Analysis and Optimization of Dust Control Hopper System

Ivo Vaicis, Alexander Janushevskis, Ilmars Viksne, and Janis Auzins

Abstract Bulk cargo transportation and loading is one of the common industrial problems because during this process dust spread from cargo to the environment. Especially significant dust concentration is observed in industrial areas such as harbors, cargo terminals, and production areas. Different dust suppression systems are used to reduce the amount of dust spreading in environment during granular cargo loading process. In this paper particle flow through the hopper nozzle is analyzed under different conditions, depending on vibration frequency. Distribution of particles by their size at hopper nozzle outlet is analyzed numerically. Frequency analysis of dust hopper for simplified FEM model is performed.

Keywords Dust control · Metamodeling · Vibration analysis · Discrete element method · Shape optimization

1 Introduction

Air pollution in urban areas is a common issue to ensure environmentally friendly conditions for inhabitants. Bulk cargo transferring in industrial areas such as terminals and harbors is one of the significant causes of air pollution. In many cases dust spread can be observed when granular material is transferred from one location to another. Dust spread creates not only environmental pollution but also cargo losses, which during some time period can cause negative economic influence.

Different systems are used to minimize the amount of dust spread by cargo [1]. Dust control hopper (DCH) system, shown in Fig. 1, is analyzed in this paper. DCH is used to transfer different granular materials as grain, sand, ore and others. The main purpose of DCH is to achieve stable granular material flow at DCH outlet nozzle [2].
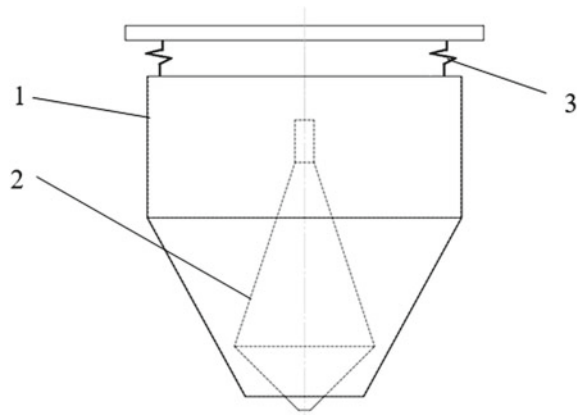
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Fig. 1 Dust suppression
system: 1—hopper, 2—plug,
3—springs

Dust particles must be concentrated at flow center, therefore limited from spreading in environment. To obtain stable material flow at DCH outlet nozzle, mechanical or electromechanical control systems are applied [3].

Hoppers can be divided into two types—mass flow and funnel flow. At mass flow, hopper material that enters hopper inlet is discharged first. At funnel flow, hopper material which enters first is discharged last [4].

2 Characteristics of Bulk Material

2.1 Parameters of Packing

DCH is used for different granular material loading. For bulk loading the material property is not the same as simple summation of the physical properties of single particle. To describe the properties of bulk material different parameters are involved. Fraction voidage (1) is used to define interstitial void volume in the unit bulk void of particle assemblage [5].

$$\Phi_p = 1 - \varepsilon \tag{1}$$

where Φ_p is the fractional solids;
    ε is the fractional voidage.

Bulk density (2) is the apparent density of a powder mass, given by the mass per bulk volume of powder [5].

$$\rho_b = \rho_p(1 - \varepsilon) \tag{2}$$

where ρ_b is the bulk density;

ρ_p is the particle density.

The bulk volume of powder of unit mass, which is the inverse of bulk density, is used to describe apparent specific volume (3) [5].

$$V_s = \frac{1}{\Phi_p} = \frac{1}{1 - \varepsilon} \tag{3}$$

where V_s is the apparent specific volume.

Bulk volume of solids in comparison with the unit volume of particles is defined as bulkiness (4). To describe ratio of the void volume to the net volume of particles, void ratio (5) is used [5].

$$\Phi_b = \frac{1}{\Phi_p} = \frac{1}{1 - \varepsilon} \tag{4}$$

$$\Phi_v = \frac{\varepsilon}{1 - \varepsilon} \tag{5}$$

where Φ_b is bulkiness;

Φ_v is void ratio.

3 Vibration Analysis of Bulk Solids

Different researches show that the applied horizontal vibration to hopper system leads to increment in mass flow rate at hopper outlet nozzle. For small vibration velocities it takes small effect on mass flow rate [6].

