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Procedia Manufacturing 11 (2017) 2252 – 2259

Procedia MANUFACTURING

27th International Conference on Flexible Automation and Intelligent Manufacturing, FAIM2017, 27-30 June 2017, Modena, Italy

# Particle Size Distribution Estimation Of A Mixture Of Regular And Irregular Sized Particles Using Acoustic Emissions

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**Abstract**

This works investigates the possibility of using Acoustic Emissions (AE) to estimate the Particle Size Distribution (PSD) of a mixture of particles that comprise of particles of different densities and geometry. The experiments carried out involved the mixture of a set of glass and polyethylene particles that ranged from 150-212 microns and 150-250microns respectively and an experimental rig that allowed the free fall of a continuous stream of particles on a target plate which the AE sensor was placed. By using a time domain based multiple threshold method, it was observed that the PSD of the particles in the mixture could be estimated.


Peer-review under responsibility of the scientific committee of the 27th International Conference on Flexible Automation and Intelligent Manufacturing

*Keywords:* Manufacturing Improvement, Process Optimisation, In-line Monitoring, Lean Production, Process Monitoring, Non-Contact Measurement, Acoustic Emissions, Particle Sizing, Particle Size Distribution

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## 1. Research Motivation and Introduction

Washing powder needs to fulfil certain standards before it can be sold, in the Procter and Gamble (P&G)

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Peer-review under responsibility of the scientific committee of the 27th International Conference on Flexible Automation and Intelligent Manufacturing
doi:10.1016/j.promfg.2017.07.373

production setting the necessary quality checks are carried out offline. These quality checks consist of a wet chemistry test to measure the chemical properties of the powders and also a physical inspection to obtain the particle size distribution (PSD). In addition to the quality check procedures being offline, internal reports from P&G has suggested that the wet chemistry test is "slow and expensive".[1,2] And in the case of the physical checks, it involves the use of a dry sieving process which is time consuming, limited to offline use and cannot measure large agglomerate.[1](due to sieve blockage) This has necessitated the development of real time process monitoring sensors to provide the online data needed for statistical validation of product quality and to provide the opportunity to apply a control loop approach to real time process control, which in term would help ensure the process assumes a lean and automated manufacturing flow which is not reliant on human accuracy. Acoustic Emissions (AE) was chosen as the sensing method for this research due to being non-invasive, low cost and possessing primary sensitivity to frequencies which particle events emanate.[2]

The aim of the research is to experimentally investigate the potential of using AE to monitor the Particle Size Distribution (PSD)of powder mixtures using a laboratory based powder free flow rig. This paper details the results of a set of laboratory based experiments carried out as part of this ongoing research. [2]

The term particle size is a feature attributed to particles with diameters that typically range from nanometers to millimetres.[1] The Particle Size Distribution(PSD) of a mixture of particles is seen as an important quality check factor in powder agglomeration, coal mills, pharmaceuticals and fluidization industries as this influences the bulk and flow properties of the particles.[2,3,5] This has thereby led to the development of various particle monitoring technologies which include but are not limited to the following; electrostatic sensing, imaging, sieving and weighing, Near Infrared Spectroscopy(NIR),Acoustic Emissions(AE),Focused Beam Reflectance Measurement(FBRM),microwave and vibration.[6-17]The work reported in this paper is based around the use of AE to estimate the PSD of a mixture of particles.

Pioneering work in particle sizing with AE began with Leach et al in 1977 with the use of a rotating drum and a condenser microphone.[18] The results reported by Leach showed that there is a linear relationship between particles of various sizes and their resulting AE amplitude.[ 18] The experiments carried out by Buttle et al helped to validate Leach's theory and provide a mathematical representation of the same phenomena.[19] To estimate particle size, Buttle used a quantitative particle sizing approach, this method was has been seen to be unfeasible to apply in industrial settings due to the nature of the deconvolution method and limitations in dealing with processes where particle impacts overlap each other.[ 2,20] Other particle sizing systems based on AE that can be used online in an industrial setting were designed by Bastari et al and Chen et al used a data driven approach based around trained neural networks to estimate particle sizes, as the system is based around a neural network a full understanding of the decision making process is not completely understood.[3,21] A more hybrid signal processing method was adopted by Hu et al and Ren et al, Hu et al utilised a time domain based amplitude threshold approach to help classify particle of different sizes but the method was seen to be in accurate in accurately classifying particles under 90microns.[ 5,20] Ren et al used a wavelet based algorithm to estimate the sizes of different particles but due to the nature and calibration of the signal processing method would not be adaptive enough to work in settings where powder mix ratio varies significantly.[22] From the literature, it would appear that there does not exist a hybrid signal processing method which is sensitive enough to be deployed in a process where the powder mix ratio varies significantly from batch to batch. Therefore in this research a hybrid signal processing PSD estimation method that can be used in powder processes and sensitive enough to detect significant PSD variations would be designed. This appears to be the knowledge gap from the literature and would form the body of knowledge being contributed to the literature by this research. The successful design and implementation of this PSD estimation system online would come with the merits of a low hardware complexity and possess a quicker computation time than its predecessors.

