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Acoustic design criteria for naturally ventilated buildings

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This paper proposes satisfactory indoor noise level criteria for office buildings which are compatible with achieving minimum natural ventilation standards set out in green building rating systems for sustainable building design. Indoor air quality standards related to the use of natural ventilation in buildings conflict with the control of ingress of external noise through ventilation openings to meet internationally recognized background noise limits for building use. These standards generally assume, however, that buildings are sealed and airconditioned to meet the stated recommended indoor noise levels. It is not feasible that these noise standards can be expected or are appropriate to be achieved in naturally ventilated buildings. Therefore, to account for the thermal comfort benefit of natural ventilation and the ability to locally control natural ventilation and noise levels by closing of windows, an allowable exceedance of the recommended indoor noise levels is explored. The allowable deviation from existing background noise level guidelines is determined, which is considered to be an acceptable compromise for increased thermal comfort.

1 Introduction

1.1 General

The use of natural ventilation in buildings is generally accepted as a sustainable design strategy because of the assistance it provides in terms of increased occupant productivity, and the benefits it provides in terms of reduced energy consumption and running costs [1]. The increased use of outdoor air ventilation above the minimum rates required by ASHRAE standards, for both mechanical ventilation and natural ventilation methods, is a general goal for sustainable building design. The use of low contaminant emitting materials is also a consideration.

The use of natural ventilation in buildings conflicts, however, with the control of ingress of external noise through ventilation openings. International standards [2, 3] provide recommended guidelines for internal background noise limits for building use. These international standards generally assume, however, that buildings are sealed and airconditioned to meet the stated recommended indoor noise levels. Therefore, in many projects, the use of natural ventilation is considered infeasible because of noise issues – either because the perceived high noise environment cannot be controlled with practical measures to the levels recommended in international standards, or that the cost of noise mitigation measures outweighs the benefits of natural ventilation.

It is not feasible, however, that these noise standards can be expected to be achieved in naturally ventilated buildings due to the openings required to allow air to enter and exit buildings. As a compromise for the non-acoustic benefits natural ventilation provides, alternative approaches are offered to quantify an acceptable exceedance in noise level standards already set for sealed, airconditioned buildings.

1.2 Previous Research

There are no internationally recognized standards for internal background noise limits with the use of natural ventilation. Previous research suggests, however, that allowable indoor noise levels with the use of natural ventilation could be higher than for a sealed, airconditioned building, because of the non-acoustic benefits that natural ventilation provides. Wackernagel et al [4] indicate that internal noise levels of up to 65 dBL_{Aeq} could be acceptable in naturally ventilated offices. Surveys carried out by various researchers were summarized and collated by Ghiaus and Allard [1] and showed that 55 - 60 dBL_{Aeq} is acceptable in open plan offices and that current international noise standards are unnecessarily stringent to be applicable for naturally ventilated buildings. McCartney and Nicol [5] showed that tolerable internal noise levels in European offices is around 60 dBL_{Aeq}.

2 The Role and Benefits of Natural Ventilation

The role of natural ventilation in buildings can be summarized as follows:

- Improves indoor air quality by decreasing the concentration of indoor air pollutants.
- Improves thermal comfort conditions in indoor spaces.
- Decreases the energy consumption of air conditioned buildings.

As a compromise to higher noise levels due to external noise ingress, the benefits that natural ventilation provide includes lower running costs, reduced use of refrigeration and airconditioning, simpler and accessible personal environmental control, reduced space requirements for mechanical plant, and increased occupant productivity. A controlled increase in background noise levels could also have a positive acoustic benefit in terms of providing masking noise within the space, the problem identified previously with the use of passive cooling systems. The benefit, however, would be highly dependent on the acoustic character of the external noise being used to provide masking.

3 Legacy Acoustic Criteria Used for Naturally Ventilated Buildings

3.1 Human Sensitivity to Noise Levels with Natural Ventilation

The sensitivity of humans to noise in sealed airconditioned buildings is well documented [1] and studies have been carried out to determine appropriate quantifiable measures to deal with sensitivity to noise. When natural ventilation is used in buildings, however, people's sensitivity to noise

changes. This change in sensitivity can be attributed to the following factors:

- The expectation of a low noise level environment is lower.
- The appreciation of non-acoustic benefits facilitates compromise with noise levels.
- Office layouts (open plan) in green buildings provide occupants with greater awareness and therefore tolerance of surrounding activities.
- Climate – people in countries where windows are customarily open for most of the year seem to be more tolerant of noise [6, 7].

