A Study of Classroom Acoustics and Its Effects of Listeners' Locations on Speech Intelligibility

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ABSTRACT

Attending a class and listening to a lecture given by an instructor is a common process in Thailand education. Ability of learning is affected by the ability of hearing the instructors' speech. Acoustical environments of the classroom, hence, can influence speech intelligibility. In this research, acoustical parameters and listeners' locations in classrooms and their effects on the speech intelligibility were studied. By using an assumption of linear systems of the classrooms, the room reverberation, background noise, and other classroom acoustical factors can be implicated as impulse responses of the system. Maximum length sequence was used to identify the impulse responses at listeners' locations in the classrooms. A clean speech, recorded in a semi-anechoic room, was convoluted with a series of the measured classrooms' impulse responses to yield a set of simulated reverberant speeches that the listener at each location in the classes would have heard. A number of volunteers were invited to test an ability of understanding the speech. The experimental results showed that the reverberation and background noise at listeners' locations severely affected the speech intelligibility. A classroom, that seemed to have a good averaged reverberation time, did not always yielded good speech clarity for all the locations in the class. In fact, for the classroom used in the study, the rear section of the class was poor for intelligibility and the back corner closed to a noise source was the worse location for speech hearing.

Keywords: Classroom Acoustics, Linear System, Impulse Response, MLS Signal, Speech Clarity, Speech Intelligibility, Reverberation Time

1. INTRODUCTION

Classrooms are places where students assemble for study, normally within a room in a building. In Thailand, an instructor usually gives a lecture at front of the classes while students sit and listen at their desks, uniformly located in the classes. Ability of learning is affected by the ability of hearing the instructors' speech. Therefore, acoustical factors of the classrooms, such as reverberation and background noise play an important role that affect the speech intelligibility. Too much noise or too much reverberation could cause student not capable of listening and also may distract student from their study, as well. There are studies about the effect of acoustical parameters to speech intelligibility found in research papers [1-3]. Effects of classroom reverberation and listeners' locations to instructor's speech intelligibility were displayed in [5]. It was revealed that for a classroom, although with good acoustical environment, if there was difference in levels of echoes at listeners' locations, ability of gaining speech intelligibility was also different. It was found that seemed that sitting at back section closed to a rear solid wall of the classroom was the worse location for the speech intelligibility. However the experimental study in [5] was conducted only for three locations, at front, middle and rear sections of the class. A completed insight into the effects of classroom acoustics on speech intelligibility at all locations would aid to justify a proper method to redesign or renovate a classroom for better speech intelligibility quality.

In this research, effects of reverberation, background noise and locations of listeners to speech intelligibility in the classrooms in faculty of engineering and industrial technology, Silpakorn University, were studied. By utilizing an assumption that a classroom is a linear system and applying a technique of using a pseudo-random signal with cross-correlation between input and output of the system, classroom impulse responses were identified. Series of the measured impulse responses were then convolved with a set of clear speech, recorded in an anechoic room, to simulate the reverberant speeches that would be heard at different locations in the classrooms. Volunteers were invited to examine for their speech intelligibility. The results of the study could be consequently used as an aid in determining if the existing classroom would be needed to be renovated and which acoustical conditions would be suitable for speech intelligibility.

2. CLASSROOM ACOUSTICS

Classroom acoustics are normally overlooked in Thailand education. Disturbing noise, echoes, reverberation, and room modes typically interfere with the ability of listeners to understand speech and may

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cause stress and deficit the health of listeners. There is no single criteria for indicating the proper room acoustics. However, some acoustical parameters effecting speech intelligibility in the classroom are background noise, reverberation time, and speech clarity.

Background noises are environmental noises always existing in the classroom. They may be noises from air-conditioning systems, electrical light bulbs, and electronic equipment. For a speech to be intelligible for hearing, the sound pressure level of the speech must be at least 10 dB above the noise pressure level.

Room reverberation is a sound echo that is reflected again and again from different surfaces of the room walls. It is indicated by the measured reverberation time (RT), normally the RT_{60}, which is amount of time required for the sound field in a space to decay 60dB. It can be measured by firing a blank pistol, exploding a balloon, or even playing a random noise through specially designed powered loudspeaker to create a loud noise around 100dB and reading the time used for the noise level to drop 60dB. Normally, the lower the RT_{60}, the better the speech intelligibility in a classroom is.