In this paper, a hybrid threshold based signal processing method used in a previous study and is capable of estimating PSD of different powder mixture variations will be used to estimate the PSD of a mixture comprising of two different type of particles with similar sizes. [ 2,20] This experimental study is important in the overall aim of the project as the washing powder compound comprises of a mixture of 10-12 different types of particles, some of which are similar in size but possess different physical properties, by applying a Design Of Experiment(DOE) sequence, this experiment in this paper has been setup using a set of experimental particles to investigate if the PSD of a mixture comprising of the two sets of particles of the same size but different physical properties and geometry can be estimated using the designed signal processing approach. [ 2,22]

## 2. Body

### *2.1 Particle Sizing With AE Theoretical Model*

When a particle of a known size hits a plate, stress waves are generated on the plate and the size of the particle is a key factor which influences the magnitude of the stress waves produced. [20] These resulting waves can be recorded by an AE sensor and are dependent on the dynamics of the particle impact, nature of stress wave propagation through the impingement medium, the sensors instrument response function in addition to the particle size. [22] This process has been modelled in form of the signal shaping chain and can be seen in Figure 1.

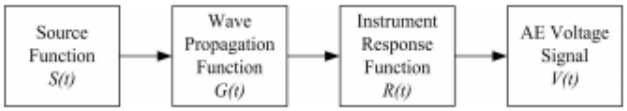


Figure 1: Signal Shaping Chain [20]

With a knowledge of the preceding three blocks in Figure 1 which produce the AE voltage the size of the impacting particle can be estimated using a quantitative particle sizing approach with the use of deconvolution techniques. [19,20] Although upon review of the work done by Buttle et al, it can be seen that such a technique would be impractical to work in an industrial where a large amount of process noise may exist and particle events overlap. [2,19,20,22] Despite this quantitative method of particle sizing not being feasible for implementation in an industrial environment, it helped to provide theoretical evidence that the resulting AE signal produced by a particle hitting a plate, carries information about the size of the impacting particle. [3]
For the reasons mentioned, authors have tried to develop various signal processing algorithms capable of working online to estimate the sizes of particles from the resulting AE measurement in an industrial environment. [2,3,5,20]

### *2.2 Experimental Details*

The experimental rig used for this study can be seen in Figure 2 and a picture of the sensor placement can be seen in Figure 3, it is the same powder flow rig as used in previous studies.[3,22] The rig is based around the flow of powder on a target plate dispensed at a known rate, and consists of a funnel of dimensions 11x18x8mm$^3$,aluminium target plate of 0.7mm thickness and a mistras manufactured PCI-2 Physical Acoustics AE sensor with a frequency bandwith of 100k-1MHz with a set sampling rate of 1Ms per second.[22, 23]

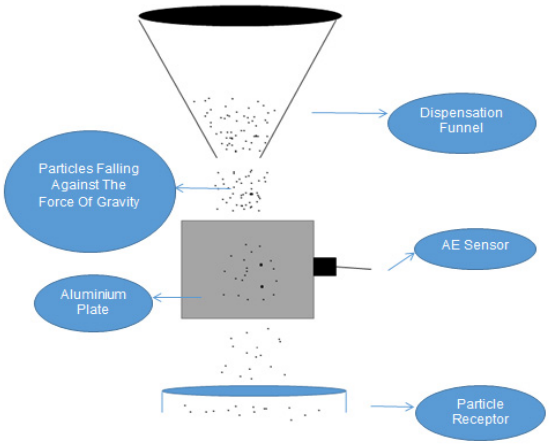


Figure 2: Experimental Setup[22]

