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Online acoustic chemometric monitoring of fish feed pellet velocity in a pneumatic conveying system

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Abstract

Fish farmers consider the cost of fish feed pellets as one of the most expensive factors in fish cultivation. Proper control of the handling and conveying systems is necessary to avoid damage and disintegration of the cylindrically shaped fish feed pellets. Pneumatic conveying is widely used to transport large quantities of fish feed. Proneness of crushing the fish feed pellets caused by pellets interaction with the inner wall of the pipeline is a major concern to the manufacturer due to the associated economic loss; pellet damage increases exponentially with the conveying air velocity. On the other hand, too low conveying rates would lead to pipeline blockages and severe pipe vibration. In order to address the foregoing issues, it is necessary to optimize the conveying velocity of fish feed pellets during pneumatic transport. Application of an on-line monitoring technique based on non-invasive passive acoustic measurements and multivariate regression modeling (acoustic chemometrics) was investigated. A partial least squares regression (PLS-R) model was calibrated to predict pellet velocity from 19 m/s to 36 m/s in a pilot scale pneumatic conveying system. The PLS-R prediction model was validated based on independent experimental data (test set validation). The root mean square error of prediction (RMSEP), slope and r^2 of the prediction results were 0.64 m/s, 1.02 and 0.97 respectively. The prediction results obtained shows the applicability of acoustic chemometrics for real-time prediction of the velocities of fish feed pellets during pneumatic conveying.

Keywords: acoustic chemometrics, partial least squares regression (PLS-R), process analytical technology (PAT), fish feed pellets, pneumatic conveying, optimization

1 Introduction

Global demand for fish products continues to increase. In order to meet this requirement, fish products come not only from wild catches but increasingly rather from land-based and off-shore fish farms. This is due to the fact that wild fisheries, which was the traditional source of fish is rapidly being exhausted all over the world therefore, prompting the need for aquaculture [1]. Fish farms however, often produce adverse environmental impacts, primarily due to unconsumed feed pellets that settle on the seabed and as a consequence excess nutrient and organic matter is accumulating [2]. There are some studies on the effect of this overloading of the seabed with organic matter as reported by Hellou et al. and Bongiorni et al. [3, 4]. Many environmental and health advocates worry about the environmental pollution from marine farms especially for large species like salmon, cod and tuna. In order to reduce the pollution problem, farmed fish must be fed optimally, and precisely with the adequate amount, type and quality of feed pellets to reduce and as much as possible eliminate this unconsumed fraction.

Fish feed pellets are cylindrical and farmed fish are sensitive to the pellet shape and easily reject non-cylindrical shaped feed. Inconsistent pellets shape result in several problems including that farmer refuse to buy fish feed that do not meet up to the required specification and which thus lead to deposition of unwanted waste - and unconsumed feed on the sea bed below the farm cages. The manufacturers of fish feed on the other hand incur an economic loss due to rejection of their products.

Pneumatic conveying is widely used for handling of feed pellets in the fish feed industries, especially during loading and unloading operations on feed carrier ships and in cage feeding at fish farms. Even though pneumatic conveying is considered as a flexible, environmental friendly, hygienic transport method for biologically sensitive products, sub-optimized conveying operations may contribute significantly to pellets degradation [5-6]. The most important reason is due to pellets impacting the inner pipe wall in the conveying system and likewise collision between pellets. The phenomenon on attrition and impact damage to different particulate materials has been studied extensively by many researchers [7-10]. A common observation is that the product damage increase exponentially as a function of the conveying air velocity where also the angle of impact has a significant influence on the product damage. On the other hand, if the conveying system is operated with a too low conveying velocity, it will be subjected to inconsistent operation due to solids deposition, or become completely inoperable because of pipeline blocking [11-13]. In general, the minimum conveying velocity can be defined as the safe air velocity for consistent transportation of pellets [14]. If the air velocity is measured at the beginning (feeding point) of the pneumatic conveying system, the air velocity further downstream will be higher caused by compressibility effects, i.e. the density decrease. The air volume flow rate downstream of the flow transmitter will be higher than the measured value if the pipeline has a constant pipe diameter.

Extensive research on pneumatic conveying technology has been carried out by Tel-Tek, Dept. POSTEC, which has developed a piece-wise scaling up technique [15-16], consisting of a computer software combined with an experimental procedure [17] to design and simulate industrial scale pneumatic conveying systems. The method can be applied to ensure optimized operation, addressing reliable operation, energy consumption and other common conveying problems like product degradation and pipeline erosion. In order to apply this technique effectively in pneumatic conveying of fish feeding, it is important to have access to a reliable real-time monitoring method for conveying velocity.

