Acoustic Monitoring of Pneumatic Transport Lines: From Noise to Information

“Mass flowrate measurements in dilute phase pneumatic transport lines using acoustic sensors”†

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Abstract

Acoustic chemometrics is an interdisciplinary approach covering diverse fields including applied engineering, electronics, signal analysis and chemometrics. The applications of acoustic chemometrics are manifold, but quantiative analysis (chemical/physical) and process monitoring and physical characterisation of products are areas in which it can be beneficially used. Potential applications in many industry sectors abound. In one particular sense, acoustic chemometrics is simple: Acoustic signals from any process or equipment, followed by some form of pertinent signal analysis, are subjected to chemometric data analysis. In this context it is often the power of multivariate calibration that comes to the fore. Here, we give one major example of the use of applied acoustic chemometrics – non-invasive monitoring of a pneumatic transport line. Noise and acoustics have been defined as follows: noise – Irregular fluctuations accompanying, but not relevant to, a transmitted signal (Concise Oxford Dictionary), acoustics – science of sound (Scribner Bantam Dictionary). The irregular fluctuations referred to above contain much valuable information, and it is the line acquisition, conditioning and analysis of such fluctuations that we are concerned with in this paper.

1. Introduction

Industrial and technological processes are always accompanied by stronger or weaker energy outputs (heat, sound, vibration, etc.). Emission of audible noise is an inherent characteristic of very many production, manufacturing, transportation and/or propulsion processes – indeed, on reflection it is well nigh impossible to conceive of any industrial/technological processes which are not accompanied by at least some form of apparently incoherent acoustic energy output – noise. Some of this noise invariably shows up in the form of vibrational energy which can be measured, and whatever can be measured can in turn be subjected to chemometric data analysis. In this context, by “acoustic output” we mean not only “true noise” in the audible range, i.e. 5-20 KHz, but we also include vibrational energy outputs in contiguous frequency ranges which for many practical purposes of technological applications of acoustic chemometrics cover the range 0-25KHz.

There are many communalities for acoustic chemometrics applications – the common ground can be outlined (the “data path” from noise to information). Figure 1 is a schematic flow-sheet for a generic data path from the acoustic phenomenon to the final multivariate calibration model, including future prediction facilities.

During its first 2-3 years of operations, the Applied Chemometrics Research Group at Telemark College/Tel-Tek has designed, built and implemented most of the necessary electronic and computer equipment, covering both fixed as well as portable sets of data acquisition tools needed for any type of acoustic chemometrics (laboratory or field-based) in close collaboration with the Oslo-based entrepreneur company “SENSORTEKNIKK A/S”, which specialises in dedicated sensor technology.

Acoustic sensor technologies include generic accelerometers (often standard industrial units are quite adequate, but sometimes also tailor-made special accelerometers). Both portable recorders and desk-top or laboratory bench PC-based data I/O links are in use.

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All hardware solutions are backed by the powerful LabVIEW software system (National Instruments Inc.), allowing for dedicated virtual instruments through the use of the graphical programming facility, G.

2. Non-invasive monitoring of the pneumatic flow behaviour of particulate materials

2.1 Context of pneumatic chemometric studies

A new concept for characterising the flow of particulate materials in pneumatic conveying pipelines has been developed experimentally by ACRG and POSTEC (Powder Science and Technology Group, Tel-Tek) during the last two to three years. By means of chemometrics, several attempts have been made to establish empirical regression models describing the connection between the flow behaviour of representative types of materials and non-invasive acoustic measurements of pipeline surface vibrations. The aim is real-time characterisation of the material flow through prediction from these non-invasive acoustic measurements, an objective which in general is too complicated for a physical first-principles approach. Experimental data are needed to develop the necessary predictive model(s). Several pilot-scale & semi-plant-scale conveying tests have been carried out on a horizontal 21-m-long, 2" pipeline with a 90° bend (see Fig. 3). "Clamp-on" surface-mounted accelerometers were used to measure the compound acoustic vibrations resulting from the internal material flow. The effect of the different radial and axial position of the sensors on the accuracy of the predicted values has been investigated for different representative types of materials, e.g. PVC granules, sand, rape seed, cement and dolomite. Here, we give some selected highlights of these studies.

At the outset, it would appear reasonable to assume that the "noise" caused by pneumatic conveying systems is a reflection both of the relevant transport system settings as well as of the material properties themselves, e.g. solids feed rate, air flow, particle size distribution, particle density, humidity – and potentially many others. Although inseparable by the human ear, each property must be assumed to contribute in principle in a tractable manner (qualitatively as well as quantitatively) to the composite acoustic impact. It is the objective of acoustic chemometrics to be able to decompose such (noisy) signals with the aim of quantification of the parameter(s) of interest. In pneumatic transport lines, the ability to measure the solids loading by a robust, non-invasive technique as well as to use this to stay clear of blockages is of critical economic importance.