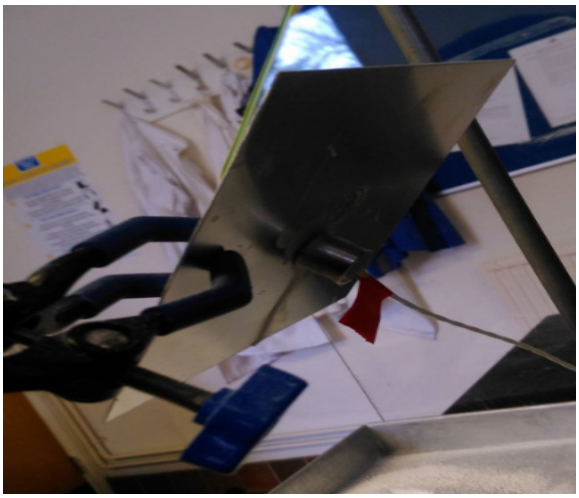

Figure 3: AE Sensor On The Back Of Experimental Target Plate

Aluminium was selected as the impingement medium due to possessing good wave propagation qualities and the AE sensor was attached to the back of the aluminium plate using a beeswax adhesive coupling.[2,22]

### *2.3 Experimental Particles*

The mixture being analysed in this paper, is based around a powder consisting of two different particles of similar sizes but different geometry and density. Glass beads where selected to represent the regular shaped particles with a high density while polyethylene(PE) was selected to represent the irregular shaped particles with a low density. Table 1 shows details of their respective physical properties.

Table 1: Particle Physical Property Table

| Particle Type | Size Distribution | Bulk Density in g/cm$^3$ | % Density Difference | Geometry |
|---|---|---|---|---|
| Glass Beads | 150-212microns | 1.490 | 76.9% | Regular |
| PE | 151-250microns | 0.344 | | Irregular |

### *2.4 Signal Processing*

The signal processing method used to analyse the data in this paper is based on a method previously developed in a previous study and was used for a different kind of powder mixture.[22] It is based around the implementation of an amplitude threshold in the time domain, to separate the signal into sections. Typically the signal is separated into a high amplitude section corresponding to the impact events from the big particles in the mixture and the low amplitude section which conversely would correspond to the smaller particles in the mixture. Within each separated amplitude section, the threshold is varied within each section with an amplitude mean extracted each time this is done. Figure 4 shows an example of how the threshold method would work for a two particle mixture, while equation 1 shows a mathematical representation.

$$M1=\frac{1}{N}\sum^{n}{}_{i=1}|x_1| \qquad (1)$$

$Th1<|x_1|>Th2=threshold\ 1/2$

Where x/x1=AE voltage amplitudes

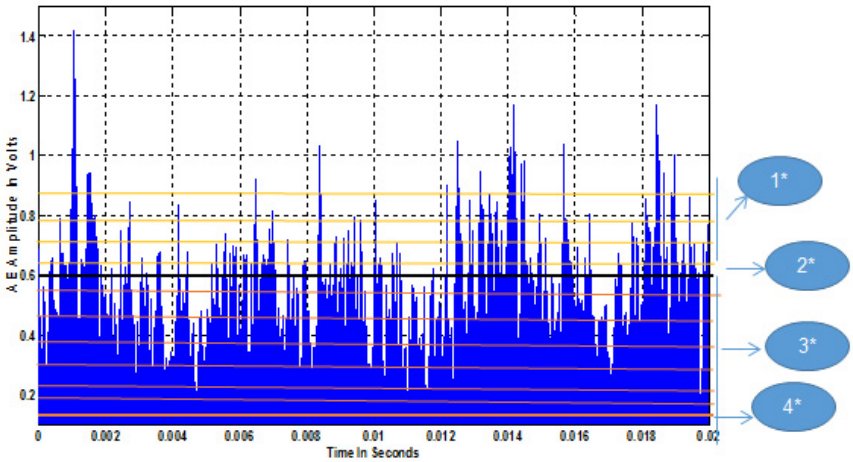


Figure 4: Graph Of Sample Absolute AE Signal Illustrating Different Thresholds

Where:
1*- only peaks above the selected threshold in this region are considered in this region
2*- a threshold which separates the high impact peaks of the big particles from the small impact peaks
3*- only peaks below the selected threshold up to 4* are considered in this region
4*-a threshold above the sensor and background noise amplitude

