MEASURING FLOW PARAMETERS OF PARTICULATE AND POWDERY SOLIDS IN INDUSTRIAL TRANSPORTATION PROCESSES

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Abstract- This paper provides an overview of existing technologies to measure flow parameters, such as material velocity and material concentration, in industrial transportation processes of particulate and powdery solids with a focus on pneumatic conveying. Restrictions, advantages and drawbacks of state of the art measurement principles are discussed. We show that capacitance-based sensing with suitable electrode topology allows for non-invasive, low-cost determination of flow parameters. Two industrial applications for material transportation - by means of pneumatic conveying and of screw conveyors - are presented.

Index terms: gas-solid flows, material conveying, capacitive sensing

I. INTRODUCTION

Conveying of solid material is performed in everyday life in a vast variety of applications, covering most industrial and agricultural domains. Unfortunately, the equipment dealing with particulate solids are in large part operated from empiricism with only little demand for accuracy. Instead, the main focus lies on repeatability, which means that the modus operandi is very often to find parameters that work adequately and then fix the operation conditions [1]. However, problems arise when the conditions change, having adverse effects on quality, safety, efficiency, or environmental sustainability. Therefore, the challenging task of monitoring the material flow and reliably obtaining the flow parameters is requested by industry as well as research [2].

Devices that measure flow parameters, such as particle or media velocity, particle concentration, and mass flow rate, are called flow meters. For industrial applications, one of the most popular methods of transporting particulate solids is pneumatic conveying [3]. Pneumatic conveyors are conveying systems for bulk solids with a closed piping system, in which material is transported by an air stream, either by means of pressure operation or by means of vacuum operation.

A typical industrial process, where pneumatic conveying is used to transport bulk solids, is the transportation of pulverized fuel to furnaces, e.g. in steel and cement production [4]. The construction and shipping industries also make use of material transportation by means of pneumatic conveying and handle for example sand or gravel. Food processing, chemical, pharmaceutical, and agricultural industries are further examples, where pneumatic conveying is extensively utilized.

An industrial flow meter has to be designed for diverse particle sizes and has to be laid out for variable transportation velocities and flow regimes, such as dilute phase flow (i.e. particles are fully suspended in the conveying gas stream [5]) and dense phase flow (i.e. particles form full-bore slugs of material [6]). A number of practical limitations and challenges are associated with parameter determination in gas-solid flows and restrict the applicability of sensor principles for pneumatic conveying: Among others, many bulk solids (e.g. sand or other minerals) are of abrasive nature. A sensor, which is inserted into the pipe, is exposed to the direct bombardment of fast and abrasive material and hence would be subject to severe wear. Furthermore, due to particle-particle and particle-pipe collisions, pneumatically conveyed material often carries electric charge [7] (also known as triboelectric charge), causing electric potentials of the order of several kV in conveyor pipelines. Electrostatic discharges present a major problem in many industrial applications [8] and must be taken into account in sensor design. Depending on the material to be conveyed and the conveying conditions, significant particle velocity and concentration profiles can be observed in a pipe cross-section [9]. These profiles may be deviating at different positions along the conveyor pipe and may vary over time.

II. STATE OF THE ART IN (GAS-)SOLIDS FLOW METERING

Due to the increasing importance of material conveying in industrial processes, a variety of flow meters, based upon different sensor principles, have been developed for bulk solids:

Flow meters based on the Doppler method evaluate the frequency shift of an electromagnetic or an acoustic wave transmitted into a gas-solid flow and partly reflected by the conveyed particles [10]. These meters find application especially in dilute phase flow measurement and allow for spatially resolving sensing when multiple transmitters are used. Common disadvantages of this method are limited penetration depth into dense material, typically costly setups and solid-borne sound restrictions.

Correlative methods are used in various embodiments to measure the material velocity in gas-solid flows: Regardless of the sensor principle used, two (ideally identical) sensors are separated by a certain distance along the flow direction. Fluctuations and disturbances in the material flow affect the measurement signals in the two sensing layers. The time needed for such disturbances to be conveyed from the sensitive area of the upstream sensor to the one of the downstream sensor is obtained by using the general cross-correlation function. With this method, one is not restricted to a specific sensor principle and hence can make use of the principle best suited for a given measurement problem [11]. The sensors in the two measurement layers may be based on ultrasonic methods [12], optical methods [13], radiation methods or the instantaneous measurement of material properties like permittivity [14], conductivity [15], charge [16] or temperature [17]. The inherent robustness to noise makes the correlation principle a commonly used technique for the measurement of the time delays in flow applications. On the other hand, an important disadvantage of cross-correlation flow meters is that the signal similarity decreases with increasing inter-layer distance [18]. This dependence is caused by rheological decomposition and non axis-parallel particle trajectories between the upstream to the downstream sensor layer.