In recent years, several on-line techniques commonly referred to as Process Analytical Technologies (PAT) have been implemented in numerous areas of science and technology for research and development and industrial process characterization. PAT was primarily intended for on-line applications in the pharmaceutical industries [18] but has since been developed for numerous other purposes and has evolved over the years and is presently dominating the field of industrial monitoring [19]. On-line monitoring techniques have been attracting many research efforts during the past years. Driven by the increasing maturity and adoption, PAT methodologies have played an important role in the optimization of industrial processes and products. Increased interest from the industry has also led to development of a new range of sensor technologies. The most desirable sensor probes are the non-invasive type which does not disturb the process and are easily mounted without any modification of the process equipment. The cost and reliability of these methods also influence on their merit and benefit.

Acoustic measurement approaches have previously been applied in powder science to characterize pneumatic flow [20]. Acoustic chemometrics is a non-invasive on-line PAT technique which has entered a new phase in recent years. The recent advances offer vast opportunities for research and development in areas of technological applications which are documented in the literature [21-25]. Mass flow rates of material transported in pneumatic conveying lines in dilute phase [21] and dense phase [26] systems have previously been investigated. Acoustic chemometrics was previously applied by Huang et al. [27] for monitoring of powder breakage during pneumatic conveying. However, literature on determination of velocity of material during transport by means of acoustic measurement and multivariate data analysis does not exist. On-line prediction monitoring of the pellet velocity gives valuable information for the process operators for optimal process operation with respect to product degradation. Another advantage is that energy consumption can also be optimized as described by Ratnayake [18].

The experiments reported here were primarily designated to improve the performance of a pellet feeder and conveying rig in a bulk carrier ship used by a fish feed manufacturer. The main objective was to improve the quality of fish feed product delivered to the customers. Material feeding from a discharge tank to a conveying pipeline was arranged through a full scale feeding valve. The main focus was to investigate how acoustic measurements and multivariate data analysis can be used to predict the pellet conveying velocity.

The tests were conducted using a pneumatic test facility in the powder research laboratory of Tel-Tek, POSTEC, Norway. The experiments were designed to include pneumatic conveying of fish feed pellets with different conveying velocities (by applying different air flow rates), under collective behavior. The acoustic chemometric approach involved recording of acoustic signals of pellets impacting the conveying pipeline during transport. Partial Least Squares Regression (PLS-R) was used for model calibration.

2 Materials and methods

The pilot scale conveying rig was designed and operated to simulate a full-scale transport facility in a bulk carrier ship used to transport fish feed pellets from the manufacturing plant to the fish farms. The conveying rig consists of several large silos with a capacity of approximately 60 tons, and pipelines with different diameters (125mm, 150 mm and 200mm).

2.1 The pneumatic conveying rig

The pilot scale pneumatic test rig was used to transport feed pellets under different process conditions. The major components of the test rig have been made by scaling down the corresponding pipe elements of a full scale feed pellets conveying rig [28]. Figure 1 shows a schematic overview of the test rig.