The thin lines in each section in Figure 4 show an example of the variation of the threshold amplitude value within each signal region. Each time a threshold is varied, an amplitude mean is extracted, and this mean value is then correlated with the mix ratio of the powder and done continuously for each possible mix ratios which need to be investigated. The best correlation plot is then chosen as the particle size estimation model. Note in this case, just one correlation plot can be used to estimate the sizes of the different particle distributions in the mixture as this is a two particle mixture.

Below is a list of the various steps involved in implementing this threshold method;

- Take the absolute of the signal to eliminate negative values
- Set a threshold above the background/sensor noise and a further threshold to separate the amplitude of the bigger particles from the smaller particles.
- Calculate the amplitude mean of the AE for each signal section and correlate each mean value the associated powder mix ratio.
- Vary each threshold (computing the AE mean and correlating this value with a mix ratio each time the threshold is varied) until the optimal threshold location is found. The best location for the threshold is determined by observing the resulting correlation plot and its respective $R^2$ value. The threshold which produces a correlation plot with the best $R^2$ is chosen as the best threshold.

*2.4 Experiment Method and Results*

For each particle mix ratio the AE was acquired on five separate repetitions by dispensing the same mass of powder through the funnel each time.
The data was analysed using the designed signal processing method and for every amplitude threshold considered the AE amplitude mean was extracted from each mix ratio repetition and then averaged out to give a representative value from each threshold before being correlated with respective mix ratio. While the resulting correlation plot

used as the particle size distribution estimation model.
For the particle mixture being considered in this paper, the resulting correlation plot of the optimal threshold yielded a curve which a sigmoid was fitted to, this sigmoid plot can be seen in figure 5.

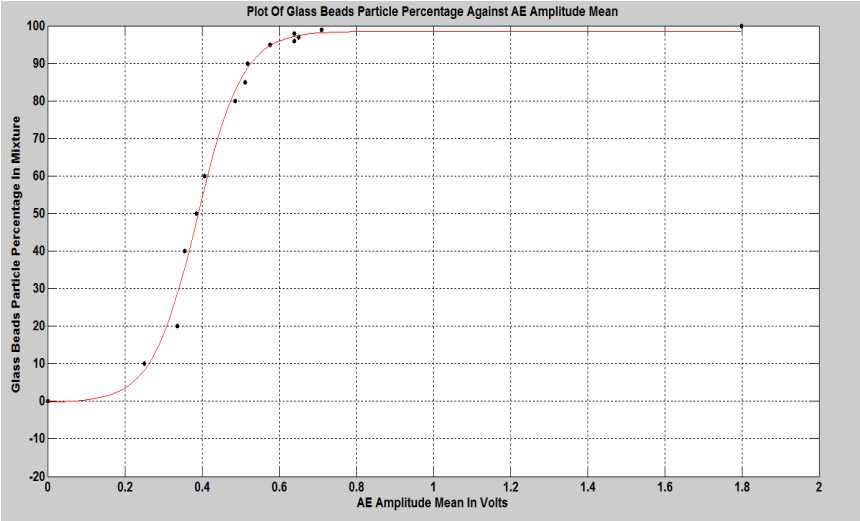


Figure 5: Plot Of Glass Beads Particle Percentage Against AE Amplitude Mean

To evaluate the accuracy of the sigmoid model, a set of separate mixtures were created using the same set of particles that were used to yield the sigmoid.
For the validation exercise, the signal acquired from each set of validation experiment was analysed using the same amplitude threshold parameters that were used to produce the sigmoid. The AE amplitude mean was extracted in each case and this value was then correlated with its particle size using the sigmoid model.
The sigmoid was able to estimate particle sizes with a 2.4% average absolute error and the plot in Figure 6 shows a comparison of the actual particle percentage against the amount estimated by the sigmoid.