Spatial filtering implies an alternative approach to correlative techniques. The basis of spatial filtering methods is the evaluation of signal amplitudes caused by moving particles through a grating-like structure of a sensor arrangement with alternating sensitivity along the pipe. The material velocity is deduced from frequency spectra of measurement data [19]. Flow meters based on spatial filtering with multiple sensing layers along the flow direction typically require larger sensor lengths than cross-correlation meters, which is detrimental for specific applications.

Optical flow analysis techniques, such as Particle Tracking Velocimetry [20] or Particle Image Velocimetry [21], are susceptible to dust development in the pipe and are typically employed for certain applications only. Other measurement principles, such as using microphones to record acoustic emissions generated by fine powder flow and granular material [22] or the use of Venturi meter [23], have been reported, but are typically designed and optimized for specific conditions to be found in certain processes. Their general application for industrial flow processing of bulk solids is very limited.

Flow meters exploiting attenuation of waves and radiation when directed through a conveyor pipe are in industrial use. Certain particles absorb microwave energy very well, so that attenuation of microwave signals due to particle interaction can be utilized [24]. Material composition and size distribution highly affects the attenuation behavior, which often requires calibration. Radiometric concentration sensors making use of the attenuation of γ-rays or x-rays [25] are generally considered to be the most reliable method to determine material concentration in gas-solid flows. Apart from high costs and safety constraints, strict import regulations make the use of ionizing radiation ill-suited for many applications.

Some approaches have been made to reconstruct cross-sectional images of a conveying process and obtain particle velocity and -concentration by means of Electrical Capacitance Tomography (ECT) [26]. Here, a tomographic image can be constructed on the basis of observed capacitance-proportional signals acquired on the outer circumference of a pipe by solving an inverse problem. As a result of the multi-sensor setup and required high sampling rates, large amount of measurement data has to be processed. Complex reconstruction algorithms typically do not allow for real-time image generation for flow applications. Promising reconstruction techniques featuring less complexity have been reported recently [27].

In some industrial fields, the weighing of material within a process is still the preferred approach. Load cells are employed for silos that store bulk solids to monitor material in- and outflow and estimate the current mass flow in an upstream or downstream pipe section. Making use of e.g. a rather simple belt-operated weighing procedure most often necessitates the interruption of the pneumatic conveying process and forces an open channel flow. Similar disadvantages are associated with impact meters [28], where the impact of the material on deflectors is determined for mass flow estimation.

Shutdown times of facilities due to sensor testing, maintenance or replacement have to be strictly avoided in production plants. The market for gas-solid flow meters is hence rather conservative and many users of process instrumentation accept existing but restricted systems rather than risking a change in technology.

Table 1 compares the different methods against possible requirements R1 to R9 and rates the applicability of the principles for the given requirement as “arbitrary/suitable” (+), “suitable with restrictions” (○), and “not suitable” (−).

R1. Robustness in rough process conditions (including mechanical, chemical, and electromagnetic disturbances)
R2. Minimum measurement error and good reproducibility
R3. Simple installation in existing systems and maintenance
R4. Ability for fast acquisition of results and on-line monitoring
R5. Low acquisition cost and maintenance costs
R6. Suitable for a broad scope of (physical and electrical) material properties
R7. Spatial resolution (i.e. a cross-sectional profile for velocity and concentration)
R8. Little or no calibration (moisture, temperature, particle size, etc.)
R9. Robust against in-pipe dust development

Table 1: Comparison of different methods to determine flow parameters in bulk solid flows

Principle	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**
Doppler Method	+[1]	○	+	+	○	−	+	○	○
Correlative Method	+[2]	+	○	+	+	+	+	○	+
Optical Method	○	+	−	○	−	−	○	+	−
Spatial Filtering	+[2]	+	○	+	+	+	○	○	+
Passive Acoustic	+	−	+	+	+	−	−	○	+
Attenuation-Based	+	○	○	+	○	+	○	○	○
Weighing-Based	○	○	−	+	○	+	−	○	+
Tomographic	+	○	○	−	○	+	○	○	+