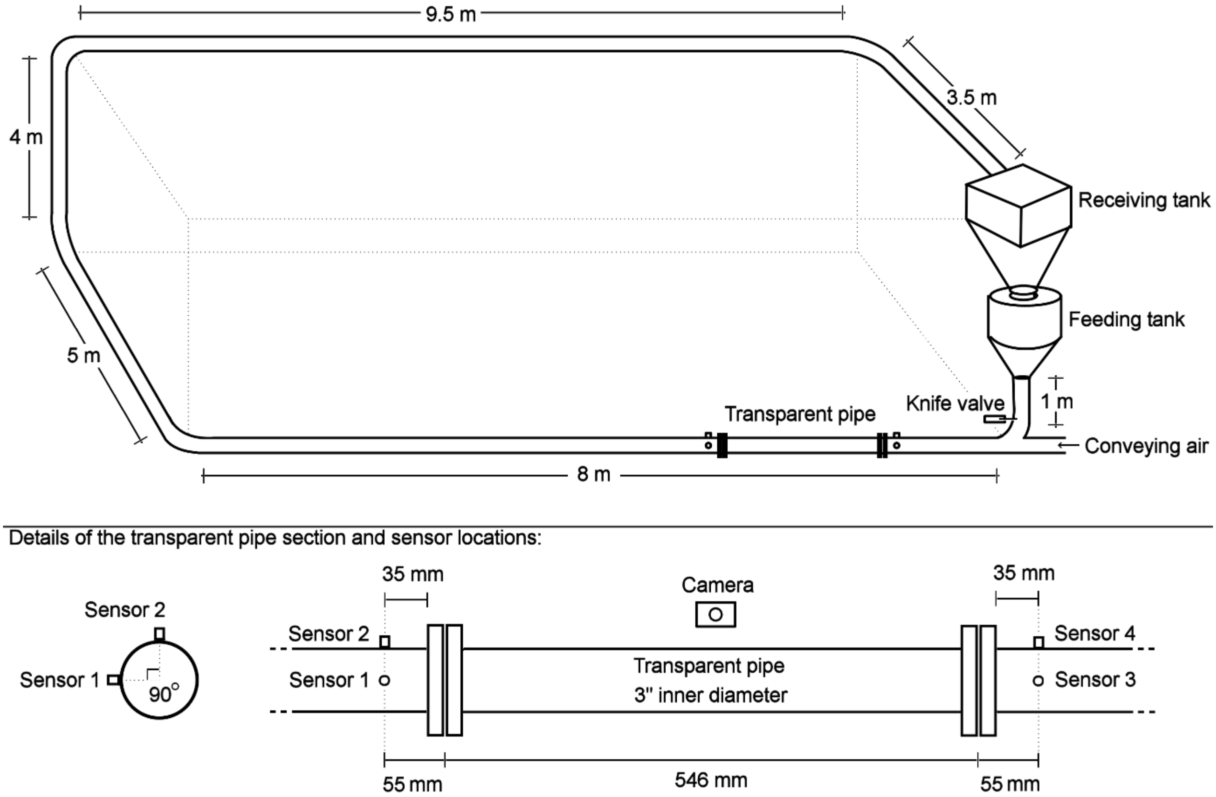

Figure 1: A schematic view of the main components of the pneumatic conveying test rig used in this study. The rig allows video capture of the fish feed pellets flow and acoustic measurements simultaneously.

The test rig consists of a discharge tank of 2.5 m^3 capacity, a receiving tank, and a 40 meter long pipeline with an internal diameter of 75 mm. On the horizontal section of the pipe just below the feeding tank (see Figure 1) a transparent pipe section was inserted to allow high speed video capture of the fish feed pellets during transport. Feeding of the material from the discharge tank to the conveying pipeline was arranged through a full scale feeding valve provided a major manufacturer. The conveying line forms a closed loop circuit with the receiving tank on top of the blow tank. The advantage of this arrangement is that the pellets in the receiving tank can be filled into the blow tank and thus make the material ready for the next experiment without removing it from the test rig.

The air supply was provided by a combined screw type air compressor and drier. The pressure and volume flow rate of supply air were controlled by a controller valve.

Traditional process measurement transmitters such as pressure, flow, temperature and humidity meters were also mounted on the transport line in order to monitor and operate the test rig properly. The rig was equipped with facilities for continuous logging of air pressure at various locations, air temperature, humidity, material transport rate etc, on a real time basis. The data acquisition and analyses were undertaken with LabVIEW® software.

The reference velocities required for calibration and validation of the PLS-R models were obtained from visual inspection of high speed video recordings of the material as it passed through the transparent section of the pneumatic transport line. The high speed video was recorded simultaneously as the acoustic spectra were acquired.

Acoustic signals were acquired from four accelerometers mounted on the test rig in four different locations on the pipeline (see Figure 1). Sensors 1 and 2 which were mounted 90^o to each other and the same was done for the other sensor pair (sensor 3 and 4).

2.2 The test material

The type of fish feed used in all the experiments was Optiline 2500 which was provided by a major producer. The fresh pellets were of cylindrical shape with 10mm length and a diameter of 9mm. The bulk density of the pellets measured under loose poured and tapped conditions was in the range of 670-720 kg/m^3. Figure 2 shows a collection of fish feed pellets with a scale attached for clarity.

Figure 2: Fish feed pellets (Skretting, Optiline 2500) used in this study. Length = 10mm and diameter = 9mm.

2.3 Acoustic chemometrics

A survey of published literature concerning acoustic chemometrics shows that it has gained widespread use in industry. The publications span a broad variety of industrial applications demonstrating the potential of the method [21-27, 29]. These applications include studies on liquids, particulate materials, and slurries. The advantages of acoustic chemometrics are:

1. Non-invasive sensor technology
2. Real time acoustic signal acquisition and processing
3. Easy clamp-on/glue-on installation of acoustic sensors
4. Several parameters of interest can be predicted from the same acoustic measurement

The main reason for choosing acoustic chemometrics is the on-line and non-invasive nature of this measurement approach which allows monitoring without disturbing the process. Non-invasive methods are especially desirable in pneumatic conveying systems because intrusive sensors will lead to deposition of materials on the sensors and in some cases this will lead to clogging of the pipelines. Clogging of process pipelines might result in shutdowns or influence the measurements so these become non representative or fail capturing the real behavior of the process. Furthermore, the total cost including both acoustic monitoring equipment and installation is relatively low compared to other on-line methods. Interested readers are referred to Esbensen et al. [21] and Halstensen & Esbensen [24] for more details on the principles and theory of the acoustic chemometric approach.

