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PRE-PROCESSOR FOR VENTILATION MEASUREMENT ANALYSIS

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ABSTRACT

It is well known that the introduction of tracer gas techniques to ventilation studies has provided much useful information that used to be unattainable from conventional measuring techniques. Data acquisition systems (DASs) containing analog-to-digital (A/D) converters are usually used to perform the key role which is reading and saving signals to storage in digital format. In the measuring process, there are a number of components in the measuring equipment which may produce system-based noise fluctuations to the final result. These unwanted fluctuations may cause discrepancy in computations, especially when non-linear algorithms are involved.

In this study, a pre-processor is developed and used 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 measured during leakage and ventilation tests in a model test room. The signal analysis functions embedded in Matlab are used to carry out the digital signal processing (DSP) work.

KEYWORDS

Tracer Gas Measurement; Digital Signal Processing; Correlation Analysis; Signal Noise; Air Leakage

INTRODUCTION

In ventilation research, tracer gas techniques are very useful to quantify the physical phenomena occurring in room ventilation. The application of data acquisition system (DAS), equipped with an analog-to-digital (A/D) converter on a personal computer, reduces the difficulty in measuring and recording tracer gas concentrations and it provides more detailed information carried in the measured signal, in real-time domain.

Although this test facility produces much information, the actual measured data may contain some unwanted components in terms of system-based noise or interference from the tracer gas analyzer, the computer, and other components used in the tests. This system noise appears as fluctuations in tracer gas measurements and could be propagated in the data analysis, especially in computati involving non-linear algorithms such as logarithmic or exponential functions.

In this study, several data pre-processing techniques have been performed to separate the potent error from the tracer gas measurements and to improve the ventilation analysis as a final goal. T moving average technique by Lee (1993) and a simple digital filtering technique by Lee and Aw (1998) have already been studied and reported. A few more advanced digital filtering techniques introduced in this paper. Finally, a tool to pre-process tracer gas measurement for further analysis also presented.

DIGITAL SIGNAL PROCESSING

A *signal* is defined as any physical quantity that varies with time, space, or any other independ variable or variables. Mathematically, it is described as a function of one or more independ variables, as in Equation (1). In this study a signal $x(t)$ (real-valued or scalar-valued) is a function the time variable t. The term real-valued means that for any fixed value of the time variable t, the va of the signal at time t is a real number.

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

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

A signal, in general, holds a characteristic called *duality* between the *time domain* and the *frequen domain*, which makes it possible to perform any operation in either domain. Usually one domain or other is more convenient for a particular operation. Based on this characteristic, *Fast-Four Transformation* (FFT), which is one of useful mathematical tools in signal processing, decompose signal in time domain into a sum of sinusoidal components in frequency domain. *Inverse-FFT* (IFF also works for the reverse function from frequency domain to time domain, see Lee and Awbi (19 for practical application of this.

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

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

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

In the case of preparing waveforms for deconvolution or dressing up the results of deconvolution, unwanted components are generally those of high-frequency noise. To reduce this noise contribution low-pass filter is used. There are a variety of filter functions that can be used, such as elliptic Chebyshev, Butterworth, and so forth.

A more sophisticated window function called *Kaiser Window* is generally used for the de: practical filters since it allows the designer the freedom to trade off the sharpness of the p stopband transitions with the magnitude of the ripples.

In signal processing, *correlation analysis*, which measures the correlation between observati different distances apart, can be used to approve the results. Suppose that there exist two real s $x(n)$ and $y(n)$ each of which has finite energy, the crosscorrelation of $x(n)$ and $y(n)$ is a sequenc which is defined mathematically as follows:

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

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

TRACER GAS MEASUREMENTS IN VENTILATION TESTS

To obtain tracer gas measurements in time domain, model tests were conducted. Figure 1 shows t schematic of the test setup used. The model room, 1.6^m x 0.8^m x 0.7^m (H), has two ceiling-mount openings to supply and exhaust ventilation air. An axial fan with speed controller was the ventilatio source. Carbon dioxide (CO_2) was used as the tracer gas and measured by a gas analyzer which generates signals, 0~1 *DCV*, 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 language, ver. 5.2.0.3084. The Matlab language was also used for the signal analysis work.

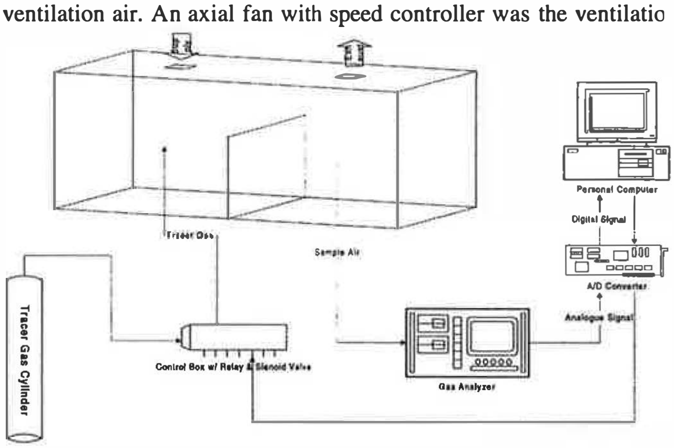

Figure 1: Schematic diagram of test setup for ventilation tests

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. The moving average was the first technique used with several periods used for averaging. The 30-points average produced the best result and was used as the basis for comparison with other techniques. This technique was used for ventilation analysis by Lee (1993). It was, however, found that this technique cause the loss of desired information from the 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 crosscorrelation 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:

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

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 (0.5*H*). 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:

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

where Q is 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 calculated by applying Equation (6) to the tracer pulse measurements in time domain, see Etheridge and Sandberg (1996).