When mixture of different size particles is flowing through the hopper under applied vibrations, segregation of material according to size can be observed [7]. Segregation of mixtures can be observed also in hoppers without applied vibrations [8], where smallest particles tend to accumulate (Fig. 2). In hopper the remains exist until the end of discharge. Particle accumulation in hopper appears along the whole length of the hopper wall [9]. Segregation amount due to the wall friction of hopper differs depending on hopper outlet angle [2].

Drag force which is acting on the particle flow have significant impact on segregation process. In vibration-induced granular material size separation of air takes large role. Air effects dominate the process of size separation; therefore particles which would rise at different conditions under applied drag force sinks [10]. Numerical model performed with working model 2D [11] with applied vertical vibrations and drag force shows particle segregation by size in Fig. 3 where smallest particles tend to move in flow center while largest particles are located at external perimeter of hopper outlet nozzle.
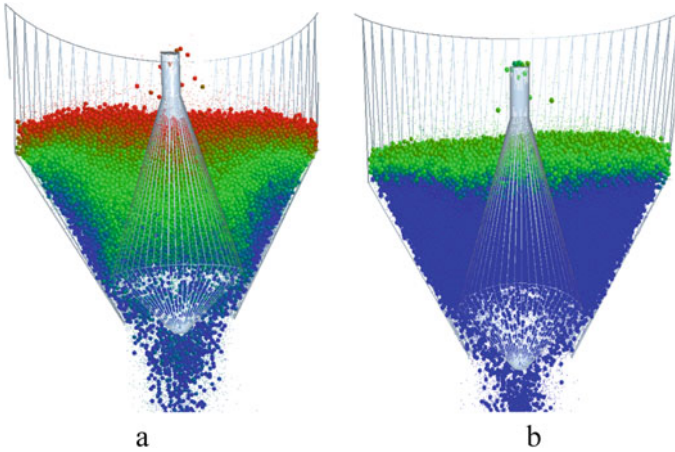
Fig. 2 Simulation of bulk accumulation using Edem [9]: **a** without applied vibrations, **b** with vertical vibrations 10 Hz
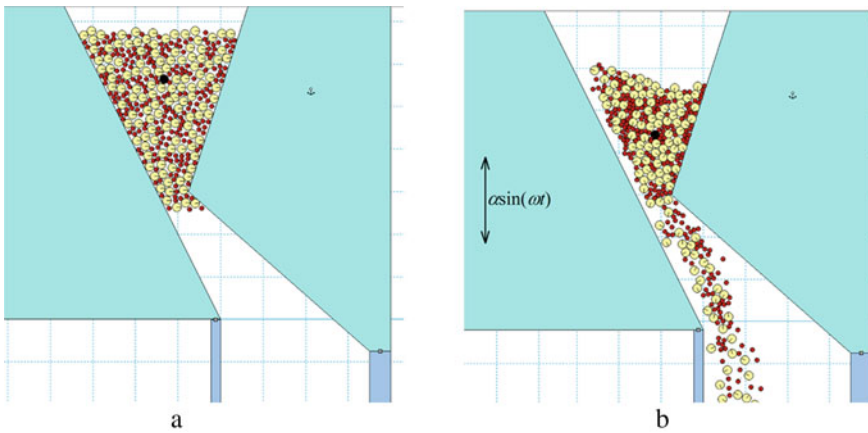

Fig. 3 2D particle flow through ½ DCH: **a** working model setup at initial time moment, **b** position of particles after 0.3 s of simulation (vibration frequency 50 Hz, amplitude 1 mm)

4 Results and Discussion

To analyze DCH system with bulk cargo under vibrations, vibrations are applied to the hopper construction in the vertical direction. Particle flow through hopper outlet nozzle is analyzed under different vibration frequencies which are applied in the vertical direction. Hertz–Mindlin contact model is used to define contact between particles and particles-geometry. Bulk material flow is analyzed as mixture of two different size particles where particles with diameter (d_1) 0.01 m takes 30% of mixture amount and particles with diameter (d_2) 0.001 m takes 70% of mixture amount.

Mass flow rate at DCH nozzle outlet is analyzed for each type of particles and different vibration frequencies. The obtained results show that applied vibrations make significant effect on mass flow rate (see Figs. 4 and 5) at outlet nozzle for bulk particles, and the effect on flow rate differs depending on particle dimensions. Small particle accumulation in hopper construction is reduced in case if vibrations are applied. Bulk flow analysis under forced vibration is a very time-consuming procedure, and for optimization purposes metamodeling approach [12] will be used.

Relative density of dust particles in horizontal section of hopper outflow is analyzed (Fig. 6). The observed relative density distribution indicates that small particles are sucked in flow center, and large particle flow is concentrated at perimeter of hopper outlet nozzle.