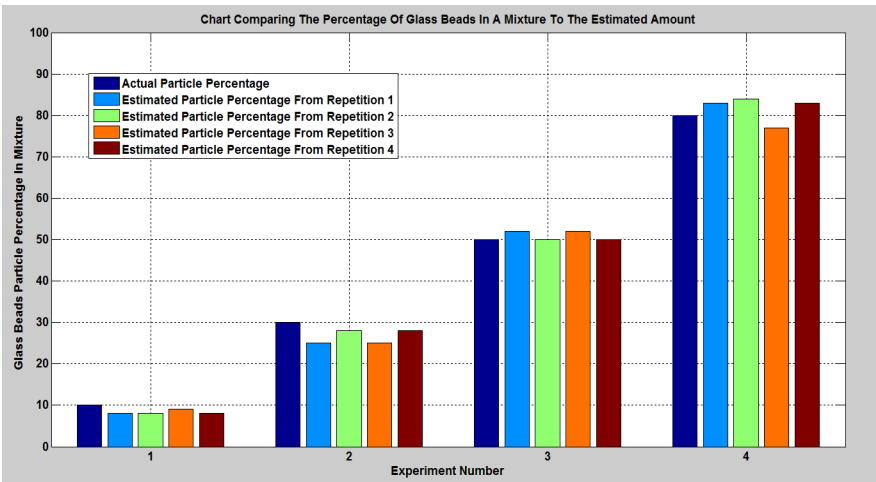


Figure 6: Chart Comparing The Percentage Of Glass Beads In A Mixture To The Estimated Amount

Comparing the results obtained here to the results obtained from a mixture comprising of two sets of glass beads in a previous study, it can be noted that mixture of the glass beads produced a higher average relative error (10%) than the mixture of PE and glass beads being considered in this study. [22] It is assumed that this is the case for two

reasons; the first is the large bulk density difference of 76.9% between the two particle types which would ensure that their AE signals are distinctively different from each other and easily separable despite being in a mixture. And the second point being the physical nature of each particle type in the mixture, the glass beads are more crystalline and harder in nature whereas the PE particles are less crystalline and not as hard as the glass beads, these factors are also believed to contribute to the good level of separation which has been achieved for their AE signal and has led to a low average estimation error.

## 3. Conclusion

This paper has details the results of a study that involved the use of AE to estimate the particle size distribution in a mixture which consists of an irregular and regular sized particles using a threshold based signal processing approach. The results obtained from the mixture being investigated produced an average relative error of 2.4% which suggests that for the experimental setting being considered in this paper, the signal processing approach is capable of estimating the particle sizes in mixtures of this kind. It is currently believed that the reason a low average relative error value was obtained is due to the bulk density difference between the particles and the distinct material properties of each particle type in the mixture which could lead to the respective AE amplitude of the particles being considered to be clearly distinguishable despite being the same size. Based on the results observed, subsequent work in this research would involve the use of this threshold signal processing method to analyse a mixture that contains the same amount of particle groups as the washing powder compound using experimental particles.

## Acknowledgements

The authors gratefully acknowledge the support of partners Procter & Gamble, IIT, Ajax, Centre for Process Innovation, the University of Birmingham, the University of Leeds, and the University of Durham. This research is part of Chariot and The Advance Manufacturing Supply Chain Initiative (AMSCII) which is a government supply chain fund which is helping to rebuild British manufacturing prowess.

## References

[1] Particle Size Tutorial, Overview Of Methods. Dispersion.com.17 Feb. 2017.

[2] Nsugbe, E, Starr, A, Foote, P, Ruiz-Carcel, C and Jennions, I. Size Differentiation Of A Continuous Stream Of Particles Using Acoustic Emissions IOP Conf. Series: Materials Science and Engineering 161 (2016)

[3] Bastari, A., Cristalli, C., Morlacchi, R.,: Acoustic emissions for particle sizing of powders through signal processing techniques, Mech. Syst. Signal Process., 2011, 25, (3), pp. 901–916

[4]Papp MK, Pujara CP, Pinal R. Monitoring of high-shear granulation using acoustic emission: predicting granule properties. J Pharm Innov. 2008;3:113–122

[5] Ren, C.J., Wang, J.D., Song, D., et al.: Determination of particle size distribution by multi-scale analysis of acoustic emission signals in gas-solid fluidized bed, J. Zhejiang Univ., Sci A, 2011, 12, (4), pp. 260–267

[6] Zhang, J.Q, Yan, Y On-line continuous measurement of particle size using electrostatic sensors Powder Technology, 135–136 (1) (2003), pp. 164–168

