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Application of Digital Signal Analysis Technique to Enhance the Quality of Tracer Gas Measurements in IAQ Model Tests

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Abstract

The introduction of tracer gas techniques to ventilation studies in indoor environments provides valuable information that used to be unattainable from conventional testing environments. Data acquisition systems (DASs) containing analogue-to-digital (A/D) converters are usually used to function the key role that records signals to storage in digital format. In the testing process, there exist a number of components in the measuring equipment which may produce system-based inference to the monitored results. These unwanted fluctuations may cause significant error in data analysis, especially when non-linear algorithms are involved.

In this study, a pre-processor is developed and applied to separate the unwanted fluctuations (noise or interference) in raw measurements and to reduce the uncertainty in the measurement. Moving average, notch filter, FIR (Finite Impulse Response) filters, and IIR (Infinite Impulse Response) filters are designed and applied to collect the desired information from the raw measurements. Tracer gas concentrations are monitored during leakage and ventilation tests in the model test room. The signal analysis functions are introduced to carry out the digital signal processing (DSP) work.

Overall the FIR filters process the CO_2 measurement properly for ventilation rate and mean age of air calculations. It is found that, the *Kaiser* filter was the most applicable digital filter for pre-processing the tracer gas measurements. Although the IIR filters help to reduce the random noise in the data, they cause considerable changes to the filtered data, which is not desirable.

Key words : Tracer gas measurement, Digital signal processing, Correlation analysis, Signal noise, Air leakage

1. INTRODUCTION

In ventilation study, tracer gas techniques are very useful to quantify the physical phenomena occurring in indoor environments. The application of data acquisition system (DAS), equipped with pc-based analog-to-digital (A/D) converters releases the difficulty in recording tracer gas concentrations, which provides further detailed information carried in the measured signal, in real-time domain (Hong *et al.*, 2007; Jayaraman, 2006; Chow, 2002; Sohn and Small, 1999; Kim *et al.*, 1993).

Although test facilities including testing and mea-

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suring device produces much information, the actual measured data contain a wide range of unwanted components in terms of system-based noise or interference from the tracer gas analyzer, the computer, and other components used in test procedures (Fischer *et al.*, 2001; Drescher *et al.*, 1997; Sherman, 1989a, b). This system noise appears normally as the fluctuations in the tracer gas measurements and could be propagated in the data analysis, especially in computation involving non-linear algorithms such as logarithmic or exponential functions, etc.

Lee (1993) applied the moving average technique for the pre-treatment of the raw measurement which provided useful information from the measurements. However, Phillips and Bragg (1994) pointed out that an averaging technique leads to a loss of useful information from the measurement. O'Neill and Crawford (1991) showed that a proper sampling interval, based on the time constant, is also important.

In this study, several data pre-processing techniques have been tested to separate the components of potential errors from the tracer gas measurements and to improve the quality of ventilation analysis as the final goal. The moving average technique by Lee (1993) and a simple digital filtering technique by Lee and Awbi (1998) have been studied and reported. A few more advanced digital filtering techniques are also introduced in this study. Finally, a tool to pre-process tracer gas measurement for further analysis is also presented.

2. DIGITAL SIGNAL PROCESSING

A *signal* is defined as any physical quantity that varies with time, space, or any other independent variables. Mathematically, it is described as a function of one or more independent variables, as in equation (1). In this study a signal $x(t)$ (real-valued or scalar-valued) is a function of the time variable t. The 'real-valued' indicates any fixed value at the time variable t where the value of the signal at time t is a real number.

$$x[n]=x(t)|_{t=nT}=x(nT) \tag{1}$$

where n is an integer number, t is a real number, T is a sampling time which is usually the reciprocal of sampling rate in hertz (*Hz*). By *sampling* (digitizing or windowing) process, an analogue signal $x(t)$ is taken at discrete-time instants. A *digital signal* $x[t]$ is in turn generated and used for the digital signal processing. Analogue-to-digital (A/D) converters conduct this sampling process with the assistance of computers.

A signal, in general, holds a characteristic called *duality* between the *time domain* and the *frequency domain*, which makes it possible to perform any operation in either domain. Usually one domain or the other is more convenient for a specific operation. Based on this characteristic, *Fast-Fourier Transformation* (FFT), which is one of useful mathematical tools in signal processing, decomposes a signal in time domain into a sum of sinusoidal components in frequency domain (Ramirez, 1985). *Inverse*-FFT (IFFT) also works for the reverse function from frequency domain to time domain, see Lee and Awbi (1998) for practical application of this.