2.2 Experimental

The pneumatic conveyor is designed for batch transport. The main components of the test rig are the blow tank, the test-section pipeline and the receiving tank. Recharging of the blow tank is taken care of by a movable silo carried by an overhead crane. The solids feed rate is either controlled by the bypass to
transport air ratio, or by a piston-operated knife valve at the bottom of the blow tank. The overall air flow rate is the summarised flow rate of transport air, fluidising air and bypass air. Each supply is controlled by a globe valve and monitored by a turbine flowmeter. The transport air is additionally equipped with a pneumatic actuator for accurate adjustment. Humidity, temperature and pressure are also monitored on the air supply side.

The conveying line used for the experiments was 21 m long and had an inside diameter of 53 mm. Apart from a 90° “long radius bend” placed 13 m away from the outlet of the blow tank, no hindrances disturb the material flow. Ten equally spaced pressure transmitters enable monitoring of the pressure progress along the pipeline and calculation of specific pressure drops. This is the “traditional” pressure drop monitoring approach. The receiving tank is placed upon three load cells enabling continuous measurements of the average mass flow – massflow solids, $M_{\text{solids}}$ – to be made. This parameter will serve here to illustrate one important “parameter of interest” in the present context. Thus the acoustic chemometric modelling will specifically be oriented towards predicting $M_{\text{solids}}$ directly from calibrated acoustic models. Our experiments have also included three other related parameters which are more or less correlated to $M_{\text{solids}}$, which accordingly is the only variable described here.

The acoustic investigations required only a few instrumentation extensions to be made to the traditional approach. One or two uniaxial accelerometers were used to pick up the characterising system vibrations. The accelerometers act as portable “clamp-on” sensors, easily mounted on the surface of the system to be monitored. They are clearly non-invasive measuring devices as there are no hindrances placed in the stream. In our application, the accelerometers are mounted directly on the outside of the enclosing pipeline with ceramic glue and/or via welded brackets, allowing the accelerometers to be screwed tight firmly. This leads to a beneficial elimination of wear and plugging compared with standard instrumentation. Figure 4 shows details of the mounting alternatives of the acoustic sensors, as compared with the standard pressure transmitters.

A dedicated Data Acquisition (DAQ) Board (National Instruments Inc.) enabling an overall high-frequency...
Fig. 5 Details of accelerometer mounting (from left to right): bottom mounting – side mounting – top mounting. Note that it is imperative to affix cabling firmly to pipeline surface to ensure that the cabling receives the same vibrations as the accelerometer bracket(s). Also note bracket preparations on pipeline surface.

sampling rate of 50 kHz was used to handle the acoustic signals. Signal conditioning is taken care of by a Programmable Differential Amplifier and Low-Pass Filter Board (Alligator Technologies), needed to enhance the signal to noise ratio and to reduce the aliasing effects always present to some extent in the analogue-to-digital conversion of real-world signals. The amplified and band-limited signals (still analogue) from this board enter the DAQ board for a digital representation, A/D conversion.

The time-domain acoustic signals from the surface-mounted accelerometers are characterised by a great deal of irregularity and may well, at a first casual inspection, appear to be no less than pure noise. Information concerning interesting phenomena is very much hidden from the human eye, and has to be uncovered by some data analytical means. The Power Spectral Density (PSD) is an advantageous signal representation in that it enables the comparison of the signal frequency contents from one acoustic record to the other, especially when using a full-spectrum approach in the subsequent multivariate calibration stage. There are many easily available facilities for virtually real-time calculation of PSDs – i.e. the effective FFT (Fast Fourier Transform) approach – e.g. lleachor & Jervis (1993).

LabVIEW™ 4.0 (National Instruments Inc.) was used throughout to control signal conditioning and the data acquisition board and to estimate the X-block FFTs. The virtual program stores both acquired (time domain) and processed (frequency domain) data; it is also equipped with useful sonogram (time-frequency) display features etc.

2.2.1 Types of powders used in the study

Five granular materials were included in the present study – see Table 1. They were chosen from a set of reference materials which are frequently used in the process industry, all of which are included in POSTEC’s standard test program. Some physical characteristics of these selected materials, determined by standard laboratory testing equipment, are also listed in Table 1. As can be seen, the chosen materials cover a reasonably wide range of physical characteristics.

The present studies all relate to representative pneumatic transportation in the “dilute phase”, which is the area of greatest industrial interest.

