimum operating conditions. Depending on

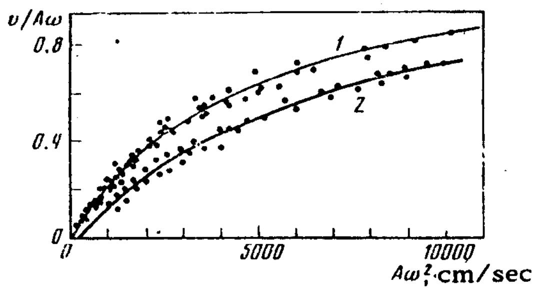

Figure 1.4 Coefficient of velocity transfer vs. vibratory acceleration of the load-carrying element.

selection of the criteria determining the desired efficiency of operation of the vibratory conveyance installation, different combinations of parameters will be optimal.

The criteria of optimality of the operating regime can generally be very diverse for different plants, conditions of use, conveyance tasks, etc. As such criteria, one can adopt, for example, the provision for the minimum total vibratory acceleration (or minimum value of one of the component of the total acceleration) of the load carrying element, achieving minimum energy consumption for transporting the load, and so on. One can demand for several indicators to be minimized simultaneously, for example, minimum dynamic loading of the plant and the lowest power-consumption. For valuation of the process efficiency, attaining a minimum vibratory acceleration of the carrying element as the most general and essential condition of efficiency of the operating regime is often required. The fact of the matter is that the maximum acceleration of the carrying element determines magnitudes of dynamic loads on the drive components and on elastic links and, hence, the cost and reliability of the installation. For example, the conveying speed in the low-speed regimes of machine operation (low frequencies and relatively large vibration amplitudes) can be increased without changing vibratory acceleration by a correct selection of the vibration angle. Experiments show that the coefficient of velocity transfer at low-speed regimes is, practically, increasing in direct proportion to the increase of the vibration angle. Hence, it follows that at a constant machine operating regime its output can be increased by increasing only the vibration angle. In practice it is not always feasible to increase the speed of conveyance by increasing vibration frequency and amplitude of