Speech clarity or C50 is defined as logarithmic ratio of energy between early arrival sound and late arrival sound of an impulse [1], as displayed in equation (1).

$$C_{50} = 10 \log \frac{\int_{0}^{50ms} p^2(t)dt}{\int_{50ms}^{\infty} p^2(t)dt} \, dB \tag{1}$$

The C_{50} can be related the speech intelligibility since the early arrival sound, including direct sound and early arrival echoes, contributes for better speech hearing, compared to that from only the direct sound [1]. In general, the higher the value of C_{50}, the better the speech intelligibility in a classroom is.

3. LINEAR SYSTEM AND IDENTIFICATION OF CLASSROOM IMPULSE RESPONSE

A classroom can be modeled as a linear system, in which the speeches from the instructor's mouth and the speeches heard by student sitting in each location in the class are input $s(t)$ and output $\varsigma(t)$ of the system, respectively. Acoustical environment of the classroom, such as reverberation and ambient noise can then be implicated as an impulse response of the linear system $h(t)$. Fig. 1 displays such the linear system.

In order to identify the impulse response of a classroom, a technique of using maximum length sequence (MLS) of signal is utilized [4][6]. The MLS signal is pseudo-random noise that has the same property as of the random noise, except that it is deterministic. The technique of using MLS to identify the system

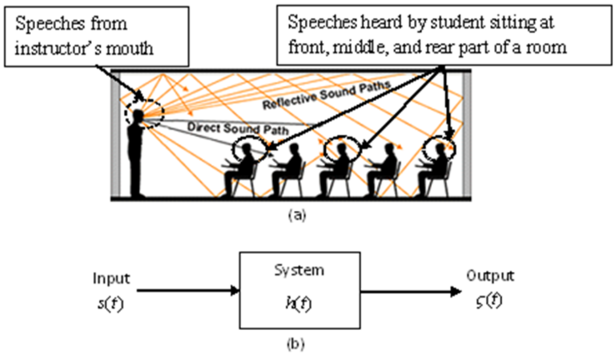


Fig.1: *A classroom (a) modeled as a linear system (b).*

impulse response is as followed. Let $h(t)$ is the impulse response of the classroom needed to identified, $s(t)$ is the MLS signal as the input to the system, $\varsigma(t)$ is the output of the system, and $n(t)$ is background noise in the classroom.

$$\varsigma(t) = s(t) * h(t) + n(t) \tag{2}$$

$$\begin{aligned} \varsigma(t) &= \int_{-\infty}^{\infty} s(t')h(t-t')dt' + n(t) \\ &= \int_{-\infty}^{\infty} h(t')s(t-t')dt' + n(t) \end{aligned} \tag{3}$$

Assume that background noise is random, at least for the range of audible frequencies. A cross-correlation between the excitation signal $s(t)$ and the measured output signal $\varsigma(t)$ can be formed as (4).

$$\phi_{s\varsigma}(\tau) = \lim_{T_0 \to \infty} 1/T_0 \int_{-T_0/2}^{T_0/2} s(t)\varsigma(t+\tau)dt \tag{4}$$

Since $s(t)$ is MLS which is pseudo-random, the cross-correlation between the noise $n(t)$ and the signal $s(t)$ converges to zero.

$$\begin{aligned} \phi_{s\varsigma} &= \lim_{T_0 \to \infty} 1/T_0 \int_{T_0/2}^{T_0/2} s(t) \int_{-\infty}^{\infty} h(t')s(t+\tau-t')dt'dt \\ &= \int_{-\infty}^{\infty} h(t') \left[\lim_{T_0 \to \infty} 1/T_0 \int_{T_0/2}^{T_0/2} s(t)s(t+\tau-t')dt \right] dt' \\ \phi_{s\varsigma} &= \int_{-\infty}^{\infty} h(t')\phi_{ss}(\tau-t')dt' \end{aligned} \tag{5}$$

In addition, auto-correlation of MLS signal $\phi_{ss}(\tau)$ concentrate at $\tau = 0$ and it can is approximately a delta function $\delta(\tau)$; i.e. $\phi_{ss}(\tau-t') \sim \delta(\tau-t')$. Hence, the equation (5) yields the impulse response of the system, $\phi_{s\varsigma}(t) \cong h(t)$.