In brief, acoustic chemometrics involves the acquisition of passive acoustic signals from systems that generate vibration recorded by attaching acoustic sensors (accelerometers) to the system and subsequently apply signal processing techniques and chemometric methods to extract the information of interest from the complex and sometimes noisy acoustic spectra. During acoustic signal acquisition, these are first filtered to the desired frequency range and amplified to maximize digital resolution in the subsequent analog to digital conversion stage. The acoustic signals are acquired in time domain and thereafter undergo a series of signal conditioning stages. The acoustic signals are subjected to digital signal processing techniques like Blackman Harris window transformation, Fast Fourier Transformation (FFT) and linear averaging in order to obtain acoustic frequency domain spectra with adequate precision. The final frequency domain spectra are also called acoustic process signatures [30-31]. Four accelerometers (Brüel & Kjær® 4518-002) were mounted at different locations on the pipeline as shown in Figure 1. The sensors were glued directly onto the pipeline used to transport the pellets. Cyanoacrylic glue was used to ensure proper acoustic coupling between the pipeline and the accelerometer. The signal cables going from the accelerometers to the data acquisition system were kept as short as possible in order to minimize influence of noise from external sources on the acoustic signals. A Signal Amplification Module (SAM) designed by Applied Chemometrics Research Group (ACRG) was used to amplify the signals from the accelerometers. The SAM is a multi-channel system for acoustic signal adaption which also includes a constant current power supply to the accelerometers. Data acquisition was achieved by using a DAQ unit (USB-6361 multifunction DAQ unit) by National Instruments connected to a dedicated computer and a NI LabVIEW® software interface.

The time domain signals from the accelerometers were sampled sequentially with a frequency of 1200 kHz corresponding to an individual channel/sensor sampling frequency of 300 kHz. Each acoustic signature was a linear average of 100 FFT spectra with 2048 frequencies. The frequency range represented by the 2048 frequencies was 0 – 150 kHz. The acoustic signatures represents the frequency distribution in the signals emitted from transporting fish feed pellets in the pneumatic conveying pipe at various air flow rates and velocities. The acoustic signatures were later subjected to chemometric modeling where PLS-R models for prediction of pellet velocity and air flow rate were calibrated and validated.

2.4 Experimental

The experimental pneumatic rig used in the conveying experiments is shown in Figure 1. The experiments were carried out according to a strict experimental procedure to ensure comparable process conditions for each conveying run. First the supply tank was filled with approximately 500kg test pellets. After adjusting the desired air supply pressure according to the intended volume flow rates and velocities of pellets. The nominal values of the air flow rates used in this investigation varied between 250 and 650 Nm^3/h. The conveying test was started by opening the main supply valve at the bottom of the feeder tank simultaneously as data acquisition was started. Data acquisition of the acoustic signals was initiated simultaneously as the recording of high speed video of the fish pellets passing through a transparent section of the pneumatic transport pipe. High speed video was recorded using an OLYMPUS i-Speed LT camera. High speed video was necessary to determine the pellet velocity accurately since it is needed as reference **y**-data in PLS-R model calibration and validation. A frame rate of 1000 frames per second was used for the high speed video recording. The reference pellet velocity from each experimental run was determined from visual inspection of the high speed videos. Pellet velocity was found from visual interpretation of the distance a pellet moved between each frame in the video as the pellet passed through the transparent section. A measuring tape mounted onto the transparent pipe was used to support the distance interpretation in each frame. Since the time between each frame in the video was 1ms the velocity could be determined from following a pellet frame-by-frame. This procedure was repeated ten times based on ten different pellets. The final velocity reference value gained from one experimental run was found as the average of those ten repetitions. The end of the conveying cycle was determined by monitoring the weight of material in the receiving tank and also the pressure signals in the conveying line.

The data sets used to calibrate and validate the PLS-R models were acquired over 4 different days. Data from two days were used for calibration and the remaining (data from the other 2 days) was used for validation. Changes in pellets size and size distribution were checked continuously to trace any significant pellets degradation, during the conveying tests. When there was indication of pellet degradation, the pellets were replaced with fresh pellets of same quality and quantity. Also special attempts were made to determine the lowest conveying velocity, without getting the conveying line blocked. From an initial series of experiments it was found that pellets could be conveyed reliably with velocities above 17 m/s. Reliable conveying was defined as pellet transportation where no fluctuations could be noticed during the conveying tests. All the pneumatic conveying experiments were classified as dilute phase pneumatic transport due to the suspension of the material in the air as it was transported.

