The effect of wind farm noise on human response: An analysis of listening test methodologies

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ABSTRACT

Despite the significance of listening tests in identifying the human response to wind farm noise (WFN), little attention has been paid to methodological approaches relevant to WFN listening tests to date. Moreover, evidence on the potential adverse effects of WFN is still not well established. This paper thereby sheds light on the different quantification approaches of human response to WFN characteristics. There is also a discussion on the quality of current evidence regarding the effect of WFN on annoyance and sleep disruption. In the context of listening tests, separating WFN characteristics can be beneficial in many ways. Firstly, acceptable threshold levels for each component of WFN for daytime annoyance and night-time sleep disturbance can be quantified. Second, the most annoying characteristic of WFN can be identified. Third, the most annoying characteristics of WFN can be identified by combining two or more components of WFN. Finally, this helps determine the sufficiency of current penalties applied to WFN characteristics.

1 INTRODUCTION

The world has expanded its use of renewable energy due to increasingly stringent emissions targets. One of the most viable renewable energy sources is wind energy, which can be classified as clean, economically profitable and environmentally friendly (Kaldellis and Zafirakis 2011). However, questions have been raised about how wind farm noise (WFN) can affect health (Schmidt and Klokker 2014). WFN contains special characteristics including low-frequency noise (LFN) and infrasonic tones, amplitude modulation (AM) (Ioannidou, Santurette, and Jeong 2016), and tonality (Søndergaard and Pedersen 2013; Yokoyama, Kobayashi, and Tachibana 2016). These characteristics seem to contribute to higher ratings of perceived annoyance, even at low sound pressure levels (SPLs), compared to other environmental noise (Janssen et al. 2011; Schäffer et al. 2016).

To assess the human response to WFN, a variety of study methodologies, including surveys and laboratory studies has been adopted. Reflecting the real impressions and conditions gives surveys an advantage over laboratory studies due to long-time exposure to WFN (Moorhouse, Waddington, and Adams 2005). However, laboratory studies can control many confounding factors, such as attitudes to wind turbines, the sensitisation of participants, the existence of economic benefits, recollection problems, wind turbine visibility and location of dwellings (i.e. rural or urban areas) (Janssen et al. 2011).

Confounding factors could affect the strength of the relationship between WFN and its effect on human response (Council of Canadian Academies 2015). Quantifying and isolating WFN characteristics contributing to annoyance ratings and sleep disruption reveals the relative likely effect of each WFN characteristic on human response (Moorhouse, Waddington, and Adams 2005). However, there has been increasing concern over the applicability of current WFN penalties (Perkins et al. 2016). Furthermore, few studies have been able to draw upon systematic research into the potential effect of WFN on humans. Accordingly, this paper evaluates the research conducted on the methods used for quantifying annoyance and sleep disruption due to WFN characteristics. In addition, further annoyance quantification methods in listening tests are proposed for future research.

2 WFN-RELATED ANNOYANCE

Annoyance due to WFN has been studied in listening tests focused on WFN special audible characteristics. However, some important parameters of these characteristics need additional investigation.

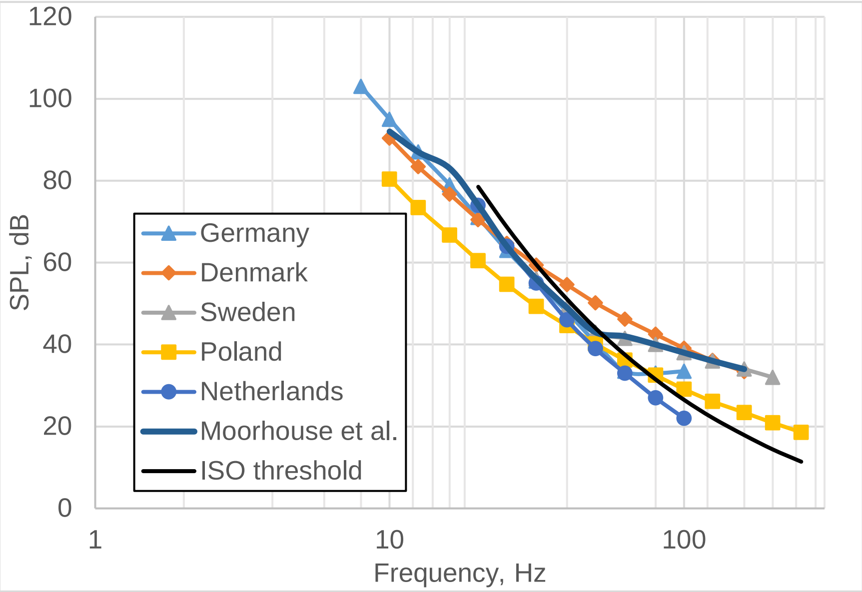
2.1 LFN AND INFRASOUND

The effect of LFN and infrasound on humans in listening tests is usually assessed by acceptable threshold levels (ATLs) and hearing threshold levels (HTLs). Some studies related to LFN HTLs have been presented to show the effect of LF pure tones on HTLs. HTLs were found to differ according to many factors (i.e. number of subjects, stimuli reproduction and rating methods). Also, they were dependent on the individuals (Sakamoto et al. 2014).

