Research on Dust Concentration Measurement Technique Based on the Theory of Ultrasonic Attenuation

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Abstract. In this paper, a method of characteristics dust concentration is proposed, which based on ultrasonic changes of MEMS piezoelectric ultrasonic transducer. The principle is that the intensity of the ultrasonic will produce attenuation with the propagation medium and propagation distance, the attenuation coefficient is affect by dust concentration. By detecting the changes of ultra acoustic in the dust, the concentration of the dust is calculate by the attenuation-concentration model, and the EACH theory model is based on this principle. The experimental results show that the MEMS piezoelectric ultrasonic transducer can be use for dust concentration of 100-900 g/m³ detection, the deviation between theory and experiments is smaller than 10.4%.

1. Introduction

In order to comprehensively and accurately detect the dust concentration information in the enclosed area, it is better to grasp the dust concentration situation, prevent the damage of excessive concentration to the operator's body, and the influence on the operation equipment and to forecasting and solve the high concentration of dust. To ensure personal safety and improve the quality of the environment play an important role [1].

At present, a variety of method for measuring dust concentration are studied at home and abroad, such as filter weighing method [2], ray method [3], piezoelectric crystal induction method, optical method [4], capacitance method [5], Charge sensing method [6] and ultrasonic method [7]. The weigh method is the most basic measurement method, but it cannot be use for continuous monitoring of dust concentration. Although the measurement of ray method is accurate, but it needs to compare with the dust sampling measurement, it is difficult to achieve on-line monitoring. For the use of low dust concentration on the ground occasions, it requires that the operator has an experience, on its use [8]. Microwave measurement of dust is in the experimental stage, optical method vulnerable to the impact of measurements [9], and the measurement is easy to make the optical system pollution, the need for frequent calibration, large maintenance; capacitance measurement of dust is safe and reliable, fast responding, etc., but its sensitivity is limited [10].

In recent years, the Los National Laboratory and the Chinese University of Shanghai Su Ming Xu team [11,12] by detected the complex wave acoustic which can be synchronized to obtain the acoustic velocity changes and acoustic attenuation phenomenon. Two kinds of acoustic characteristics were tested and analyzed; you can get more mixture of the data characteristics, to achieve the concentration and particle size distribution at the same time detection. Based on the principle of acoustic attenuation, this paper puts forward to the idea of using MEMS piezoelectric ultrasonic transducer to characterize
the measurement of dust concentration, then designed the dust concentration detection device, its structure is simple, the expense is low and the practicability is strong.

2. Ultrasonic method of principle

2.1. Theoretical model of ultrasonic concentration detection

The use of acoustic attenuation for concentration detection is mainly based on the acoustic waves in the media attenuation. The intensity of the acoustic wave decreases with the propagation distance increasing, it is called the attenuation of the acoustic. Modern acoustics think that absorption attenuation and scattering attenuation are the acoustic energy conversion and dissipation in the propagation medium, the attenuation factor contains the characteristic information of the propagation medium. Therefore, the dust concentration can be calculated by measuring the attenuation coefficient inversion. The principle of this method is shown in figure 1:

![Figure 1. Concentration detection system based on acoustic attenuation](image)

Research manuscripts reported large datasets that are deposited in a publicly available database where the data have been deposited and provided the relevant accession numbers. If the accession numbers have not been obtained at the time of submission, it will provide during review. They must be provide prior to publication.

The numerical relationship between the acoustic attenuation and the concentration of the mixture is the core technology of the acoustic attenuation method. The ECAH model is a classical model, and the mathematical expression of the model is given without derivation.

\[
\left( \frac{k}{k_s} \right)^2 = 1 + \frac{3\varphi}{jk_sR} \sum_{n=0}^{\infty} (2n+1) A_n
\]

among them:

\[
k = \frac{\omega}{C_s(\omega)} + j\alpha_s(\omega)
\]

\( k \) is the complex wave number in the mixed medium, \( k_s \) is the wave number in the continuum, \( \varphi \) represents the volume concentration of the suspended particles, \( R \) is the radius of the particles, \( \omega \) is the ultrasonic angular frequency, \( C_s \) and \( \alpha_s \) are the acoustic velocity and the attenuation coefficient of the ultrasonic medium in the mixed medium, respectively.

The model has many computational parameters, such as high calculation parameters and high computational complexity, and it is not suitable for real-time calculation. Therefore, it is necessary to establish a simpler solution model. According to the test acoustic wavelength is much larger than the dust particle size, dust particle density is much larger than the air density of the two practical
characteristics, ECAH model can be reduced step by step to reduce the difficulty of calculation, reduce the calculation of the task, equation (1) can be reduce to:

$$\left(\frac{k_1}{k_2}\right)^2 = 1 + \frac{9\phi}{jk_1^3R^3}A_k.$$  

among them: $A_k \approx i\left(k_cR\right)^3\left(1+T+is\right)$, substituting equation (3) can obtain:

$$\left(\frac{k_1}{k_2}\right)^2 = 1 + 9\phi\left(1+T+is\right)$$  

among them: $\delta_s = \sqrt{\frac{2\eta_s}{\rho_s\omega}}$, $T = \frac{1}{2} + \frac{9\delta_s^2}{4R}$, $S = \frac{9\delta_s}{4R}\left(1 + \frac{\delta_s}{R}\right)$

The EACH model under long wavelength and large density ratio is simplified, and the calculation parameters are reduced to seven. Compared with the EACH model, the computational complexity is reduced by 29%. The MATLAB is used to calculate the time consuming comparison test under the same conditions, using a simplified algorithm can reduce the calculation time by 24%.