2.5 Partial Least Squares Regression (PLS-R)

PLS-R is an empirical approach for multivariate calibration and prediction. PLS-R-1 is applied in cases where **y** contains only one variable. PLS-R-1 involves simultaneous modeling of both the independent **X** variables and the dependent **y**- reference data where both these data structures are projected onto lower dimensional underlying structures called latent variables, factors or PLS components. The PLS components are found as to provide the best possible approximation of the systematic variation in both **X** and **y**. In contrast to ordinary least squares regression PLS-R can handle co-linear data. Co-linear data is inevitable in spectroscopy as well as acoustic chemometrics since the spectra have many variables. In acoustic chemometrics it is often not possible to have equally many samples –as variables- in a calibration situation since the Y-reference values are often found based on a time consuming and/or work intensive reference method (visual inspection of high speed video frames in this case). More variables than samples in the X-data matrix is a guarantee for co-linearity were PLS-R works well but ordinary least squares fails. The **X** data matrix in this study contains the acoustic signatures resulting from pellet transport, while the corresponding **y-**vector contains the reference pellet velocities.. Only a brief description of PLS-R is presented here, interested readers are referred to dedicated literature [32-33] for further understanding of the theory, principles and application of PLS-R.

Representative calibration and validation data which properly spans the expected process variation is necessary to calibrate a reliable PLS-R prediction model. In general, the driving force behind application of multivariate calibration methods is to minimize the time-consuming effort (and cost) of performing actual **y-**measurements on a process (manual inspection of high speed video recordings in this case). The calibration and validation data were obtained from independent sets of experiments in accordance with the requirements stipulated by Esbensen and Geladi [34] regarding the necessary realism and validity of independent test set validation. Generally, visualization plots and statistical results are used for describing the prediction performance of PLS regression models. Loading weight plots shows the influence of the variables. Variables which have the high loading weight values influence the PLS-R model more than those with lower values. Determination of the optimal number of PLS-components is based on evaluation of **y-**residual variance vs. component number, where the component number corresponding to the lowest residual (lowest prediction error) is optimal; it is critical that this tuning of the PLS-R model is not based on either of the inferior, alternative validation approaches (cross-validation, leverage-corrected validation). The number of PLS components is often related to the complexity of the multivariate X-matrix and how many different influential phenomena that are varying simultaneously, however e.g. errors in X and/or Y data will often require additional components to be able include these inaccuracies in the PLS-R model. Other diagnostic plots are used in multivariate calibration depending on the purpose of the study and thus interested readers can consult dedicated literature on this topic [32-33]. The RMSEP values reports the average prediction error in original units, and is calculated in equation 1.

$$\text{RMSEP} = \sqrt{\frac{\sum_{i=1}^{n}(y_{predicted} - y_{reference})^2}{n}} \qquad (1)$$

where n is the number of reference samples in the validation data set. The relative RMSEP (relative to the average y-level) is a universal quality parameter that allows meaningful comparison across different PLS-R prediction models.

Here data analyses comprised calibration of PLS-R prediction models for both pellet velocity and air flow rate.

The volume flow rates of air is somewhat correlated to the pellet velocity, however, the pellet velocities cannot be derived from the air flow rates directly. The reason is that identical airflow rates can be used to convey with different feeding rates of material (pellets in this case) resulting in different pellet mass flow rates and different velocities.

The acoustic signatures (the **X**-data) were subjected to data pre-processing. These include auto-scaling which is a common pre-processing method involving mean centering of and variance scaling of each variable (frequency) column in the X matrix. Moving average was used to smooth the spectra (window size=19). Data pre-processing and PLS-R modeling were carried out using The Unscrambler® 9.8. No outliers had to be removed during the PLS-R calibration of the data. The underlying description of the pre-processing approaches described above is available in [33]. Optimal pre-processing methods and settings were determined from comparison of PLS-R model diagnostics such as the slope, Root Mean Square Error of Prediction (RMSEP), **y**-residual variance plots and R^2.

3 Results

The acoustic response to varying pellet velocities is shown in Figure 3 where acoustic frequency spectra from experiments with three different pellet velocities (17, 25 and 36 m/s) show the direct relationship between acoustic frequency response and the pellet velocities.