Moller (1987) investigated LFN ATLs of pure tones between frequencies 4 Hz to 31.5 Hz. A small increase in SPLs leads to a great annoyance increase when LFN becomes perceptible. For example, the SPL difference between the maximum and minimum ATLs at 4 Hz was around 12 dB, while at 31.5 Hz, it was 40 dB. Subedi et al. (2009) also studied LF ATLs using pure and combined tones for frequencies of 31.5, 50 and 80 Hz. Similar results to Moller (1987) were obtained as LFN ATLs increased with SPL rapidly.

As shown in Fig. 1, WFN criteria of LFN ATLs vary between countries (Moorhouse et al. 2005). The lowest frequency considered ranges from 8 Hz in the German criteria to 31.5 Hz in the Swedish criteria. Moorhouse et al. (2005) also recommended ATLs and HTLs for pure tones between 25 Hz and 160 Hz. Their obtained criteria curve of ATLs is also shown in Fig. 1. It should be noted that criteria like those of the Netherlands were originally derived for HTLs. In addition, the Polish criteria consider the assessment of the background noise.

ATLs and HTLs of LFN were presented in some studies using pure tones, but reliable evidence of HTLs and ATLs of infrasonic content and LFN of a realistic WFN stimulus on human responses is still lacking. For that purpose, real WFN can be filtered into specific ranges of infrasound and LFN to show their effect, rather than using pure tones.



Source (Moorhouse, Waddington, and Adams 2005)

Figure 1: LFN criteria in some countries compared to ISO threshold

2.2 TONALITY

Tonality components of WFN can potentially affect the perceived human response from wind turbines (Søndergaard and Pedersen 2013; Yokoyama, Kobayashi, and Tachibana 2016). Factors such as tonal audibility, tonal frequency, and absolute SPL can affect how annoyance is perceived from wind turbines (Yokoyama, Kobayashi, and Tachibana 2016; Oliva, Hongisto, and Haapakangas 2017).

Yokoyama et al. (2016) investigated the effect of tonal audibility on annoyance and auditory impressions with levels from -3 dBA to 15 dBA using a 3 dB step based on IEC 61400-11 (IEC 61400-11:2012). They used five frequencies for investigating auditory impression, while only three frequencies for annoyance assessment. Increasing the tone level increased the perception of tonality in the tested stimuli. In addition, a signal with tonal audibility in the range of 6 - 8 dB was considered as definitely or considerably different (in terms of perceived perception) from signals without tonality. In addition, increasing tonal audibility increased the adjustment level that makes annoyance equal between tonal and non-tonal stimuli at 45 dBA. The level of adjustment was in the range of 0.2 - 6.1 dBA.

However, until lately, the potential effect of WFN tonality on human response has not received too much attention in listening tests. For example, the effect of WFN tonality on human response can be tested at different SPLs and frequencies, and including multiple tonality components at the same time, which may be different from the perception of only one tonal component. This type of investigations can show how the tonality penalties are dependent on the tonal frequency, SPLs and the tonal components.