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

RESULTS AND DISCUSSION

The model tests were conducted under two conditions, a leakage test and a forced ventilation test. Figure 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. 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 error in further analysis.

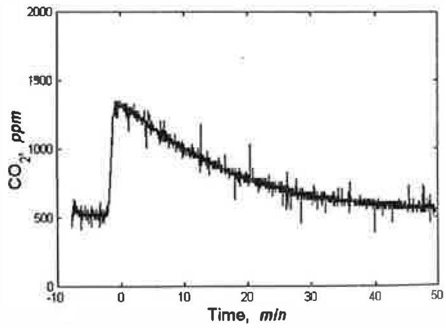

Figure 2: Raw tracer gas concentrations in the leakage test

Figure 3 shows the power spectrum of the measured tracer gas concentration using the FFT analysis. In the figure, the low frequency sources upto 50 *Hz* were collected by the Notch filter designed, while

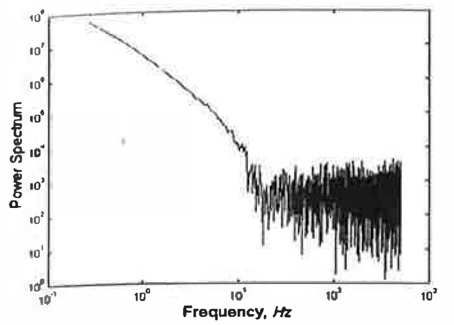

Figure 3: Power Spectrum of the raw measurement in the leakage test

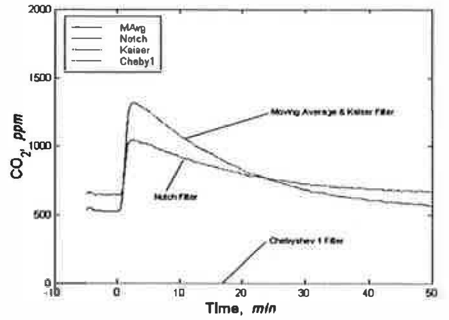

Figure 4: Digitally filtered measurements in the leakage test

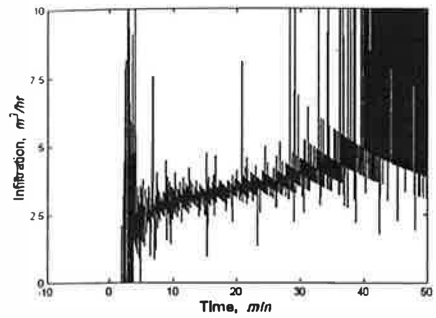

Figure 5: Air infiltration calculations using continuity for the raw measurement in the leakage test

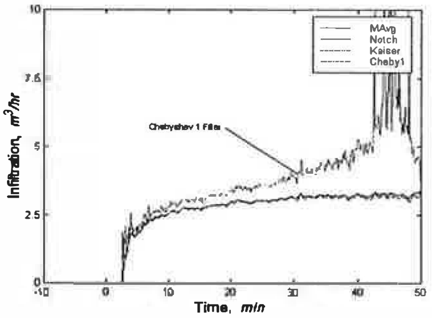

Figure 6: Air infiltration calculations for the digital-filtered measurement in the leakage test

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.

Figure 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.

Figures 5 and 6 show the calculated air change rate, using Equation (5), due to 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 shown in Figure 5. The air infiltration calculations using filtered data in Figure 6 show improved results. Although the air infiltration was almost stable during the test, the calculations by the Chebyshev 1 filter show gradual increase with time.

Figure 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 is carried out. Figures 8 and 9 show the results for the ventilation rate and the mean age of air, using Equation (6), respectively. The ventilation results show values close to that from the raw data except the moving average. In the mean age of air calculation the filtering processes gives almost identical results to that from the raw data except the *Notch* filter.

CONCLUSIONS

The digital signal processing techniques were applied to pre-process the tracer gas measurements in ventilation tests. In addition to the previous work referred to here, a few other techniques were used to provide a comparison. The major findings from this study were:

- 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 best one 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.

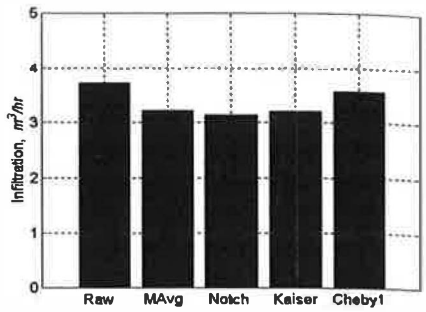

Figure 7: Air infiltration calculation in the leakage test

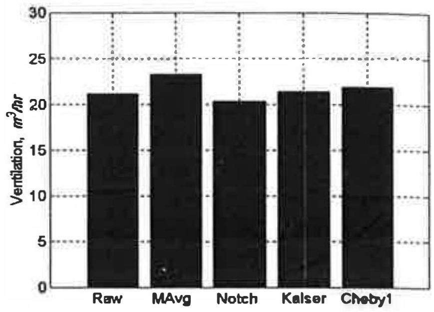

Figure 8: Ventilation calculation in the ventilation tests

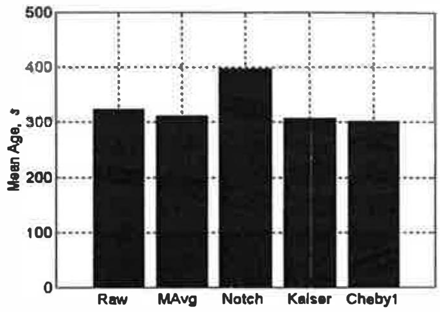

Figure 9: Mean age of air calculation in the ventilation test (Note: The time constant for the ventilation test is 72*s*.)

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