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Analysis of pipe vibration in an ultrasonic powder transportation system☆

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ABSTRACT

The transportation of dry fine powders is an emerging technologic task, as in biotechnology, pharmaceutical and coatings industry the particle sizes of processed powders get smaller and smaller. Fine powders are primarily defined by the fact that adhesive and cohesive forces outweigh the weight forces, leading to mostly unwanted agglomeration (clumping) and adhesion to surfaces. Thereby it gets more difficult to use conventional conveyor systems (e.g. pneumatic or vibratory conveyors) for transport. A rather new method for transporting these fine powders is based on ultrasonic vibrations, which are used to reduce friction between powder and substrate. Within this contribution an experimental set-up consisting of a pipe, a solenoid actuator for axial vibration and an annular piezoelectric actuator for the high frequency radial vibration of the pipe is described. Since amplitudes of the radial pipe vibration should be as large as possible to get high effects of friction reduction, the pipe is excited to vibrate in resonance. To determine the optimum excitation frequency and actuator position the vibration modes and resonance frequencies of the pipe are calculated and measured. Results are in good accordance.

1. Introduction

One very effective set-up for transporting adhesive and cohesive powders consists of a pipe, which vibrates harmoniously in axial direction at low frequency combined with a pulsed radial high frequency vibration [1,2]. The high frequency vibration accelerates the particles perpendicular to the surface of the pipe, which in average leads to lower normal and thereby smaller friction force [3].

Fig. 1 shows the experimental setup of the ultrasonic transportation system. A Voice-Coil Actuator excites the pipe to harmonic vibrations at low frequency. Only when the pipe is moving backward the effective friction between powder and pipe is reduced by switching on a piezoelectric actuator, causing a high frequency radial pipe vibration. The powder is therefore accelerated relatively strong when the pipe is moving forward and slightly decelerated when the pipe is moving backward. Operation at an axial vibration frequency of 50 Hz results in a nearly continuous powder transport. The powder velocity is adjustable by altering the vibration amplitudes and frequencies of low and high frequency excitation as well as the switching time of the high frequency vibration. This makes the device versatile for comparable high volume and fine dosing using one setup.

A simple model of the system has already been published in [1], see Fig. 2. The model is based on the assumption that the powder behaves like a rigid body with the mass m_P. The effective friction coefficient $\bar{\mu}(t)$ switches between two values depending on whether the ultrasonic pipe vibration is switched on or off. The high adhesion forces between powder and pipe are considered by a constant normal force $F_{adhesion}$. Viscous damping is considered by a velocity-dependent force with a parameter $2\delta = d/m_P$. As for fine powders it is very hard to determine parameters like friction, adhesion and viscous damping, the parameters were estimated by fitting model results to measurements. Fig. 3 shows the comparison of the mean powder velocity from measurements and corresponding simulations.

However, the comparison of model and measurements often led to unexpected results. After removal and installation of the pipe, deviating results of the mean powder velocity were obtained. This observation suggested that the high frequency vibration had changed after re-installation of the pipe.

Also, as parameters were only estimated by fitting model results to measurements, the physical relationships between the pipe vibration and friction reduction are not considered in this model. Therefore, estimated friction parameters can only be used for

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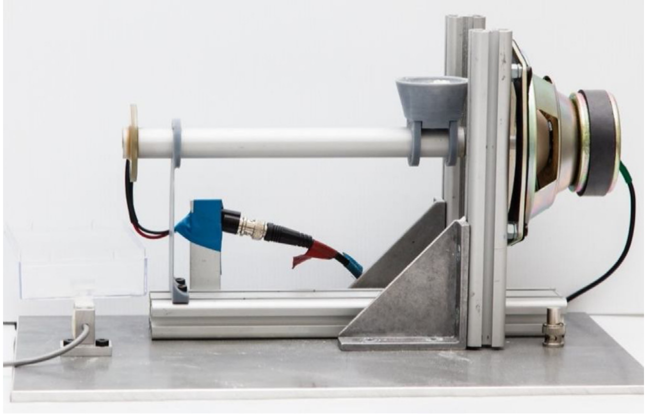

Fig. 1. Experimental setup of the ultrasonic powder transportation system.

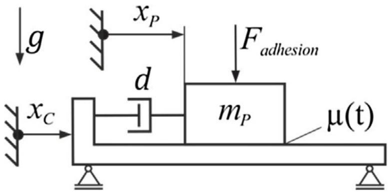

Fig. 2. Rigid body model of the powder transport system.

unchanged excitation of the high-frequency vibration. A physical coefficient of friction can not be used since the coefficient of friction depends primarily on the radial vibration, which – at this high-frequency vibration – is not constant over the pipe length. Therefore, a locally resolved calculation is needed to analyze the friction reduction in detail.

Within this contribution the pipe vibration is analyzed using the finite element method and measurements.