2.2. MEMS piezoelectric ultrasonic transducer

The numerical relationship between the acoustic attenuation and the concentration of the mixture is the core technology of the acoustic attenuation method. The ECAH model is a classical model, and the mathematical expression of the model is given without derivation.

Acoustic field method for concentration detection, the characteristics of ultrasonic transducers on the test results have a decisive role. In this paper, the transducer is optimized from the aspects of piezoelectric material, center frequency, direction angle, ultrasonic radiation surface and acoustic matching layer. The structure as shown in figure 2.

![Figure 2. MEMS piezoelectric ultrasonic transducer structure](image)

Acoustic waves in the process of propagation due to the increasing area of acoustic waves caused by the unit to receive area on the energy reduction, the attenuation of acoustic waves is mainly reflected in absorption attenuation and scattering attenuation, the acoustic intensity is inversely proportional to the propagation distance, that satisfies:

$$P = \frac{P_0}{x^2}$$  

the attenuation intensity is used to characterize the intensity of acoustic waves with the propagation medium and attenuation characteristics. Experimental study has shown that both absorption attenuation and scattering attenuation follow the exponential form and can be express as:

Absorption attenuation: $P = P_0e^{-\alpha_{att}x}$  

Scattering attenuation: $P = P_0e^{-\alpha_{sca}x}$
the two forms of attenuation are consistent, and the attenuation coefficients are related to the dielectric properties. Therefore, the two declines are call "medium-dependent attenuation", the corresponding definition expression is:

\[ P = P_0 e^{-(\alpha_m + \alpha_v)x} = p_0 e^{-\alpha x} \]  

in the equation (8): \( P_0 \) is acoustic intensity of the acoustic source, \( P \) is observation acoustic intensity, \( x \) is observation distance, \( \alpha \) is correlation coefficient of the medium. The correlation coefficient of the medium is relate to the change of the acoustic intensity and the observation distance, which is a constant. In the case of observation distance and medium certain circumstances, from the equation 1.8 can obtain: dust concentration and the sensor acoustic intensity is into an exponential relationship, acoustic intensity changes can be converted into voltage signals through the signal processing circuit, and then sent to the computer, dust concentration can be calculated from the voltage measurement.

3. Measuring device design

This section may be divide by subheadings. It should provide a concising and precise description of the experimental results, their interpretation as well as the experimental conclusions is can be draw. Authors should discuss the results and how they can be interpret in perspective of previous studies and of the working hypotheses. The findings and their implications should be discuss in the broadest context possible. Future research directions may be highlight.

In order to improve the accuracy of the measurement, the change of the sensor induce voltage which is as large as possible under the change of the dust concentration. The parameters of the sensor are set as follows: Center frequency, Test interval, Pitch and outer radius. For the test, as shown in figure 3. The working principle of the test device is applied 3.3v drive signal to the sensor, through the continuous jet to form a high concentration of clouds, changing the size of the dust to adjust the size of the dust concentration, the concentration of dust in the MEMS piezoelectric ultrasonic transducer can be changed. For each dust concentration, the nozzle of the high-pressure gas is close when the display value of the measuring device is stabilize, and the measure value of the dust is record by the data processing software.

**Figure 3. Micro dynamic cloud simulation device**

The voltage measurement device uses STM32T8U6 microcontroller as signal processing and control core, and the principle diagram as shown in figure 4. After the MEMS piezoelectric ultrasonic transducer transforms the acoustic intensity signal into the voltage signal, the signal processing unit amplifies and filters the voltage signal, the filtered signal is sent to the single chip microcomputer for A/D conversion and calculation processing, and then by the display device output dust concentration measurement.
4. Experiment method and result analysis

4.1. Experiment method
The experiment uses iron powder to simulate dust, talc powder is the main component of $Fe_2O_3$, it is reddish brown, fine micron grade powder, as shown in figure 5. The experiment uses a small cloud concentration simulation device to generate dynamic clouds. The maximum average concentration of single injection is 900g/m$^3$, which can form high concentration cloud by continuous injection. By changing the mass of the dust to adjust the concentration, you can change the density of the MEMS piezoelectric ultrasonic transducer. For each dust concentration, the nozzle of the high-pressure gas is close when the display value of the measuring device is stabilize, and the measured value of the dust is recorded using the data processing software.