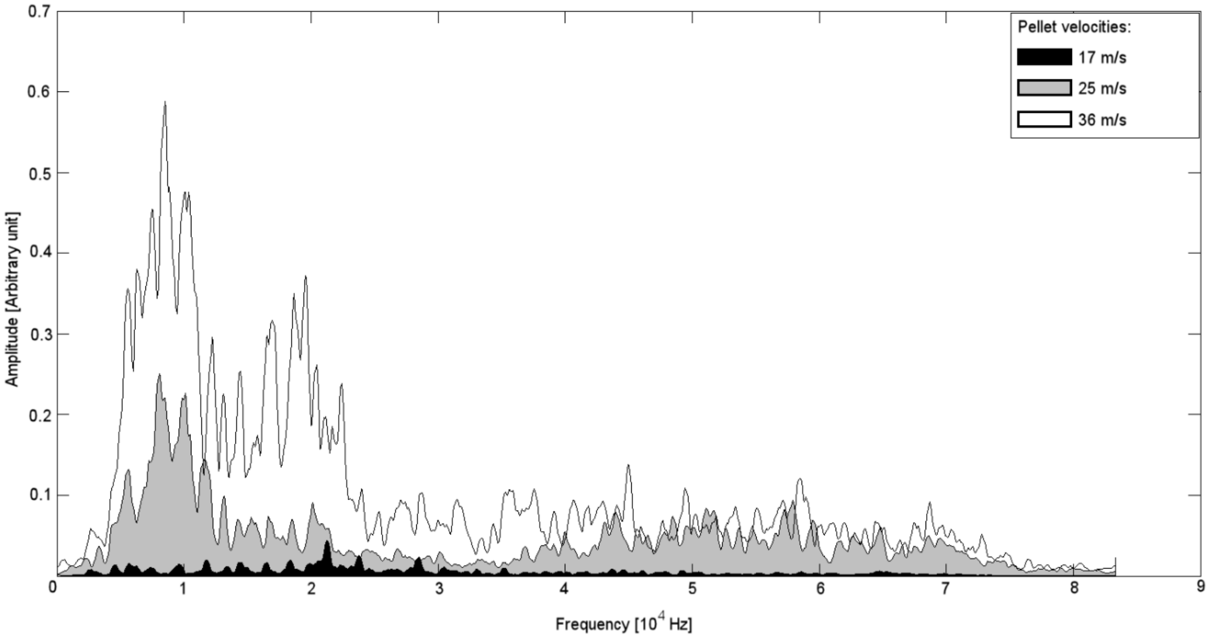

Figure 3: Acoustic spectra from sensor number 3 for 3 different pellet velocities.

The acoustic frequency distribution is different in the three spectra. The lowest velocity has an acoustic response which has its main peak around 22 kHz, while the higher velocities have the highest peaks around 10 kHz. Another observation is that the acoustic spectra representing 25 m/s has almost the same level as the one for 36 m/s from 45 kHz and up while the lower part is significantly different. PLS-R is a method suitable of finding the underlying covariance structure in such complex matrices; the loading-weight spectrum shows the most influential *effective* frequency contributions.

3.1 Fish pellets conveying velocity PLS-R prediction results

Optimal sensor location for acoustic monitoring is in most cases system-dependent and it is necessary to investigate this in each individual case. The locations of the four sensors on different sections of the pipe (see Figure 1) were primarily decided based on experience with similar systems and the constraint that all sensor locations had to be located close to the transparent section from where the reference velocities were obtained. It is critically important for PLS-R modeling that the reference values and the corresponding acoustic measurements are comparable. The same (identical) pellets which are measured with the acoustic sensors should be captured on the video recordings. This is possible since the sensors are located so close to the video camera that it will take only 14 - 30ms from a pellet is captured on video until it is measured by the acoustic sensor.

PLS-R models based on data from the four different sensor locations were compared and evaluated. Prediction results for the pellet velocity based on data from sensors 1-4 is presented in Table 1.

Table 1
PLS –R validation results for the four sensor (accelerometer) locations (y = velocity).

Sensor location	#PLS components	RMSEP [m/s]	*rel*RMSEP % [%]	Slope	R^2
1	1	4.29	25.2	0.21	0.25
2	1	4.07	23.9	0.46	0.32
3	3	0.64	3.8	1.02	0.97
4	3	1.73	10.2	0.91	0.89

As can be seen in Table 1 sensor 3 shows the best overall prediction performance based on RMSEP, Slope and squared correlation r^2. The diagnostic plots and results for the PLS-R model based on sensor 3 are shown in Figure 4. The optimal number of PLS components is three which were determined from interpretation of the y-residual validation variance plot shown in figure 4 (lower left).

Evaluation of the loading weights for the three PLS-components shows a clear indication that the PLS-R model utilizes information in all the full frequency range for prediction. The loading weights of the first and second PLS-component, however has most influence. The scatter plot of predicted vs. measured reference samples shows a squared correlation coefficient r^2=0.97 which is relatively high. The slope and RMSEP were 1.02 and 0.64 m/s, respectively.

The predicted versus reference plot (Figure 4, lower right) shows PLS predictions based on independent test set data which were not used for calibration of the conveying velocity model. The results are promising for on-line prediction of the conveying velocity of fish feed pellets.