4. MEASUREMENTS OF IMPULSE RESPONSE

Measurements of classroom impulse responses were done by using the MLS signal and techniques of cross-correlation as the previous section. At first, the binary MLS was generated by using a computer programming, played through a self-powered loudspeaker, and then recorded in a hemi-anechoic room. This recorded signal would be used as the input of the system. Fig. 2 displays the anechoic room at the department of electrical engineering, Silpakorn university and a system used in the study. It consisted of a JBL EON 315 self-powered loudspeaker, a Bruel&Kjaer 4189 condenser microphone, and a NI PXI-4461 dynamic signal acquisition (DAQ) with a PXI-1042 chassis and embedded controller. The system could be programmed to function as a recorder, sound generator, and signal processor as needed

Fig.2: *Hemi-anechoic room and system used for generating and recording MLS signal.*

The recorded MLS signal was played through the same set of dynamic DAQ and loudspeaker. The loudspeaker was located in front of the class at the instructor's place, and a condenser microphone was used to record the signal at each of listener's locations in the classes. This recorded signal is the output $\varsigma(t)$ of the system. The output $\varsigma(t)$ was then cross-correlated with the input $s(t)$ as described in equation (4) to obtain the impulse response. Fig. 3 shows the measurement setup for measuring the impulse response and fig. 4 displays a part of LabVIEW codes, developed for determining the impulse responses of the room systems. It is noted that a digital high-pass filter with 20Hz cutoff frequency was applied to get rid of the DC bias of the measurement system, especially from condenser microphone.

Fig.3: *Setup for measurement of classroom impulse response.*

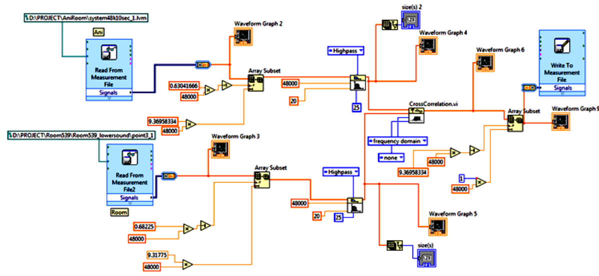


Fig.4: *A part of LabVIEW codes developed for measuring the classroom impulse response.*

4.1 Effect of Impulse Response Averaging

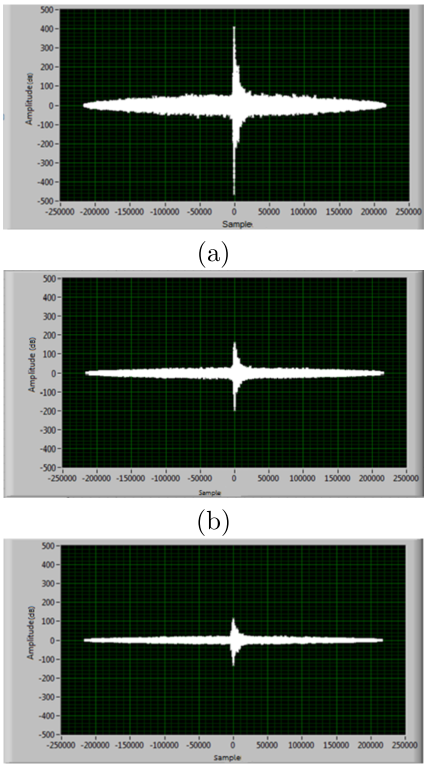
A set of experiments was conducted to see an effect of averaging to the reduction of a background noise and the enhancement of signal-to-noise ratio of the measured impulse response. The MLS length of 5 seconds was used as the system input. The results of impulse responses, which were averaged from 1, 5 and 10 measurements, are displayed in fig. 5 (a), (b) and (c), respectively. It can be seen that as the number of measurement used for averaging increased, the level of background noise decreased. Therefore, averaging could reduce the background noise. However, it may not increase signal-to-noise ratio of the measured impulse responses, since it could reduce the peaks of the measured impulse, as well. From these results, the identification of room system's impulse responses without averaging was chosen for other experiments in this study.