[1] For clamp-on
[2] For non-invasive principle

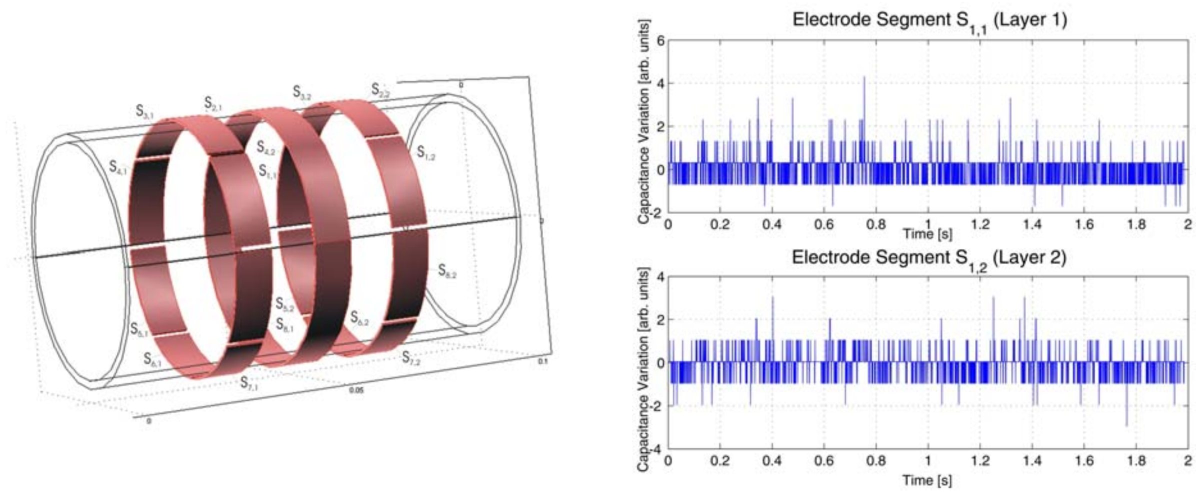
III. APPLICATION: FLOW METER FOR DILUTE PHASE FLOW

In this section, the topology, structure, and operation of a novel, correlation-based flow sensor is presented. A non-invasive capacitive sensor has been developed that comprises three rings of electrodes with a certain inter-layer distance in flow direction [29, 30]. The electrodes are produced on a flexible print and wrapped around a section of non-conductive pipe (sight glass). The layout of the sensor is shown in figure 1a. Two of the electrode rings are subdivided into multiple segments while the ring in-between is continuous. An electrical signal can be supplied to each of the segments. These transmitter segments are consecutively excited with a high frequency signal and the inter-electrode capacitance between an active transmitter and the common receiver ring on virtual ground is determined. Every conveyed material has a dielectric permittivity ε_r, which is higher than that of air ($\varepsilon_{r,air}$=1), and which fairly affects the capacitance. The capacitive sensor can be operated with a sampling rate of about 4 kHz for a complete measurement sequence.

The number of segments per layer dominates the spatial resolution but does not limit the principle of operation. Practical measurements with this sensor principle have been conducted using a horizontal pipeline with 49 mm internal diameter. Poly pellets are a common bulk material for different industrial processes. Such pellets with an average equivalent volume diameter of about 3.8 mm have been pneumatically conveyed in the test setup.

Figure 1b shows measurement results obtained during dilute phase flow of poly pellets for two corresponding segments (i.e. the inter-electrode capacitance between activated segment $S_{1,1}$ and the receiver is plotted as well as the capacitance between activated segment $S_{1,2}$ and the receiver, compare figure 1a). Although the quantization noise is rather high, good results for the correlation function could be obtained.

The cross-correlation functions for a signal of segment $S_{1,1}$ with all other segment signals in layer 2 is shown in figure 2. It is obvious that the signals of $S_{1,1}$ (layer 1) and $S_{1,2}$ (layer 2) show the best match and that the correlation of opposed segments (e.g. $S_{1,1}$ and $S_{4,2}$) provide less significant peaks, but even for the latter case, this peak can still be detected. The velocity values are derived from the peak positions of the cross-correlation functions shown in figure 2.



(a) (b)

Figure 1. (a): Topology of the sensor front-end with two segmented transmitter layers and one common receiver ring in-between and (b): Measurement results for two corresponding segments in dilute phase flow [30].