4.2. Experiment results
Ultrasonic transducer is used to test, adjusting the weight of dust, through the dust concentration, the actual value and the measured value of the curve shown in figure 6: Dust concentration between changes, the two curves are consistent, with consistency. Table 1 for the specific experiment data, the maximum measurement error is 10.4%, the minimum is 2.56%, the average error of 7.14%.
Figure 6. Experimental results

Table 1: Dust concentration test data.

| Dust concentration (g/m³) | 900 | 850 | 800 | 750 | 700 | 650 | 600 | 550 | 500 |
|--------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Measurement (g/m³)       | 817 | 789 | 752 | 737 | 641 | 614 | 578 | 531 | 459 |
| Average (g/m³)           | 809 | 781 | 761 | 741 | 661 | 631 | 567 | 513 | 462 |
| Measurement error (%)    | 794 | 764 | 770 | 726 | 668 | 629 | 572 | 528 | 468 |
| Average (g/m³)           | 821 | 775 | 735 | 722 | 677 | 613 | 569 | 522 | 475 |
| Measurement error (%)    | 813.47 | 8755.47 | 30.866 | 4 | 2 | 13 | 4.6 | 2.56 | 4.2 | 5.17 | 4.62 | 6.6 |

MEMS piezoelectric ultrasonic transducer is used to test, adjusting the weight of dust, through the experimental device to detect the corresponding dust concentration, the actual value and the measured value of the curve are shown in figure 6: Dust concentration between changes, the two curves are consistent. Table 1 for the specific experiment data, the maximum measurement error is 10.4%, the minimum is 2.56%, the average error is 7.14%.

According to the experimental results can be conclude as follows:
1. When the dust concentration varies from 100 to 900g/m³, the measured value of dust concentration is close to the actual value, the average deviation is 7.14%, and linearity is good and can be used for dust concentration detection.
2. When the dust concentration is greater than 750g/m³, the measured curve tends to be gentle, because the dust concentration is high, due to electrostatic adsorption, pressure pump pressure...
and other restriction, will be precipitate in the experiment device. Therefore, the ultrasonic change no longer obvious, and the measurement device shows that the value change is no obvious.

3. Dust measurement range and the actual engineering application has a certain gap, this has a greater relationship with the test platform itself, because the dust flow rate through the pipeline is not accurate, resulting in increasing bias.

5. Conclusion
The basic principle of ultrasonic measurement of dust concentration is study, and designed MEMS piezoelectric ultrasonic transducer, dust concentration experiment is carry out using a test platform. The measuring results show that when the dust concentration is between 100-900 g/m$^3$, the deviation between theory and experiments is smaller than 10.4%. The results show the consistency of theoretical analysis and experiment test. It can meet the accurate detection of dust concentration by the small cloud concentration detection system. The detection system can be use for industrial dust concentration detection, industrial dust early warning, and other high concentration of workplaces dust concentration detection, and so on.

References
[1] Ziliang Wang, Development and Application of Dust Concentration Sensor [J]. Industrial Safety and Environmental Protection, 2006, 32 (4): 24-27.
[2] Aiqing Guo, Status and thinking of dust monitoring technology in China [J]. Chinese Journal of Safety Science and Technology, 2001, 21 (5): 35-38.
[3] Zonglun Li, etc. Application of β-ray Dust Measuring Instrument in Coal Mine Dust Concentration Monitoring [J]. China Mining Industry, 2010, 36 (3): 107-109.
[4] Litchford R J, Sun F, Few J D, et al. Optical measurement of gas turbine engine soot particle effluents [J]. Journal of Engineering for Gas Turbines & Power, 1998, 120(1):69-76.
[5] Geng Lu, Method for detecting two-phase flow phase concentration based on capacitance measurement and PCA method [J]. Journal of China Jiliang University, 2003, 14 (1): 15-18.
[6] Sibiao Zhao, etc. Study on Dust Concentration Measurement Based on External Charge Principle [J]. Instrument Technique and Sensor, 2010 (6): 15-16.
[7] Ni W, Ultrasonic attenuation model for measuring particle size and inverse calculation of particle size distribution in mineral slurries [J]. Journal of Central South University (English Edition), 2006, 13 (4): 445-450.
[8] Weidong Li, etc. China’s coal industry dust concentration monitoring technology status and development trends [J]. Mining Safety and Environmental Protection, 2005, 32 (s1): 66-67.
[9] Kerker M. The Light Scattering of Light and Other Electromagnetic Radiation [J]. 1969.
[10] Chun M H, Sung C K. Parametric effects on the void fraction measurement by capacitance transducers [J]. International Journal of Multiphase Flow, 1986, 12(4):627-640.
[11] Mingxu Su, etc. Measurement of Particle Size by Ultrasonic Attenuation [J]. Journal of Instrumentation, 2004, 25 (s1): 1-2.
[12] Mingxu Su, etc. Determination of Particle Size and Concentration in Suspension by Ultrasonic Attenuation [J]. Acta acoustica Sinica, 2004 (5): 440-444.