4.2 Effect of MLS Signal Length on the Measured Impulse Response

To select a suitable length of the MLS signal to be used as the system input for measuring the room impulse response, four sets of binary MLS signals $s(t)$ having different signal lengths of 1, 3, 5, and 10 seconds, were tested. Fig. 6 shows the results, in which the room impulse responses were successfully measured. It is obviously seen that the input signal length of 10 second yielded the impulse responses with the best signal-to-noise ratio, compared to that obtained from using shorter MLS signal length of 5, 3 or 1 second. Hence, the signal length of 10 seconds would be used as the proper length of MLS signal for the rest of this study.

5. EXPERIMENT ON EFFECTS OF CLASSROOM REVERBERATION ON SPEECH INTELLIGIBILITY

In this experiment, four types of classrooms in the faculty of engineering and industrial technology were studied and the classroom RT_{60} was measured by using a pistol to generate a loud impulse having sound pressure levels of 90-100 dBA. For each classroom,



(a)

(b)

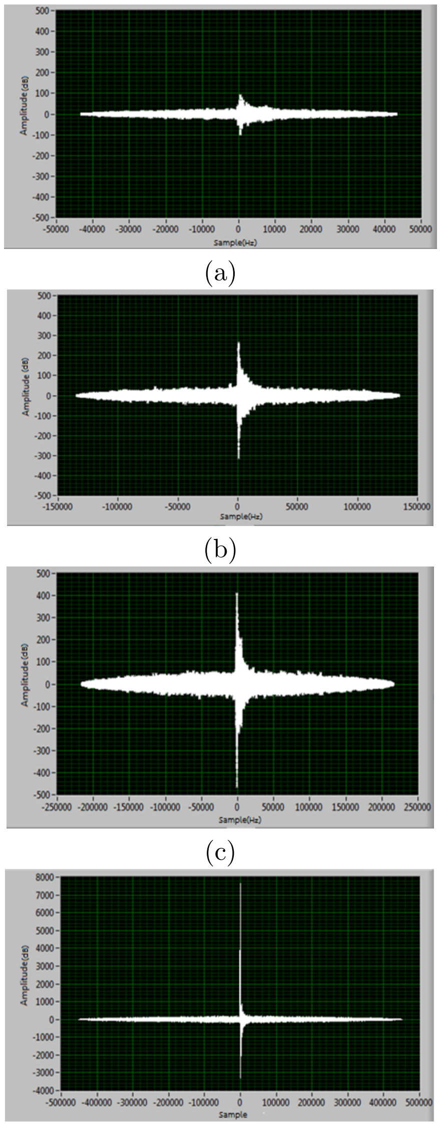
(c)

Fig.5: *Room impulse response averaged from the number of (a) 1 measurement, (b) 5 measurements and (c) 10 measurements.*

about 20 RT60 measurements were done at three listeners' locations. The rooms' description and the averaged RT_{60} are displayed in table 1.

To study effects of classroom reverberation and listeners' locations on speech intelligibility, first, the impulse responses of each classroom at a particular listening-position were identified. Such the classroom impulse response was assumed to completely represent classroom characteristic, that when it was convolved with an instructor's speeches, it yielded the resulted speeches as if the speeches came from the instructor speaking at front of the classroom. Sets of test speeches for speech intelligibility experimentation were simulated by the convolution between clean speeches recorded in anechoic room with the impulse responses measured at each location in the classrooms. The 23 volunteers were invited to examine the clarity of hearing the test speeches. Fig. 7 displays the diagram summarizing the experimental steps. Fig. 8 shows an example of a clean speech, a measured impulse response, and the test speeches, resulted from the convolution.