Signal generation is usually associated with a *system* that corresponds to a stimulus or force. A system may also be defined as a physical device that performs an operation on a signal. For example, a *filter* used to reduce the noise and interference corrupting a desired information-bearing signal is also called a *system*. In this case the filter performs some operation (s) on the signal, which has the effect of reducing (filtering) noise and interference from desired information-bearing signal. When a signal is passed through a system, as in filtering, the output will be a processed signal. The processing of the signal involves filtering the noise and interference from the desired signal, which is referred to as *signal processing* (Kamen and Heck, 1997).

The major purpose of signal filtering is to extract or block unwanted components from a waveform. The mathematical foundation of filtering is *convolution*. A digital filter's output $y(n)$ is related to its input $x(n)$ by convolution of its impulse response $h(n)$:

$$y(n)=x(n)*h(n)\equiv\sum_{k=-\infty}^{\infty}x(k)h(n-k) \tag{2}$$

where, k=number of spectral data points in frequency-domain, x=original vector in time-domain, n=length of input vector.

In the case of preparing waveforms for de-convolution or dressing up the results of de-convolution, the unwanted components in indoor environment are generally those of high-frequency noises generated by electric devices. To reduce this noise contribution, a low-pass filter is used in this study. There are a variety of filter functions that can be used, such as elliptical, Chebyshev, Butterworth, and so forth. A more sophisticated window function called *Kaiser window* is generally used for the design of practical filters since it allows the designer the flexibility to trade off the sharpness of the pass-to-stop band transitions with the magnitude of the ripples (Castleman, 1996).

In signal processing, *correlation analysis*, which measures the correlation between observations at different distances apart, can be used to approve the results. Suppose that there exist two real signals $x(n)$ and $y(n)$ each of which has finite energy, the cross-correlation of $x(n)$ and $y(n)$ is a sequence r_{xy}, which is defined mathematically as follows:

$$r_{xy}(l)=\sum_{n=-\infty}^{\infty} x(n)y(n-l) \tag{3}$$

where the index l is the time shift (or lag) parameter, 0, ± 1, $\pm 2 \cdots$, and the subscripts xy on the cross-correlation sequence $r_{xy}(l)$ indicates the sequences being correlated. Two signals correlated here could be input and output signals after the filtering process. The autocorrelation can be also achieved by correlating the same signal, xx or yy. The autocorrelation $r_{hh}(l)$ of the impulse response $h(n)$ exists if the system is stable. Furthermore, the stability insures the system does not change the type (energy or power) of the input signal (Chatfield, 1996).

3. TRACER GAS MEASUREMENTS IN VENTILATION TESTS

To obtain tracer gas measurements in time domain, model tests were carried out. Fig. 1 shows the schematic of the test setup used. The model room, 1.6^m

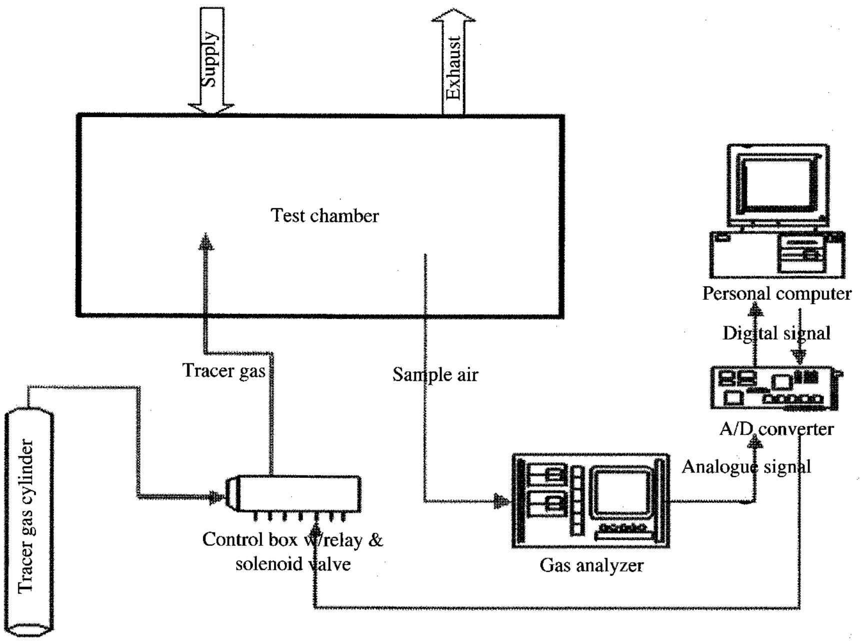

Fig. 1. Schematic diagram of test setup for ventilation tests in this study.