2.4 Implementation/data recording optimisation

Several initial series of investigations were carried out in order to facilitate an optimised basis for establishing accurate and representative prediction models for the materials; such experimentation was directed towards all the necessary basic implementa-
Table 1  Physical and pneumatic conveying characteristics of test materials

| Material       | Particle density [kg/m³] | Poured bulk density [kg/m³] | Mean particle size [μm] | Minimum fluidisation velocity [m/s] | Wall friction angle against ST37 [°] | Static angle of repose [°] | Dynamic angle of repose [°] |
|----------------|--------------------------|-----------------------------|-------------------------|------------------------------------|-------------------------------------|-------------------------|--------------------------|
| PVC granules   | 1414                     | 518                         | 472                     | 8.1·10⁻²                           | 19.7°                               | 37°                     | 35°                      |
| Sand           | 2645                     | 1590                        | 687                     | 2.5·10⁻¹                           | 16.3°                               | 36°                     | 33°                      |
| Rape seed      | 1164                     | 687                         | 1650                    | 4.3·10⁻¹                           | 18.7°                               | 30°                     | 30°                      |
| Microdol 100   | 2865                     | 1212                        | 66                      | 3.2·10⁻⁴                           | 26.1°                               | 63°                     | 39°                      |
| Cement         | 3095                     | 734                         | 11                      | 1.0·10⁻⁴                           | 29.3°                               | 65°                     | 33°                      |

tion optimisation of, e.g. air flow rate and solids flow rate regarding accelerometer/amplification/filtering responses, etc. It is of importance to acquire acoustic signals with the highest possible quality, and this is effected by signal conditioning optimisation, i.e. grounding, gain setting, cut-off frequency as well as different amplification gain settings. In order to optimise PSD (Power Spectral Density) estimation, the number of periodograms (temporary PSD) used to produce one final average PSD and the number of samples used to compute each periodogram are two essential parameters. The use of a frame size of 4096 together with 75 averages proved to be useful average data acquisition parameters over all the selected materials. Care also has to be taken when estimating the PSDs in order to preserve the information and minimise "spectral leakage", Ifeachor & Jervis (1993). We do not report the full range of these basic, but nevertheless crucial, results here; suffice it to refer to M.Sc. theses by Saudland (1996), Svellestuen (1997) and Halstensen (1997).

All initial implementation/recording optimisation (see below) was based on traditional so-called experimental screening designs, while the subsequent application runs were for the most part based on the random design approach, Esbensen et al. (1994).

2.5 Optimising acoustic sensor position(s) – main experiment series

First results were based on a bottom-mounted accelerometer located near the pipeline inlet, at the first straight pipeline position (Fig. 3). Because most practically obtainable flow patterns have a positive vertical concentration gradient (top to bottom), and since homogeneity certainly increases along the pipeline, it was quickly discovered that it was also of great interest to try out different vertical as well as horizontal downstream sensor positions. Figure 7 shows the six principal sensor positions investigated in one of our main experimental series, in which four vertical and two horizontal principal positionings were tested out. It was decided early on to focus on the straight part of the pipeline to avoid roping and other additional unpredictable effects caused by the bend – and later follow-up experiments have indeed verified impressively that it is not possible to characterise the in-line transportation regimen immediately after the bend with any similar degree of precision as for our other acoustic results to be presented, or at least that it requires considerably more sophistication to even try this. Besides this, the straight pipeline results are fully adequate for the present feasibility study, because such straight pipe sections are – needless to say – an integral part of any pneumatic transportation system.

2.5.1 Data analysis

The regression model to be developed through the use of multivariate Partial Least Squares (PLS) calibration describes the relationship between the acoustic signals and – in this context – the measured flow characteristics, and is thus typically to be used in future real-time predictions of flow behaviour, Msolids. Multivariate calibration in general deals with the two matrixes X and Y containing the independent input variables and the dependent response or output vari-
The validity range of the Mfsolids model is determined abundantly by our preliminary studies: Saudland (1996), Svalestuen (1997), Martinussen (1996). Descriptions of the two most frequently used methods Principal Component Analysis (PCA) and Partial Least Squares Regression (PLS-R) will not be given here: Those interested are referred to Martens & Naes (1989), Wold et al. (1984), Geladi & Kowalski (1986) and Esbensen et al. (1994).

The two multivariate calibration matrixes in the present experimental context contain the FFT spectra in the X-block (PSD spectra), and Mfsolids as the Y-vector. We have investigated several other parameters of interest, but will not report these here, partly because there is often a moderate degree of correlation between most of these parameters, but mostly because we are only interested in showing the principal feasibility of the acoustic chemometric approach. The validity range of the Mfsolids model is determined by the range of the design variables in the X-block. It is, of course, imperative that the calibration data sets span the important process variations in a way representative for future industry use/operation, and this is ensured by POSTEC. Thus the present X-data contain the optimally recorded, relevantly signal-analysed (Fourier-transformed) acoustic spectra, characterising a broad set of operating conditions for industrial pneumatic powder transportation, while the Y-vector consists of the traditionally measured (integrated load weighting) solids flow rate, Mfsolids.