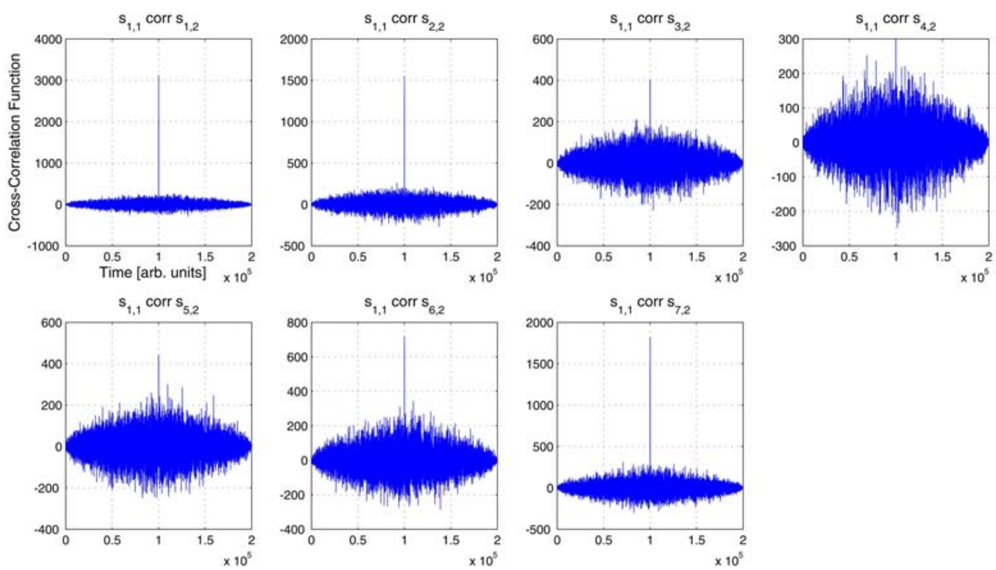
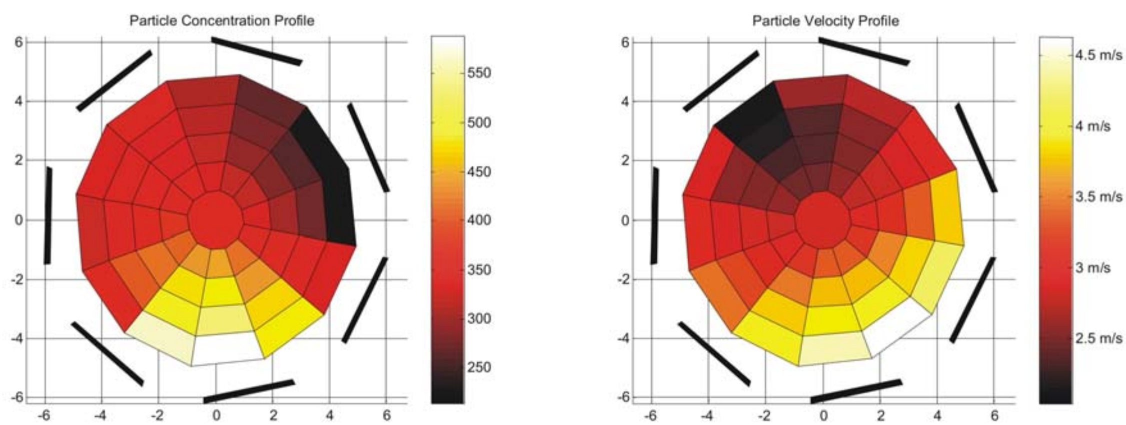


Figure 2. Cross-correlation functions of a signal of segment $S_{1,1}$ and all other segment signals of layer 2 [30].

With increasing distance between the pair of segments, the sensitivity of the topology moves towards the centre since signal similarities are only obtained in overlapping sensitive areas of both segments. Thus, a profile can be reconstructed by mapping obtained velocity information onto the corresponding sensitive area of the pipe cross-section. The particle concentration is obtained by evaluating the signal energy and hence the height of the peaks rather than the position of the cross-correlation functions. Under the assumption of dilute phase flow (low volumetric concentration of particles), the peak height of the cross-correlation function is a good approximation for the (relative) particle concentration. Again, the profile is reconstructed using a linear back projection approach. The reconstructed particle velocity profile of practical experiments with plastic pellets under dilute phase flow conditions is shown in figure 3a. This profile exhibits faster particle velocities close to the pipe bottom for the test setup. The reconstructed particle concentration profile, which is shown in figure 3b, features higher concentrations towards the pipe bottom. Both reconstruction results are in good accordance with the high-speed camera observations.