With regards to people's general sensitivity to noise, people generally accept a slightly higher level of variable noise from outside the building compared with the constant level of mechanical services noise. If the occupants know that all of their ventilation is achieved through openable windows, and they are free to open or close windows, then again they will accept a higher noise level than if the room is mechanically ventilated. A space which is only mechanically ventilated is considered a 'controlled' space and the occupants expect noise to be controlled to a low level.

On the hottest days occupants will generally accept a slightly higher noise level in order to have additional cooling via openings.

3.2 Acoustic Criteria Used Previously

3.2.1 Previous Project Experience

A review of project work carried out by the author indicates that criteria adopted for the break-in of external noise to office buildings is typically compatible with the equivalent mechanical services background noise limit that would be set for the particular occupied space. Break-in noise limits have therefore been set as a tolerable exceedance of the mechanical services background noise criteria. For example:

- External noise break-in related to NC or NR curves eg. L_{Aeq} = NR35 + 5, L_{A1} = NR
- Logarithmic sum of all noise sources in the occupied space in terms of L_{Aeq} = NR limit for building services.
- An allowable excess in octave bands (5 dB at low frequencies and 3 dB at mid to high frequencies) above an NR curve.

3.2.2 Challenging Legacy Criteria

The criteria used previously (given above) give rise to the following considerations and challenges:

- For criteria given in relation to NR or NC curves, by definition and intent of the use of NR and NC curves, the noise sources should be constant and steady state, without audible tones or fluctuations in noise levels. This would most likely not be the case for external noise sources adjacent to naturally ventilated buildings.
- For criteria given in terms of L_{Aeq}, this noise descriptor is defined as an energy equivalent time averaged noise level that expresses the time-varying sound level for the specified period as though it were a constant sound level with the same total sound energy as the time-varying level. This implies that the criteria represent a time averaged noise level, and the instantaneous noise level at any one time has a high probability of being higher than the L_{Aeq}. For the use of natural ventilation, this could be considered acceptable because of the non-acoustic benefits that natural ventilation provides and the "adjustment" in human sensitivity to noise with the use of natural ventilation.
- For criteria given in terms of L_1, this implies that for 99% of the time, the noise criterion is met. This may be considered to be a conservative target given the non-acoustic benefits that natural ventilation provides, and the human sensitivity to noise discussion above.

The choice of an appropriate statistical noise descriptor for assessment of noise break-in via naturally ventilated building facades warrants a standalone subjective assessment. As a starting point for this research, however, L_{Aeq} has been chosen for this assessment, as it is compatible with the perceived acceptance of humans to higher and more variable noise levels with natural ventilation.

4 Proposed Study

4.1 Assumptions

Many assumptions have been made during this study in the interest of achieving some meaningful conclusions. The intent is to use this study as the starting point for a more comprehensive assessment over the next two years. The assumptions for this initial study are as follows:

- The goal for the assessment was restricted to assessing speech intelligibility levels in offices affected by external noise sources, and does not account for internal office activity noise sources.
- The assessment was carried out for a one-off configuration of open window area, distance from the window and elevation of the window above the principal noise sources.
- The window was sufficiently open so that the principal transmission path for external noise was via the opening.
- The noise source recordings taken were representative of typical street activities in Manhattan, New York, with no preference given to particular intermittent noise events or absence thereof.
- The speech level used in presenting word score lists for subjective testing was calibrated and normalized to 68 dBL_{Aeq} at 3 ft on axis.
- Speech intelligibility has been assessed in terms of the Articulation Index (AI).

4.2 Outline Methodology

The aim of the assessment was to use subjective word tests to ascertain the level of impairment of speech intelligibility in the presence of external background noise entering office buildings via natural ventilation openings. Background

noise levels were varied in 3 dB increments to determine the sound pressure level at which the level of speech intelligibility in offices would be unsatisfactory.