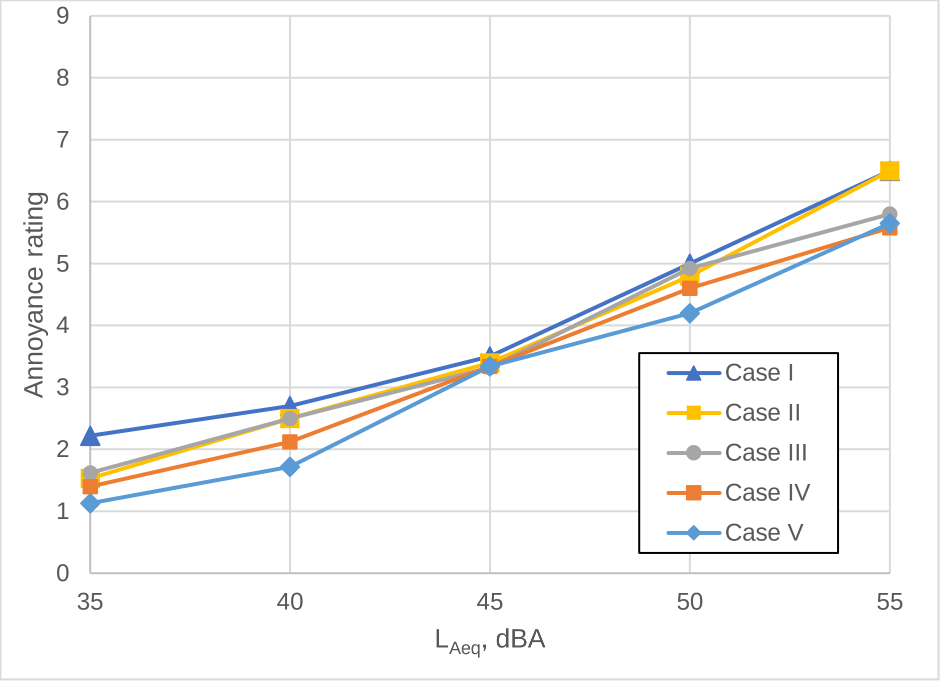
2.3 AM

AM of WFN can increase perceived annoyance significantly (Lee et al. 2011; Hünerbein et al. 2013). Therefore, various aspects of AM were investigated in listening tests including modulation depth, modulation frequency, and its temporal effects. Lee et al. (2011) used two samples in their listening tests recorded at a distance of 62 m from a wind turbine, in two different locations. A modulation frequency of 0.865 Hz was observed for the two samples. In this study, thirty participants were involved. In addition, for the annoyance rating of different modulation spectra, a numerical scale of annoyance ratings (an 11-point scale) was used. Annoyance ratings in their study are shown in fig. 2. It can be seen that SPLs were more significant on the perceived annoyance than modulation spectra.

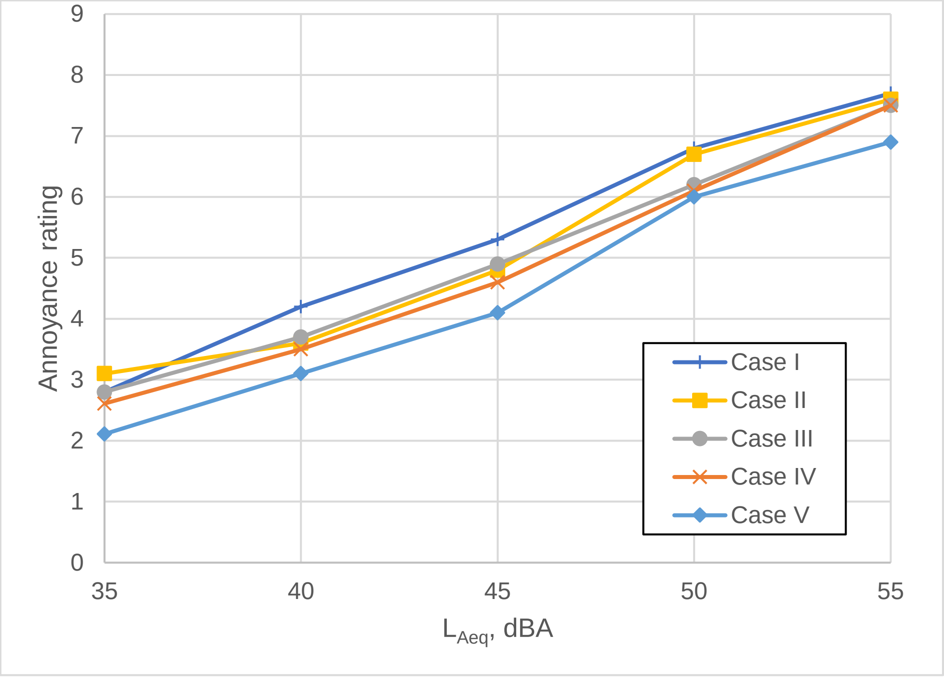
An 11-point scale was also used by Hünerbein et al. (2013) to rate annoyance. The signals were dominated by two frequency ranges, which were 200 - 600 Hz and 500 - 1000 Hz. Similar to Lee et al. (2011), the increase of SPL and modulation depth significantly increased annoyance ratings as shown in fig. 3. In addition, using the paired comparison method, annoyance ratings were less significant for modulation depths above 4 dBA as shown in fig. 4. Moreover, higher SPLs had lower level adjustments. This shows that modulation depth is more annoying at lower SPLs. However, in current penalties, this variability of adjustment with SPLs is not considered.