(a) (b)

Figure 3. (a): Reconstructed particle velocity profile and (b): Reconstructed relative particle concentration profile for dilute phase flow of plastic pellets [30].

IV. APPLICATION: FLOW METER FOR SCREW CONVEYOR

The principle of transporting material by means of an Archimedes screw is very well known, especially in bulk materials handling. Such a conveyor basically consists of screw-shaped blades on a rotating axis in a closed pipe [31]. With the blade movement, the material is pushed through the transportation pipe. Screw conveyors are remarkably versatile and they are hence used in all areas of bulk materials handling. Among others, their advantages are a steady operation principle, the control of mass flow via revolution speed of the screw, and the ability of horizontal and inclined material transportation. A typical and widespread application of screw conveyors in domestic tasks is to use them for transporting wood chips into a burner of a heating system. The transported mass can only be roughly estimated by knowing the revolution speed of the screw drive and the mean mass (or volume) of the transported material per revolution of a blade. The material fill level (i.e. the height of material in each individual "pocket") in such a horizontal setup may vary dramatically, leading to erroneous results for the transported mass. Figure 4 shows the principle of material transportation by means of a screw conveyor and illustrates the different batches of material separated by the screw blades [32].

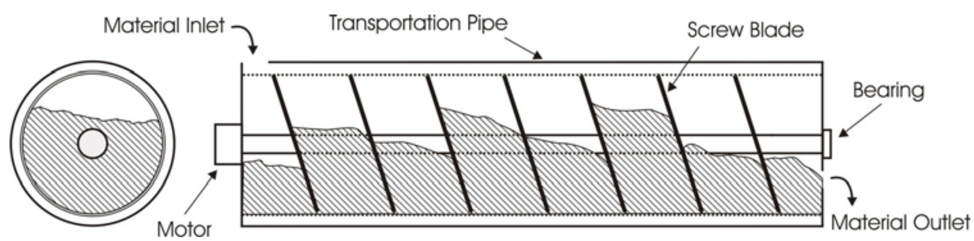


Figure 4. Material transportation through a screw conveyor showing different fill levels [32].

The revolution speed of the screw can be reliably determined by analyzing the motor rotation speed that drives the screw. However, to avoid expensive cabling and electromagnetic disturbances caused by long cable duct through industrial environment, an all-in-one sensor solution for both revolution speed and fill level is desirable.

A flow meter for bulk solids flow through a screw conveyor is presented in [32]. An electrode topology similar to figure 1a is mounted on the outer surface of the non-conductive conveyor pipe (sight glass). Also, for this application capacitances between subsequently activated transmitter segments and a common receiver ring are measured.

With every turn of the screw, a metal blade passes the sensitive area of the segmented electrode setup and causes field draining effects, resulting in a decreasing capacitance while the blade is present in the vicinity of the active transmitter (i.e. field suction caused by the metal screw). The period of time when the screw does not affect the capacitance of a given segment to the receiver ring is used to determine the fill level in the conveyor pipe. Figure 5 shows the principle of operation for the proposed flow meter to obtain revolution speed and fill level and hence allows for the calculation of the material volume flow.

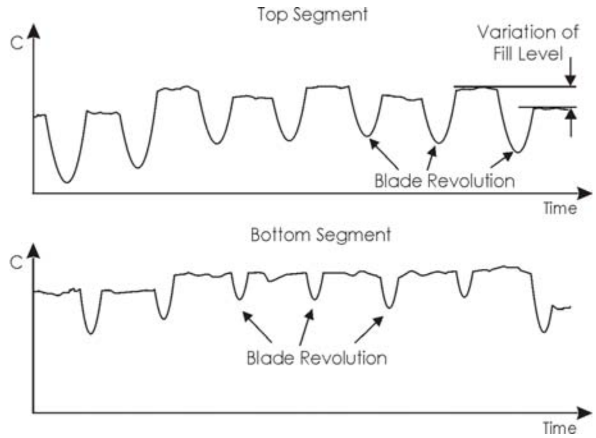


Figure 5. Principle of operation of the screw conveyor flow meter to determine revolution speed of the screw and material fill level.

Figure 6 shows a photo of the capacitive setup with a segmented ring of transmitters comprising 16 electrodes and a continuous receiver ring. The second layer of segmented electrodes is used to study the radial movement of particles, caused by wall friction. The horizontal screw conveyor in the photo is approximately half filled with grain and fill level variations can be observed even for short conveying lengths.