Result of reverberation effect on the speech intelligibility is shown in table 2. It is clearly seen that classrooms with less RT yields better speech intelligibility. About 90% of volunteer stated that the room with RT of 1.09 seconds was good in speech intelligibility, and 95% of the volunteers said that the speech clarity of the room with RT of 1.12 seconds was fair or good. In contrast, for the room with large RT, speech clarity is poor. As noticed, for the rooms with RT of 1.52 seconds and 1.79 seconds, respectively, about 75% and 100% of the volunteers mentioned that the speech intelligibility in the rooms was poor to very poor. In addition, it was also noticed that the room with or without curtains had different RT_{60}. Hence, when the curtains were opened, the room would yield different effects on ability to hear speeches than when the curtains were closed.



(a)

(b)

(c)

(d)

Fig.6: *Impulse response of a classroom obtained from using four different lengths of input MLS signals; (a) 1 second, (b) 3 seconds, (c) 5 seconds, and (d) 10 seconds.*

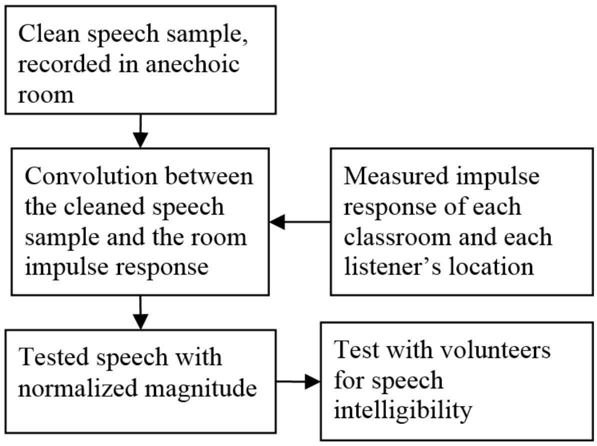
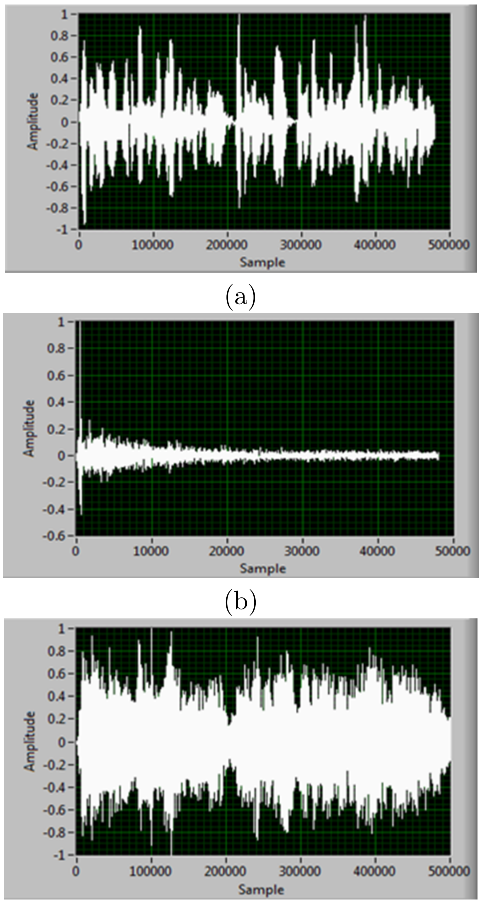


Fig.7: *Summary of the experimental processes used for studying speech intelligibility.*



(a)

(b)

(c)

Fig.8: *(a) Clean speech record from anechoic room (b) measured impulse response of a classroom, and (c) test speech obtained from the convolution.*

Table 1: *Classroom Description and Measured Reverberation Time (RT_{60}).*

Room No.	Classroom description	Volume (m^3)	Measured RT_{60} (seconds)		
			At front	*At middle*	*At rear*
R.539	Solid wall, Curtain on two wall-sides, floor filled with desks	525	1.09	1.11	1.14
R.146 (with curtain)	Solid wall, curtain on windows and three side-walls, filled with student chairs	680	1.12	1.13	1.15
R.146 (no curtain)	Solid wall, no curtain, filled with student chairs.	680	1.52	1.71	1.69
R.139	Solid wall, no curtain, filled with student chairs	320	1.79	1.85	-