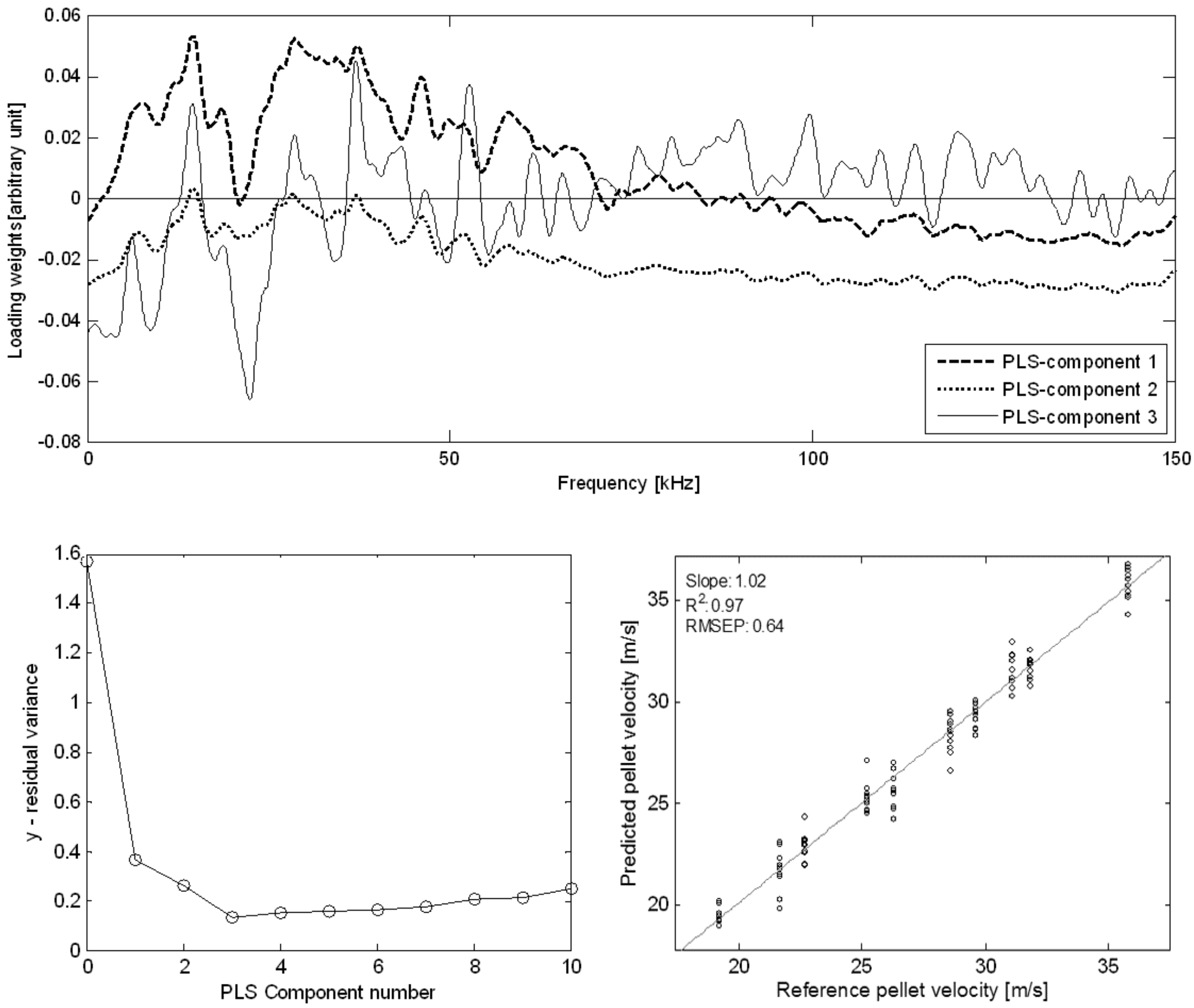

Figure 4: PLS-R model for pellet flow velocity. Top: loading-weights plot for $W_{1\text{-}3}$. Lower left: ***y****-residual validation variance plot showing that three is the optimal number of PLS-components. Lower right: Predicted vs. reference pellet velocity.*

3.2 Air flow rate PLS-R prediction results

Results showed that sensor 3 acquired the most informative acoustic signals also for prediction of air flow rate as can be seen in Table 2. This is the same sensor location as was found best also for prediction of pellet velocity (section 3.1).

Table 2
PLS-R validation results for the four sensor (accelerometer) locations (y = air flow rate).

Sensor location	#PLS components	RMSEP [Nm^3/h]	*rel*RMSEP % [%]	Slope	R^2
1	1	77.54	23.86	0.12	0.22
2	1	77.06	23.71	0.12	0.23
3	3	29.06	9.68	0.95	0.89
4	3	33.38	10.27	0.91	0.86

From Table 2 it can be observed that sensor 3 has slightly better prediction results than sensor 4 based on the diagnostic results RMSEP, Slope and R^2. The diagnostic plots from the air flow rate model are not shown here.