Perception of hearing and annoyance due to AM was studied by Yokoyama et al. (2013). Synthesised WFN was used with a general slope of -4 dB/octave, based on WFN measured between 252 m and 908 m from wind turbines. The increase of the modulation index increased the amount of adjustment. For instance, using WFN at a SPL of 45 dBA, the SPL was adjusted by 2.5 dBA at a modulation index of 10 dBA, whilst it was adjusted by 0.75 dBA at a modulation index of 2 dBA. Moreover, differences in annoyance ratings increased between participants at higher modulation indices. Furthermore, as shown in fig. 5, the sensation response of AM fluctuation began at about a modulation index of 1.85 dBA. A positive response of 50% of participants was at a modulation index of 2 dBA. Above a modulation index of 2.2 dBA, all participants could perceive a fluctuation sensation.

Ionandou et al. (2016) studied the effect of the modulation frequency, modulation depth and intermittence properties on the perceived human response. It was found that the modulation depth was the most annoying characteristic of WT AM. WFN signals filtered between 200 Hz to 1200 Hz, with a modulated frequency of 600 Hz, were used. AM was also classified as normal AM (NAM) and other AM (OAM). OAM is usually more intermittent and occurs at lower modulated frequencies with larger modulation depths than NAM. The effect of modulation frequency with intermittent AM periods was insignificant, compared to the modulation depth. However, using periodic characteristics of AM, Hünerbein et al. (2013) found that the modulation frequency affects perceived annoyance significantly in which increasing the modulation frequency increased the annoyance.



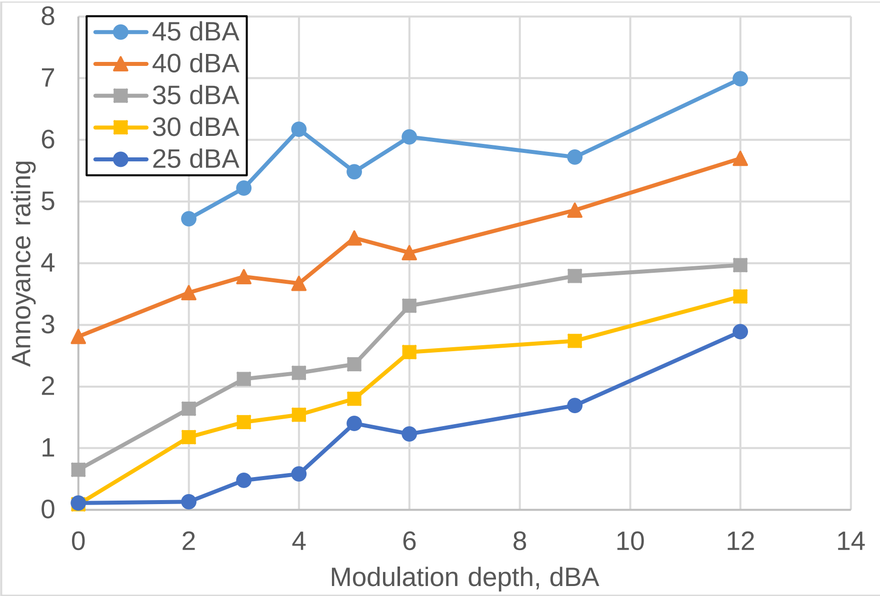
(a)



(b)

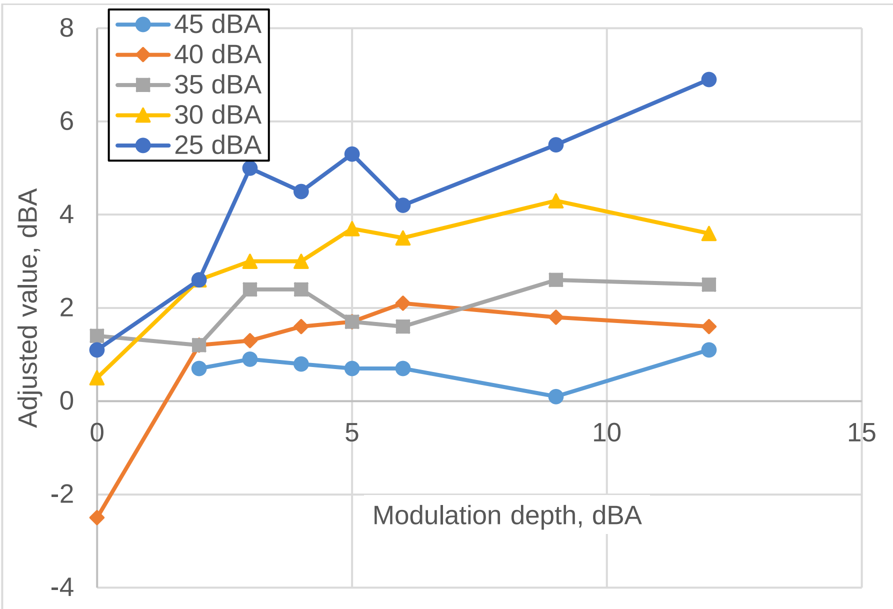
Source (Lee et al. 2011).