DCH is made from different materials depending on bulk material used. The commonly used materials for these systems are aluminum and plastics. For different DCH materials whose properties are given in Table 1, the frequency analysis is

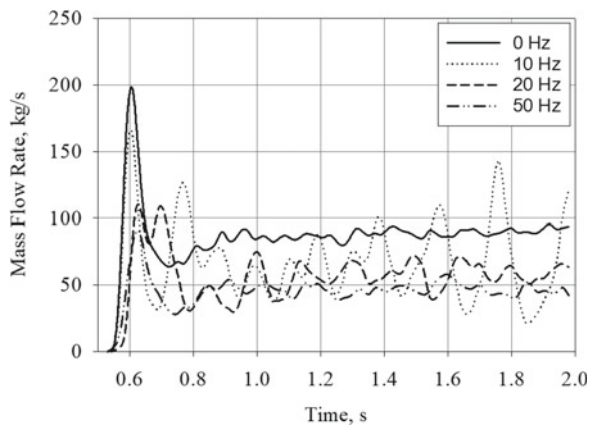**Fig. 4** Mass flow rate for particle $d_1 = 0.01$ m

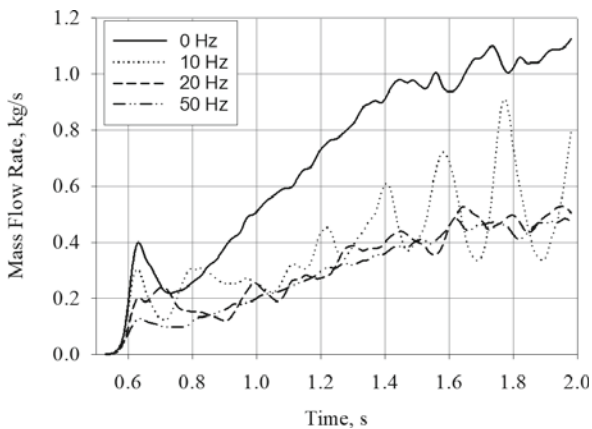**Fig. 5** Mass flow rate for particle $d_2 = 0.001$ m

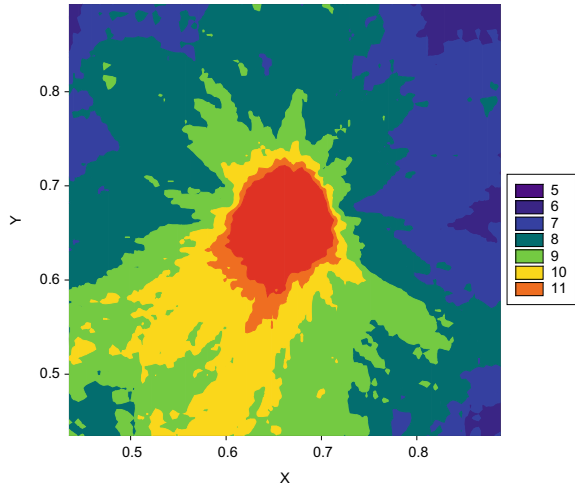**Fig. 6** Relative density of dust particles in horizontal section of outflow

Table 1 Mechanical properties of DCH materials

No.	Elastic modulus, MPa	Poisson's ratio	Shear modulus, MPa	Mass density, kg/m^3
1	69000	0.33	27000	2700
2	2410	0.3825	866.7	1300

performed and lower natural frequencies and mode shapes are shown in Table 2.

Table 2 Comparison of natural frequencies and mode shapes

	Frequency, Hz				
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Material 1, thickness 3 mm	99.298	100.68	119.38	199.4	150.24
Material 2, thickness 3 mm	27.123	27.525	31.964	31.971	41.039
Mode shape (top and axonometric view)					

5 Conclusions

Performance analysis of particle mixture flow through DCH can be used for further analysis of vibration impact on particle flow discharge rate and segregation processes. Metamodeling approach can be used for optimization of DCH parameters such as silo outlet angle, vibration frequency and so on to obtain optimal particle flow through DCH system to minimize dust spread in environment.

Numerical simulations show that vertical vibrations have significant effect on mass flow rate at hopper outlet nozzle. Accumulation of small particles in hopper changes with different vibration frequencies.

Particle segregation at horizontal section of hopper outlet nozzle can be observed, where smallest particles concentrate at the center of mass flow. The gained flow data and models can be used for further optimization of hopper parameters to obtain particle flow state with minimized dust spread.

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