The optimal number of PLS-components shown in the second column of Table 2 is again found based on the y− residual variance plot. The RMSEP of the predictions from the airflow rate model with three components was 29.06 Nm^3/h (within the range 350-650 Nm^3/h) which is 9.68% of the range.

4 Discussion

Acoustic chemometric studies related to characterization of particulate material and pneumatic transport lines have been well established in previous studies [21-24]. Previously published literature on acoustic chemometrics for particle characterization has shown that it is possible to predict particle size, moisture content, crystallization point etc. In this work variation in the mentioned parameters will not influence the predictions of pellet velocity nor airflow rate because the particle characteristics such as shape and size are here supposed to be constant.

The pellets degradation is usually very high, when the gas-pellets mixture is conveyed at high velocities. Therefore, determining the optimal velocity for conveying of fish pellets is a necessary to minimize degradation of feed pellets during pneumatic transport. In order to optimize the pellet velocity it is necessary to be able to control the velocity, and in order to control it is necessary to measure the pellet velocity. The information on feed pellet velocity can effectively be used in system optimization [28] and with a practical implementation it is possible to start the work to find the optimal velocity. From following this approach it will be possible to solve the problem of economic loss and environmental pollution associated with fish pellet breakage during pneumatic transport

The initial sensor location(s) which was tested were determined by studying the configuration and dimensions of the pneumatic conveying pipe. The best sensor location in a system has been discussed to be a consequence of several dynamical issues [29]. It is however, recommended to investigate the optimal location(s) in each application because several factors such as type of medium (liquid, gas, particulate, fluid) and nature of the test system are the determinant factors. The localization of the four sensors used in this work was primarily a result of acquiring the acoustic signal within the vicinity of the section modified for the video capture such that comparison of the data from the sensors and the video could be made. Sensor number three was identified as the best sensor location for prediction of both pellet velocity and airflow rate. The reason why sensor three and four showed significantly better results than the other sensor pair (sensor one and two) most likely results from the fact that sensor three and four are located closer to the bend (see Figure 1) than the other sensor pair (sensor one and two). Pellets impacting the inner wall of the bend generate acoustic vibrations which have much higher amplitudes than what is the case in the other section (where sensor one and two are located) which is straight. The transparent section made of plastic -together with the rubber gaskets used between the flanges -isolate a relevant part of the signal picked up by sensor 3 and 4 from propagating to the other side of the transparent section where sensor 1 and 2 were mounted. Table 1 and 2 shows that the PLS-R models based on sensor three and four, three PLS-components are utilized, while the PLS-R models based on sensor one and two, only one PLS-component is used. As described above regarding optimal sensor location, one can deduce that the signal to noise ratio in the acoustic signals from sensor one and two is significantly lower than for the other sensor pair (sensor three and four). This is one of the reasons why also the models based on sensor one and two only can utilize one component as component two and three were not stable enough to be considered in the interpretation of components as described in the PLS-R method section.

Separate PLS-R prediction models were developed for pellet velocity and air flow rate. Airflow rate and pellet velocity modifies the acoustic spectra differently. Variation in the airflow rate affects only part of the acoustic spectrum which the PLS-R model identifies during model calibration/validation. Prediction of several output parameters from the same acoustic spectrum demonstrates one of the advantages of acoustic chmeometrics.
There was a strong correlation between the airflow rates in the pneumatic conveyor and the velocity of materials being conveyed. Although airflow rate and pellet velocity are related the pellet velocity cannot be derived from the air flow rate directly. This is because a fixed airflow rate is capable of transporting material with different mass flow rates. .

The present work has shown that acoustic chemometrics can be reliably adopted for monitoring of systems parameters when fish pellets are conveyed pneumatically. The prediction results for both pellet velocity and airflow rate are promising for on-line, real-time monitoring of fish pellet conveying systems for control and optimization of pellet velocity.

5 Conclusion

This study focused on development of an acoustic monitoring technique for prediction of the velocity of fish feed pellets during pneumatic transport making it possible to control and optimize the conveying velocity. Several sensor locations were investigated; sensor 3, mounted on the side of the pipeline close to the feeding tank, was found optimal. Sensor 4 mounted on top of the pipeline 90 ^{o} to sensor 3 produced results only slightly worse than sensor 3.

The PLS-R prediction model from the best sensor location 3 provided the best prediction results reported as slope (0.98), R^2 (0.91) and RMSEP 1.5m/s (within a range of 19.3-35.5 m/s). RMSEP=0.68 m/s corresponds to an average prediction error of 3.8% relative to the range average.

From this investigation, it has been established that the velocities of the fish feed pellets can be reliably monitored by acoustic chemometric technology which will make it possible to reduce the negative environmental impact and assist in resolving the economic loss experienced for non-optimal transport of fish feed pellets due to disintegration during transportation.

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