[7] Xu, R., Particle Size And Shape Analysis Using Laser Scattering And Image Analysis Using Laser Scattering And Image Analysis Revista Latinoamericana de Metalurgia y Materiales, Vol. 20, N°2, 2000, 80-84

[8] S. Watano, T. Numa, I. Koizumi, Y. Osako Feedback control in high shear granulation of pharmaceutical powders Eur. J. Pharm. Biopharm., 52 (2001), pp. 337–345

[9] O'Neil, A. J., Jee, R. D., & Moffat, A. Measurement of the percentage volume particle size distribution of powdered microcrystalline cellulose using reflectance near-infrared spectroscopy. *Analyst*, 2003, 128, 1326–1330

[10] Otsuka M, Comparative particle size determination of phenacetin bulk powder by using Kubelka–Munk theory and principal component regression analysis based on near-infrared spectroscopy. Powder Technology 141 (2004) 244 – 250

[11] Huang, J., Kaul, G., Utz, J., Hernandez, P., Wong, V., Bradley, D., Nagi, A., O'Grady, D., 2010. A PAT approach to improve process understanding of high shear wet granulation through in-line particle measurement using FBRM C35. J. Pharm. Sci. 99, 3205–3212.

[12] Papp MK, Pujara CP, Pinal R. Monitoring of high-shear granulation using acoustic emission: predicting granule properties. J Pharm Innov. 2008;3:113–122

[13] Kumar, V., Taylor, M.K., Mehrotra, A. and Stagner, W.C. Real-time particle size analysis using focused beam reflectance measurement as a process analytical technology tool for a continuous granulation-drying-milling process AAPS Pharm. Sci. Technol, 14 (2013), pp. 523–530

[14] Yu, Z. Q.; Chow, P. S.; Tan, R. B. H. Interpretation of focused beam reflectance measurement (FBRM) data via simulated crystallization. Org. Process Res. DeV. 2008, 12, 646–654

[15] Greaves, D.; Boxall, J.; Mulligan, J.; Montesi, A.; Creek, J.; Sloan, E. D.; Koh, C. A. Measuring the particle size of a known distribution

using the focused beam reflectance measurement technique. Chem. Eng. Sci. 2008, 63 (22), 5410–5419.

[16] Roßteuscher-Carl. K., Fricke. S., Hacker M.C., Schulz-Siegmund M., In-line monitoring of particle size in a fluid bed granulator: investigations concerning positioning and configuration of the sensor, Int. J. Pharm. 466 (2014) 31–37.

[17] Hancke GP, Malan R. A modal analysis technique for the on-line particle size measurement of pneumatically conveyed pulverized coal. IEEE Trans Instrum Meas 1998;47(1):118.

[18] Leach. M.F., Rubin G.A., Williams J.C., Particle size determination from acoustic emissions, Powder Technology 16 (1977)153–158.

[19] Buttle. D.J., Martin. S.R., Scruby C.B., Particle sizing by quantitative acoustic emission, Research in Nondestructive Evaluation 3 (1991) 1–26.

[20] Hu, Y., Huang, X., Qian, X., et al.: Online particle size measurement through acoustic emission detection and signal analysis. Proc. IEEE Int. Instrumentation Measurement Technology Conf., May 2014, pp. 949–953

[21] Chen. X.M., Chen D.Z, 2008. Measuring average particle size for fluidized bed reactors by employing acoustic emission signals and neural networks. Chem. Eng. Technol. 31, 95–102

[22] Nsugbe E, Starr A, Jennions I and Ruiz-Carcel C Online Particle Size Distribution Estimation Of A Particle Mixture In Free Fall With Acoustic Emission 2017(being reviewed by the Journal Of Meas. Sci. and Instrumentation)

[23] PCI-2 Based AE System User's Manual

# Particle size distribution estimation of a mixture of regular and irregular sized particles using acoustic emissions

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2017-09-18

Nsugbe E, Starr A, Jennions I, Ruiz Carcel C, Particle size distribution estimation of a mixture of regular and irregular sized particles using acoustic emissions, Procedia Manufacturing, Vol. 11, 2017, pp. 2252-2259

http://dx.doi.org/10.1016/j.promfg.2017.07.373