(W) $\times 0.8^m$ (D) $\times 0.7^m$ (H) (volume 0.896 m^3), has two ceiling-mounted openings to supply and exhaust ventilation air and an axial fan with speed controller was the ventilation source. Carbon dioxide (CO_2) was used as the tracer gas and measured by a gas analyser (Model SB-421, ADC) which generates signals, $0 \sim 1$ *DC volts*, corresponding to the measured concentrations. The computer controlled the tracer gas generation through the A/D converter and the control box. Two mixing fans were used in the model for the leakage tests. The test procedure was coded and run using Matlab codes developed by the author, ver. 5.2.0.3084 (Mathworks, 1998). The Matlab language was also used for subsequent signal analysis work.

The analogue signal from the tracer gas analyzer was continuously digitized by the DAS at a preset sampling rate 1 *Hz*. Different sampling rates were tested by Lee and Awbi (1998) and concluded that 1 *Hz* is fast enough to capture the variation in tracer gas concentrations occurring in room ventilation, although the sampling rate may go down further if necessary without influencing the final accuracy.

To improve the quality of the measured data, several pre-processing techniques were applied to the data analysis. The moving average was the first filter technique used with several averaging periods. The 30-points average produced the best result and was used as the basis for comparison with other filters. This technique was used for ventilation analysis by Lee (1993). It was, however, found that the technique causes the significant loss of desired information from the measured signals (Phillips and Braggs, 1994). The simple Notch filtering technique was introduced by Lee and Awbi (1998). The propagated fluctuation in ventilation calculation disappeared after applying this technique, although the pure Notch filter required some modification to achieve reliable cross-correlation between the raw and the filtered signals.

In addition, a few more digital filters were applied in this study. The design of digital filter is classified into two categories; finite impulse response (FIR) and in-finite impulse response (IIR). The major difference between the two systems is the feed back sequence from the output to the input for subsequent iterations as shown for IIR below:

$$\text{FIR: } y(n) = \sum_{k=0}^{M-1} b_k x(n-k);$$

$$\text{IIR: } y(n) = -\sum_{k=0}^{N} a_k y(n-k) + \sum_{k=0}^{M-1} b_k x(n-k) \quad (4)$$

where, a and b are the coefficients and other variables are the same as in Eq. (2).

In FIR systems, the functions of Rectangular, Bartlett, Hamming, and Kaiser window were used to design the digital filters and the Kaiser window function was used for comparison. In IIR system, the functions of Butterwork, Chebyshev 1, Chebyshev 2, and Elliptic window are used to design the digital filters and the Chebyshev 1 window function was used for comparison.

The digitally filtered data using the several techniques mentioned above were then used for ventilation analysis, such as air change rate and mean age of air at the local sampling point under the outlet opening ($0.5H$). Considering continuity equity on a control volume in the test room gives equation (5). The time-serial tracer gas measurement at a certain point in the model room can be used to obtain the local air change, see Lee (1993) for more detail, using the equation: (Said, 1997; Sandberg and Stymne, 1989)

$$Q = -\frac{V}{t} \ln \frac{C(t) - C_{out}}{C(0) - C_{out}} \quad (5)$$

where Q is the air change rate m^3/s, V is the room volume m^3, t is the elapsed time s, $C(t)$ is the measured tracer gas concentration *ppm*, C_{out} is the background tracer gas concentration, and $C(0)$ is the tracer gas concentration when the tracer decay begins in the test room. It implies that the air change rate can be estimated by conducting tracer gas measurements at a local point in the test room for local air change rate and at the outlet opening for room air change rate. The local mean age of air $\bar{\tau}_p$ was then calculated by applying equation (6) to the tracer pulse measurements in time domain (Karlesson and Moshfegh, 2007; Etheridge and Sandberg, 1996;

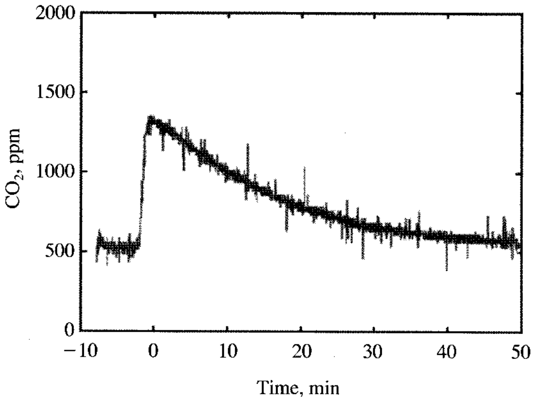

Fig. 2. Raw tracer gas concentrations in the leakage test.