Table 2: *Effect of Reverberation to Speech Intelligibility.*

Room No.	RT_{60} (second)	Speech Intelligibility Test Result (percent of volunteers, judging about clarity ranking from excellent to poor)				
		Excell-ent	*Good*	*Fair*	*Poor*	*Very poor*
R.539	1.09	0.00	91.30	8.70	0.00	0.00
R.144 (with curtain)	1.12	0.00	13.00	82.60	4.40	0.00
R.144 (no curtain)	1.52	0.00	0.00	26.10	69.56	4.34
R.139	1.79	0.00	0.00	0.00	17.40	82.60

6. EXPERIMENT ON EFFECT OF ACOUSTICAL CONDITIONS AT LISTENERS' LOCATIONS ON SPEECH INTELLIGIBILITY IN CLASSROOMS

For studying effect of acoustical condition, such as background noise and reverberation time at listeners' locations on speech intelligibility, the classroom R.539 with the averaged RT_{60} of 1.11 seconds, was chosen to be used in the experimentation, since it seemed to provide best acoustical condition. The levels of background noise at 30 locations in the room R.539 were measured by using a class-1 Cirrus sound level meter of model CR:821A. Fig. 9 displays noise levels of the classroom R.539 under a normal use condition (e.g. air conditioning system and light bulbs were turn on). As seen, the levels of background noise at the location near air conditioners were high, around 46-47 dBA and at the location away from the air conditioners were low, about 44-45 dBA. However, because of room modes which were highly condensed at room's corners, the levels of background noise were highest at the corners closed to noise sources.

Reverberation condition at listener location in the room R.539 was measured and displayed in RT_{60}. As noticed in fig.10, at the front locations of the room, the measured values of RT_{60} were small around 1.01-1.04 seconds, and were high at back session of the class. The highest value of the measured RT_{60} was found to be as high as 1.14 at the corner, closest to the air conditioner of the back session of the room.

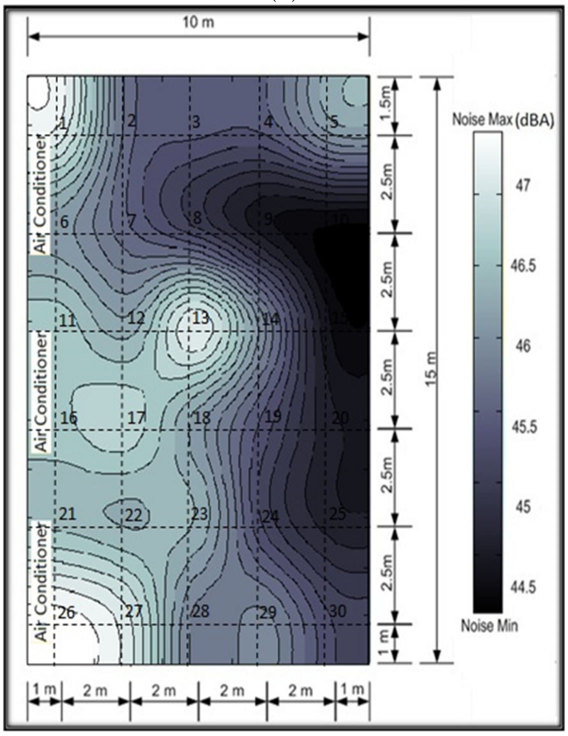
Impulsive sounds generated by using a pistol, as displayed in fig. 11(a), were recorded at listeners' locations and later used for calculation of speech clarity (C_{50}) by using equation (1). Fig.11 (b) represents the calculated speech clarity at the 15 listeners' locations of the classroom R.539. As seen, locations at front session of the classroom yielded good speech clarity. The C_{50} values were above 27. In contrast, locations of rear session of the classroom yielded low speech clarity. Especially at the left corner of the rear session, closed to the air conditioner, the speech clarity was lowest at C_{50} of 19.14.