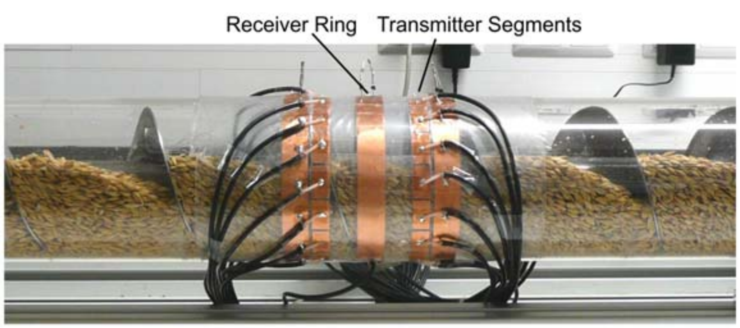


Figure 6. Setup of the capacitive flow sensor mounted on a non-conductive screw conveyor pipe.

Figure 7 shows a set of measurement data for all 16 segments over time. The test cycle comprises a screw conveyor operation of three revolutions without material, 15 revolutions with a test material less than half filled (125 g of corn in-between two blades), and additional three revolutions without material. The periodicity caused by the passing blades is significant in both operations with and without material. The screw revolution speed can be determined reliably.

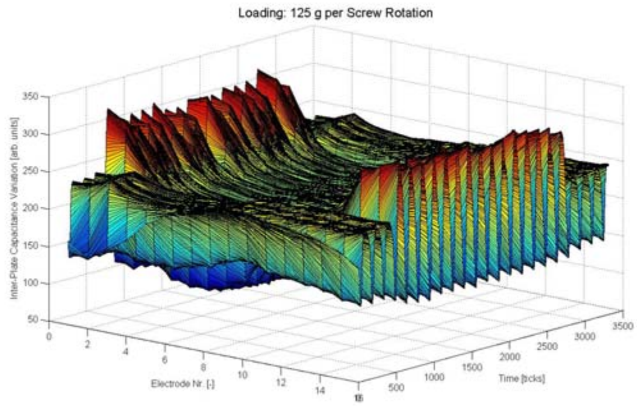


Figure 7. Measurement results with partly filled conveyor pipe.

For the determination of the fill level, two effects have to be considered: When material is present in the vicinity of transmitter segments (covered bottom electrodes 1 and 16 and also their neighbors 2 and 15), the material permittivity improves the coupling of the field from transmitter to the receiver and increases the inter-electrode capacitance. Uncovered segments (e.g. top segments) are less affected and field suction effects caused by the material below can be observed that decrease the segment capacitance value to be evaluated. Both effects can also be obtained by means of simulations [32] and used for reliable material fill level measurement in the setup.

Figure 8 shows measurement results for one specific transmitter electrode (i.e. bottom electrode 1) when the conveyor is operated with dry corn and without material.

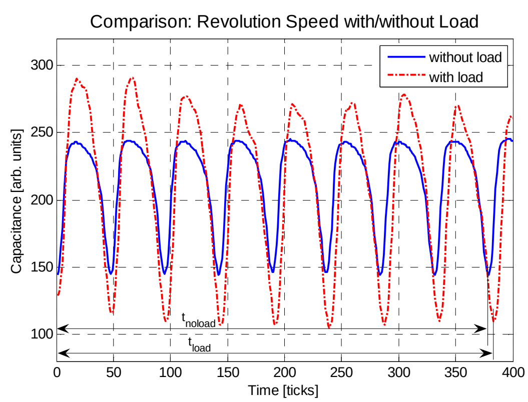


Figure 8. Bottom segment signal when the screw conveyor is operated with dry corn (with load, dashed-dotted red line) and without load (solid blue line).

It can be seen that due to the permittivity of the test material the field coupling and field suction effects are enhanced and that the revolution speed decreases due to the load (i.e. $t_{noload} < t_{load}$) even though the conveyor is operated under the same conditions.

V. CONCLUSION

This paper gives an overview of the state of the art in flow parameter determination of powdery and granular material in bulk solids conveying. The different methods are compared and rated according to key requirements. A cost-effective, non-invasive capacitive topology with multiple transmitter electrodes and a common receiver ring is presented and its applicability for flow sensing is shown for material transport by means of pneumatic conveying and by means of screw conveyors.

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