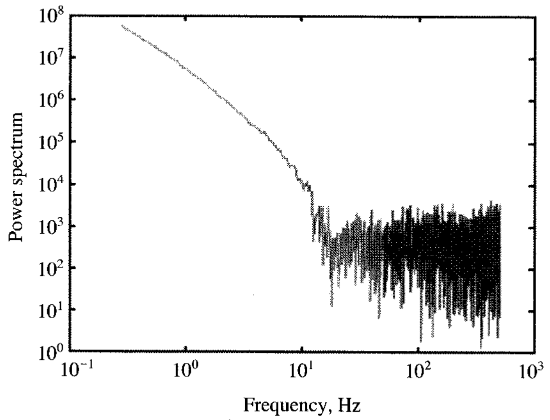

Fig. 3. Power spectrum of the raw measurement in the leakage test (using low-pass filter under 50 Hz).

Legus, 1977).

$$\bar{\tau}_p = \frac{\int_0^\infty tC_p(t)dt}{\int_0^\infty C_p(t)dt} \quad (6)$$

4. RESULTS AND DISCUSSION

The model tests were conducted under two conditions, a leakage test and a forced ventilation test. Fig. 2 shows a measured signal in the leakage test. For these tests, two mixing fans in the model test room were used to achieve a fully-mixed condition.

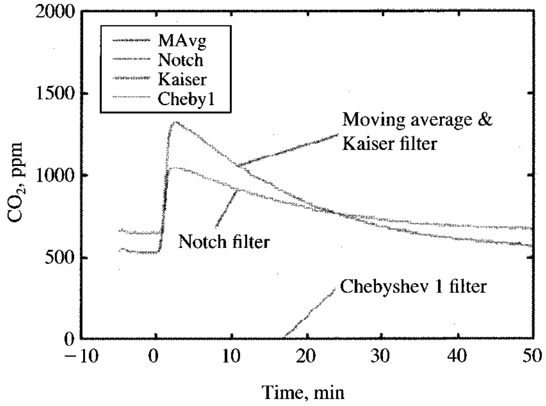

Fig. 4. Digitally filtered measurements in the leakage test.

Then tracer gas was injected into the model for a certain time period and the tracer decay was measured and recorded. The variation in the tracer gas concentration is easily observed from the measurement with small fluctuations, which could cause errors in subsequent analysis.

Fig. 3 shows the power spectrum of the measured tracer gas concentration using the FFT analysis. In the figure, the low frequency sources up to 50 *Hz* were collected by the Notch filter designed, while frequency sources higher than 50 *Hz* were removed. The other digital filters were created in different manners and used to collect the desired power source in the measured signal.

Fig. 4 shows the digitally filtered signal by the moving average, Notch filter, Kaiser filter (FIR), and Chebyshev 1 filter (IIR). The moving average and the Kaiser filter do not create significant change in the filtered data, but the Notch and the Chebyshev 1 filters do.

Fig. 5 and 6 display the calculated air change rates, using equation (5), by the infiltration in the test room. The ventilation system for these tests was running in pulling mode and formed negative pressure in the test room which caused air infiltration through invisible gaps. As the calculation for the air infiltration involves logarithms, the small fluctuations in the measured data are propagated and this causes difficulty in obtaining accurate value, as

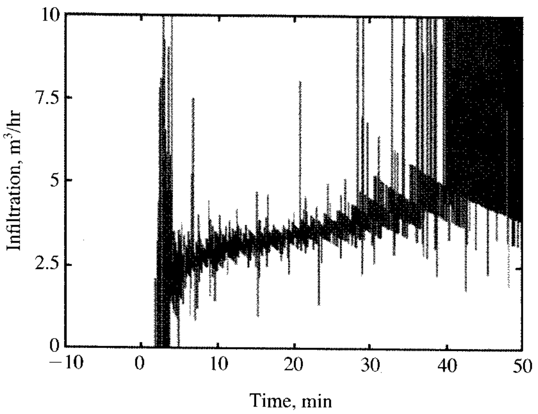

Fig. 5. Air infiltration calculations using continuity for the raw measurement in the leakage test.

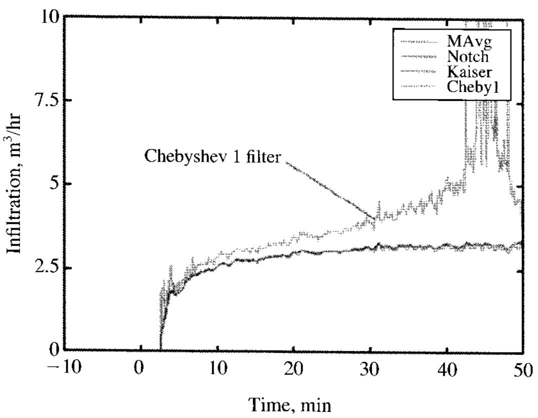

Fig. 6. Air infiltration calculations for the digital-filtered measurement in the leakage test.