Investigation on effects of acoustical condition at 15 different listeners' locations on speech intelligibility in the classroom R.539 was completed by using 30 volunteers to listen the test speech obtained by convolution between the measured impulse responses of each location and a cleaned speech sample. Table 3 displays the results of listening at 15 different listeners' location of the class. As seen, more than 90% of the volunteers revealed that sitting at front locations of the class, locations of 1 to 5, were good or excellent for speech intelligibility, and about 60% of the volunteers indicated that sitting in the middle locations of the class, locations 6 to 10, yielded fair ability to grasp speech content. However, more than 80% of the volunteer stated that the ability to understand the speech were poor or very poor, when sitting at rear section of the class, locations 11 to 15. The worse location for speech intelligibility was at the rear corner in the back session. The results agreed well with the measured RT_{60} and C_{50}. As RT_{60} increased or C_{50} decreased, the speech intelligibility tended to drop.

7. CONCLUSIONS

Classrooms were modeled as linear systems, and their impulse responses were measured by using MLS signal and cross-correlation. Results of experiment

(a)



(b)

Fig.9: *(a) Instrument and measurement of background noise in a classroom (b) Contour displaying background noise levels (in dBA) at 30 locations in the classroom R.539.*

showed that the longer MLS signal's length was used, the better signal-to-noise ratio of the measured impulse responses would be obtained. Classrooms with different reverberation time (RT_{60}) values were tested for their speech intelligibility by volunteers, listening to a series of test signals that simulated the speeches with acoustical conditions at listeners' locations. It was found that the classrooms with averaged RT_{60} of 1.0-1.2 seconds yielded good and fair speech intelligibility, while the classrooms with RT_{60} greater than 1.5 seconds influenced poor speech clarity.

To investigate if a room with good averaged RT_{60} would permit good speech clarity at all listeners' locations, the classroom R.539 with averaged $RT_{60}$of 1.07 were used. Background noise, RT_{60} and values of speech clarity (C_{50}) of the classroom were examined.

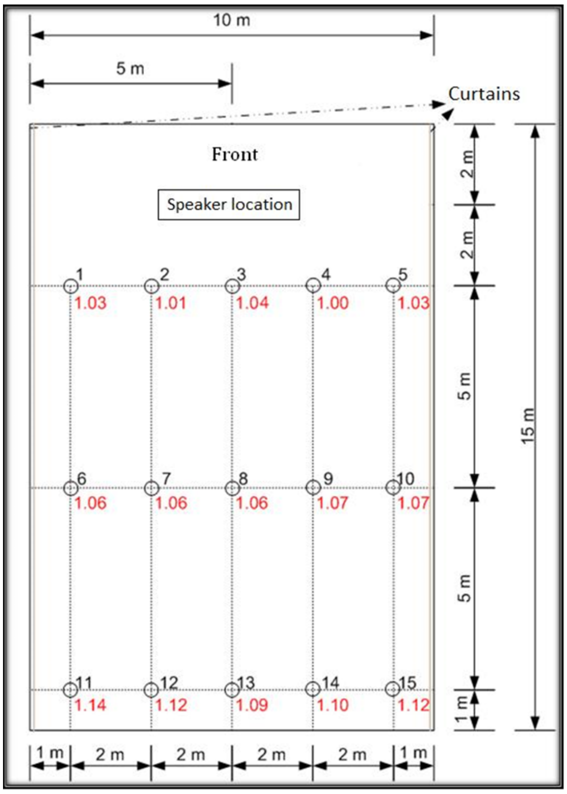
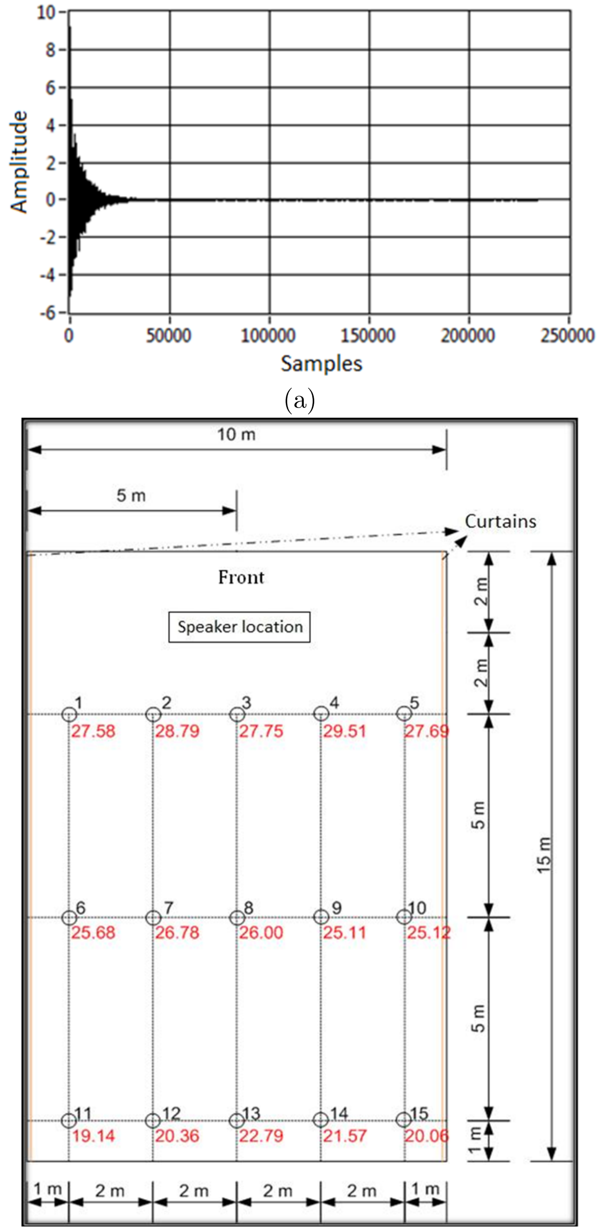