4.3 Testing Procedure

1) A series of 5 min recordings were carried out using a Soundfield microphone in downtown New York. Recordings were carried out under the following conditions:

- The measurement position was 3 ft from the open window inside a private office.
- Windows were opened to the point typical for natural ventilation of the space.
- The noise sources in the chosen recording included typical street activities such as general traffic flow, individual vehicle events, voices, and audible signal for reversing of vehicles.
- Sound levels were measured concurrently inside and outside the building using a sound level meter to give an indication of level difference across the open window in third octave bands.

2) Stimulus word lists were generated by a trained female speaker, at a calibrated level in the Arup Acoustics NY SoundLab. Modified Rhyme Tests (MRT) were carried out in accordance with ANSI S3.2-1989 [8]. The word lists were played back to 15 test participants using a single loudspeaker (mono) located directly in front of the listener at a distance of 6 ft. The level of reproduced speech at the listening position was 59 dBL_{Aeq}, measured during playback of the entire MRT set of 500 words.

3) A randomized playback system for the word lists was developed with a MATLAB script and a graphical user interface was used to facilitate the tests.

4) The calibrated noise recordings were played back during the balanced word score tests via a 12 loudspeaker ambisonic set-up in the Arup Acoustics NY SoundLab.

5) A 20 word MRT was carried out for 9 randomized increments of recorded background noise level to ascertain the impairment of speech intelligibility as the level of background noise changes.

5) The level of speech intelligibility (SI) was quantified by the % of correct words, in accordance with ANSI 3.2-1989 [8]. The SI values were then converted to equivalent values of Articulation Index (AI) using the method given by AS 2822-1985 [9].

6) The % of correct words was correlated with a "good" standard of speech intelligibility (AI > 0.45) expected for satisfactory office communication [9].

7) The internal break-in noise level limit (L_{Aeq}) appropriate for speech intelligibility in naturally ventilated office spaces was then determined.

5 Results and Discussion

The results of the subjective testing are given in Table 1 below.

The results in Table 1 indicate an AI > 0.45 is achieved for an internal noise level of 59 dBL_{Aeq} or a signal to noise ratio of 0.6. These results are consistent with the results of previous research given in Section 1.2.

The results demonstrate that the allowable level of external noise break-in to naturally ventilated buildings can be set higher than for sealed and mechanically ventilated buildings, whilst still maintaining a good level of speech intelligibility within office spaces. This provides opportunities for introducing practical and less stringent noise mitigation measures, if necessary, for naturally ventilated buildings at a reasonable cost in the context of the building construction budget.

6 Future Work

In order to produce a research outcome within a given time constraint, many assumptions have been made. The intent is to continue this research, using the results of this study as a starting point. Considerations for future work include:

- A more comprehensive range of external noise sources will be considered including construction noise, freeway noise, aircraft and mechanical plant noise.
- A more thorough assessment of an appropriate noise criterion descriptor will be carried out, with consideration given to octave band or third octave band criteria, to account for the variability of masking of speech intelligibility according to the frequency of noise.
- Carry out a multi-sensory assessment, including the benefits of fresh air provided by natural ventilation assessed concurrently with external noise break-in.
- Introduce office activity noise as part of the background noise in office spaces.

Acknowledgments

I would like to acknowledge the hard work of Joseph Digerness in preparing and coordinating the subjective testing for this research.

This research was funded by an internal Arup Research Grant.

S/N, dBA	Traffic Noise		Articulation Index (AI)		Speech Intelligibility Scores		Subjective Assessment
	Gain, dB	L_{Aeq}, dB	Avg	Std. Dev.	Avg	Std. Dev.	
12.6	-9	47	0.70	0.26	98.0	3.7	Excellent
9.6	-6	50	0.60	0.30	96.0	4.9	Good
6.6	-3	53	0.70	0.27	97.2	5.5	Excellent
3.6	0	56	0.50	0.30	94.4	5.3	Good
0.6	**3**	**59**	**0.50**	**0.26**	**94.4**	**4.8**	**Good**
-2.4	6	62	0.35	0.23	86.8	10.7	Fair
-5.4	9	65	0.35	0.27	87.6	10.0	Fair
-8.4	12	68	0.30	0.07	81.6	10.0	Fair

Table 1 Test Results

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