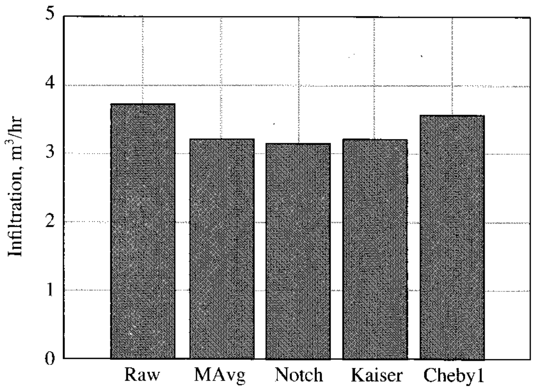

Fig. 7. Air infiltration calculation in the leakage test.

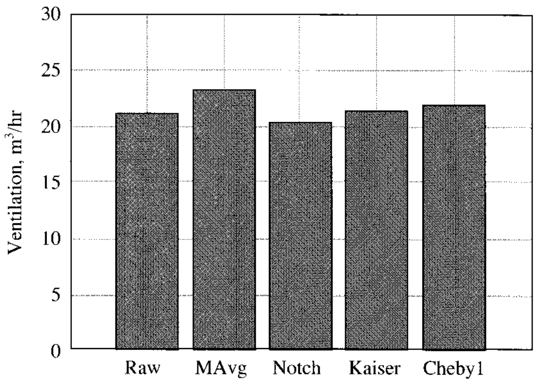

Fig. 8. Ventilation calculation in the ventilation tests.

shown in Fig. 5. The air infiltration calculations using filtered data in Fig. 6 show improved results. In fact, the air infiltration was physically stable during the test. The calculations by the Chebyshev 1 filter show gradual increase with time, while other filters produces stable infiltration results.

From the results considering Figs. 4 and 6, it can be concluded that the Kaiser filter in this study properly processes the signal of CO_2 measurement without causing any significant change in the raw signal.

Fig. 7 shows a comparison between the calculated air infiltration rates. Frequency analysis was performed to find the air infiltration rate. The value having the highest frequency in the histogram analysis was taken to be the air infiltration rate. The tracer gas measurement was repeated for the ventilation test and the same analysis was carried out. The general procedure of signal processing for the ventilation test is identical to the procedure for the leakage test and the final result from the ventilation test is presented. Figures 8 and 9 show the results for the ventilation rate and the mean age of air, using equation (6), respectively. The ventilation results present values close to that from the raw data except the moving average. In the mean age of air calculation the filtering processes produces almost identical results to that from the raw data except the *Notch* filter.

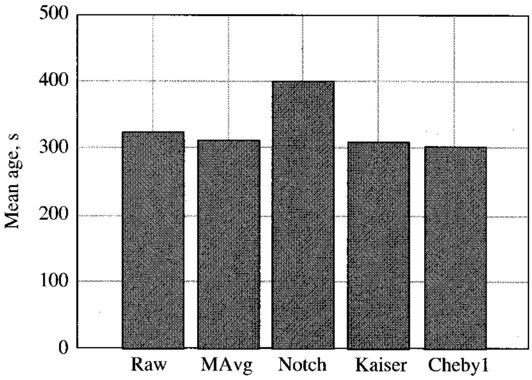

Fig. 9. Mean age of air calculation in the ventilation test (Note: The time constant for the ventilation test is 72s).

5. CONCLUSIONS

In order to enhance the quality of trace gas measurements in IAQ study, the digital signal processing techniques were applied to pre-process the tracer gas measurements. In addition to the previous work referred to here, a few other techniques, including notch filter, Kaiser filter, Chebyshev filter, were used to provide a comparison.

From this study, it is found that tracer gas measurements in ventilation tests are necessary to be pre-processed before further analysis to reduce uncertainty which may corrupt the desired information. Although the moving average technique used removes the random fluctuations from the measurements, it is not reliable enough to achieve stable ventilation calculation. The standard notch filter used in this study does not produce good results compared with other filters and may need some modifications before it is applied.

Overall the FIR filter produces better results compared with other filters for ventilation rate and mean age of air calculations. Among those tested, the *Kaiser* filter was the most feasible digital filter for pre-processing the tracer gas measurements. Although the IIR filters help to reduce the random noise in the data, they cause considerable changes to the filtered data, which is undesired.

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