Fig.10: *Values of measured RT60 at listeners' locations of 1 to 15 in the classroom R.539.*

At the locations closed to air-conditioners, the levels of background noise were about 2 to 3 dBA higher than other locations. At the corners, the values of RT_{60} were high and C_{50} were low, compared to other listeners' locations. These were due to room modes which tended to magnify a sound or noise of various frequencies at the room corners and then could hamper the ability of grasping speech contents. Experimentation on speech intelligibility by volunteers also revealed that listeners' locations did affect ability of hearing the speech contents.

The locations yielding good speech clarity were at front section of the class, having RT_{60} of 1.01 to1.04 seconds and C_{50} above 27.5. The middle of the class having RT_{60} of 1.06 to 1.07 seconds and C_{50} of 26 to27 yielded fair speech intelligibility. However, the rear part of the class, having RT_{60} of 1.09-1.16 seconds and C_{50} below 23, permitted poor speech intelligibility. The worse location for listening in the class was at the back corner closed to a noise source.

A significant of this research was a disclosure that, although a classroom seemed to have good acoustical condition for listening, it did not guarantee to yield good speech intelligibility for all listeners' locations in the classroom. Room acoustics should not be overlooked in education since it affected the ability of hearing and understanding the contents of instructor speeches in the class.



(a)

(b)

Fig.11: *(a) A recorded sound pressure of an impulse sound (b) Values of speech clarity measurement at listeners's locations of 1 to 15 in the classroom.*

8. ACKNOWLEDGEMENTS

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Table 3: *Results of Speech Intelligibility Test in the Classroom R.539 at 15 Listeners' Locations .*

Listeners' Locations	Test Result of Speech Intelligibility (Percent of volunteers, stating about clarity ranking from excellent to poor)				
	Excellent	*Good*	*Fair*	*Poor*	*Very poor*
1	60.00	33.33	6.67	0	0
2	70.00	30.00	0	0	0
3	56.67	40.00	3.33	0	0
4	60.00	36.67	3.33	0	0
5	50.00	23.33	23.33	0	3.34
6	3.33	13.33	56.67	23.33	3.34
7	0	6.67	60.00	26.66	6.67
8	0	20.00	60.00	16.67	3.33
9	13.33	16.67	66.67	3.33	0
10	10.00	3.33	60.00	23.33	3.34
11	0	3.33	20.00	20.00	56.67
12	0	6.67	3.33	30.00	60.00
13	0	10.00	0	46.67	43.33
14	3.33	3.33	0	50.00	43.34
15	10.00	0	3.33	3.33	83.34

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