2. Pipe vibration analysis

In the following, the pipe vibration of an aluminum pipe with an outer diameter $D_o = 20\,\text{mm}$, inner diameter $D_i = 18\,\text{mm}$ and length $L = 235\,\text{mm}$ is analyzed. The vibration is excited by a ring-shaped piezoelectric ceramic (PIC181) with dimensions $D_o = 50\,\text{mm}$, $D_i = 20\,\text{mm}$, $L = 5\,$ mm, which is bonded to the aluminum pipe using a two-components epoxy adhesive (Pattex Stabilit Express).

Fig. 4 shows the pipe coordinates used within the analysis. The variables u, v, w are displacements in axial, torsional and radial direction of each point of the pipe shell, whereas x and ϕ describe location coordinates. To get highest amplitudes, the pipe vibration is excited at a resonance frequency of about 35 kHz by applying a harmonic voltage on the piezoelectric actuator, which is adhered to the pipe at $x \approx 0$.

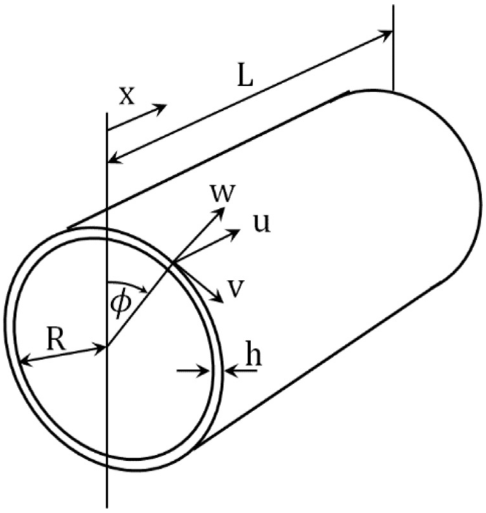

Fig. 4. Pipe coordinate systems.

The pipe vibration was measured with different kinds of Laser-Doppler-Vibrometers. For measuring the radial vibration amplitude $\hat{w}$ along the longitudinal axis x of the pipe an out-of-plane Scanning Vibrometer was used whereas the longitudinal vibration $\hat{u}$ along the longitudinal axis x was measured with an in-plane Vibrometer. These measurements were done for different angles ϕ on the pipe surface.

Measurements of the radial pipe vibration are shown in Fig. 5. The vibration amplitudes differ for different angles ϕ. It is therefore not radial-symmetric. The maximum vibration amplitude was measured at $\phi = 20°$. Also there is a phase difference of about 180° between the radial amplitude $\hat{w}(x)$ at $\phi = 0°$ and $\phi = 90°$, which suggests an elliptical deformation of the pipe profile.

An appropriate model of the pipe vibration was built using finite-element-simulation in Ansys. The pipe was meshed using a number of each 50 3D volume elements along the pipe coordinate x as well as the pipe coordinate ϕ. 2 elements were set on the pipe thickness h. Material parameters for the aluminum pipe were taken from literature (modulus of elasticity $E = 70GPa$, Poisoní s ratio $\nu = 0.34$, density $\rho = 2700\,\text{kg/m}^3$). Using a harmonious analysis with excitation of the piezoelectric actuator at a frequency of 35 kHz the pipe vibration was analyzed.

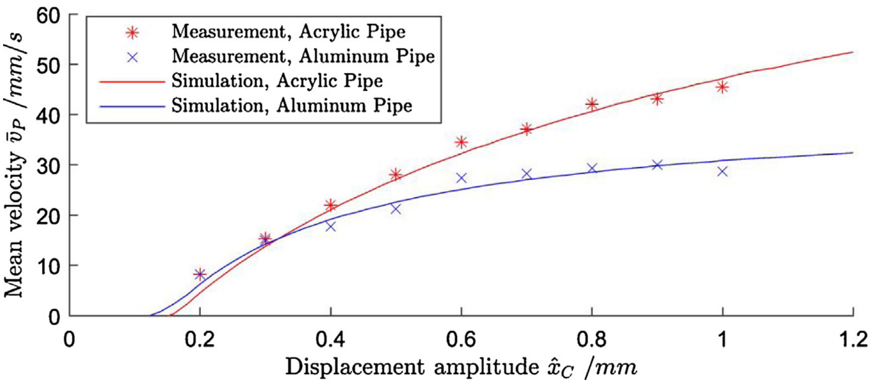

Fig. 3. Comparison of mean powder velocity from simulation and measurements. Measurements were done at an electrical power of $P_{Piezo} = 0.5\,\text{W}$ at the piezoelectric actuator. Simulation parameters were $\bar{\mu}_{US}/\bar{\mu}_0 = 0.63$, $\delta = 8\,\text{kg/s}$ for the acrylic pipe and $\bar{\mu}_{US}/\bar{\mu}_0 = 0.4$, $\delta = 30\,\text{kg/s}$ for the aluminum pipe.