2.5.2 Results
The first result to be presented concerns deployment of one single accelerometer – in the very first straight pipeline position, only some 70 cm downstream of the powder inlet (this position corresponds to C1 in Fig. 7). We are currently collecting synoptic experience on all 7 principal powder types for the whole range of relevant operating conditions, in order – hopefully – to get some initial insights into the underlying systematics of acoustic X→Y relationships. For this inaugural acoustic chemometric application, a satisfactory first-order model can be achieved, explaining (82.75)% of the (Y, X) variance, and giving rise to the predicted vs. measured evaluation shown in Figure 9.

Clearly this model merits further sophistication; the slope of a fitted pred. vs. meas. regression line is only 0.79 and the correlation coefficient: \( r^2 = 0.82 \). This result required four PLS components, as validated by full cross-validation based on a total of 20 objects/runs. The choice of full cross-validation was guided by inspection of the pertinent t-u plots (Esbensen et al. 1994). This result constitutes only the very first (ever) acoustic prediction of intrinsic pneumatic transportation monitoring parameters, derived directly from simple, inexpensive, robust passive on-line sensors. As such it must be characterised as promising, although clearly not yet optimised by any means.

Second-generation refinements were carried out as a direct continuation, but now focusing on which combination of two accelerometers in vertical positions 1 and 2, respectively (Fig. 7) – in any permutation – did the best job of laying the foundation for on-line prediction of the solids mass flow rate. These comparisons were based upon identical predicted vs. measured multivariate calibration cross-validations in order to ensure that all influencing factors were incorporated.
Table 2 Comparative statistics for fitted regression models pertaining to alternative two-accelerometer configurations, cf. text.

| Sensor positions | Slope | Offset | Correlation ($r^2$) | RMSEP | PLS components |
|------------------|-------|--------|---------------------|-------|----------------|
| C1-C2            | 1.04  | -0.68  | 0.88                | 362.22| 2              |
| B1-C2            | 1.04  | 5.75   | 0.88                | 376.70| 2              |
| C1-B2            | 1.02  | 29.87  | 0.86                | 392.48| 2              |
| B1-B2            | 1.02  | 29.32  | 0.85                | 406.75| 1              |

This table demonstrates that it is possible to obtain much-improved prediction validations based on these second-generation refinements. For the best four two-sensor combinations (Table 2), slopes are very close to 1.00, for a fraction Y-variance explained spanning 85-88%. The combination B1-C2 was chosen, Svalsetuen (1977). From Figure 7 it will apparent that this corresponds to a side-mounted position "close" to the powder inlet, in combination with a bottom-mounted position well "downstream". There are many powder-science reasons why this particular combination is readily acceptable as a likely "best". But most especially because a bottom-mounted sensor in the C1 position is not generally desirable, as it is sure to be affected by "bottom-drag", i.e. self-damping.

We end this section by showing final results for PVC spherules, sand, cement & microdol.

These are very satisfactory results for a first attempt at developing a novel technique for on-line acoustic chemometric monitoring:

|        | Slope     | Corr. coef. ($r^2$) | RMSEP   | # PLS components |
|--------|-----------|---------------------|---------|-----------------|
| PVC    | 1.00      | 0.88                | 9.8     | 4               |
| Sand   | 1.04      | 0.90                | 8.5     | 4               |
| Cement | 0.92      | 0.85                | 11.2    | 2               |
| Microdol 100 | 0.92  | 0.85                | 8.6     | 3               |

*) RMSEP's calculated w.r.t. half the spanning X-range.

Fig. 10 Final predicted vs. measured evaluation plot for PVC - see text for details. Note how the fitted regression line is very close to origin.

Fig. 11 Final predicted vs. measured evaluation plot for sand. Note how the fitted regression line is very close to origin.
The final model evaluations for PVC and for sand were based on 25 new runs/objects; full cross-validation was again used. Cement and dolomite evaluation is based on the direct calibration cross-validation results. These results were also corroborated by other internal re-runs carried out as independent, part test-set confirmations, alas with slightly too few objects for a complete test-set validation yet – the prime objective being to investigate the feasibility of the technique being developed. Work continues on characterising all seven powder types used by Martinussen [1997] in his Ph.D research, including pertinent test-set validations, etc., and will be reported in due time.

3. Discussion

By any standards we call the above very promising first results. We envisage a fertile and flowering immediate future for this type of non-invasive (non-interfering) acoustic process/product monitoring. The very last point to be made here in fact concerns the distinction between a non-interfering and an actively interfering mode of acoustic chemometrics. All of the above has been concerned with acoustic chemometric listening in completely “as is” – there is absolutely no interference or modification necessary, nor any other active interaction with the object/process being characterised – by passive acoustic chemometrics.

5. References

General technical references:

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