Figure 2: Annoyance ratings at different modulation spectra for (a) Sample 1 (b) Sample 2



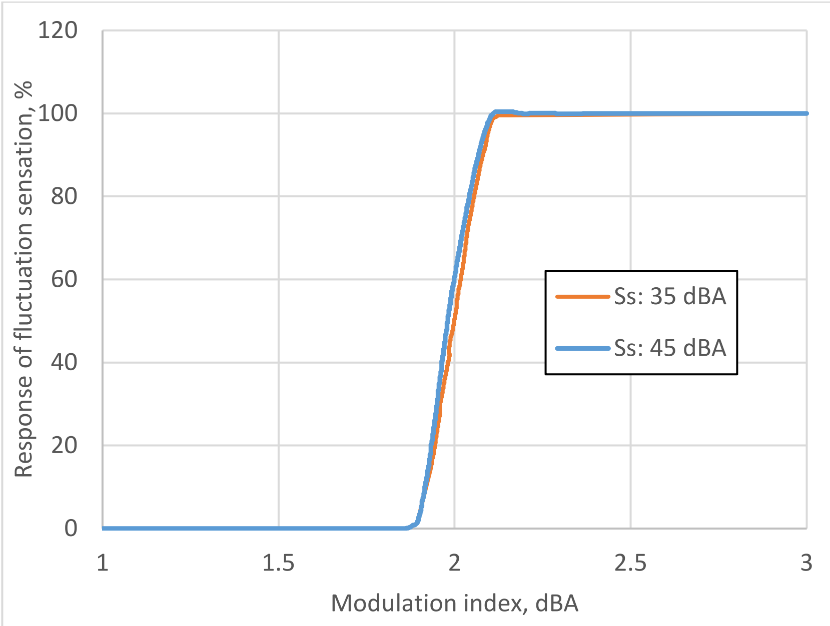
Source (Hünerbein et al. 2013)

Fig. 3. Annoyance ratings at different sound levels



Source (Hünerbein et al. 2013)

Fig. 4. The values of adjusted levels when comparing AM WFN and unmodulated WFN



Source (Yokoyama, Sakamoto, and Tachibana 2013)

Fig. 5. The percentage of fluctuation sensation response vs. modulation index

Available dose-response relationships of WFN do not consider the effect of different AM properties on perceived annoyance (i.e. modulation depth, modulation frequency, SPLs, and WFN spectra). Some limitations are found when quantifying AM such as the method of subject selection, and the limited studied variables. For instance, Ionandou et al. (2016) studied samples at one SPL only, and the Salford study (Hünerbein et al. 2013) did not include people with previous exposure history to WFN. Also, perceived annoyance from AM WFN below 200 Hz has not been studied. Understanding the effect of modulation frequency on the perceived annoyance with different SPLs and intermittence properties is also required.

3 WFN-RELATED SLEEP DISTURBANCE

Besides the perceived annoyance, WFN may affect human health and well-being as it may cause stress and sleep disruption (Schmidt and Klokker 2014). WFN is likely higher than the background noise during the night-time compared to the daytime, meaning that WFN may have an effect on sleep disturbance, especially at high SPLs (van den Berg 2005). However, there is a noticeable inconsistency regarding the effects of WFN on sleep (National Health and Medical Research Council 2015; Micic et al. 2018). Insignificant effects of WFN on sleep were reported in some studies (Michaud et al. 2013; Jalali et al. 2016), while another objective study has reported that WFN can have some effects on sleep (Smith et al. 2016).

Michaud et al. (2013) measured the objective sleep response due to WFN using actigraphy. Their results suggested that there were no significant effects of WFN on sleep. However, the actigraphy measures used in their measurements have some problems when classifying wake (Marino et al. 2013). Furthermore, the effects of LFN and infrasound on sleep were not quantified as they measured overall A-weighted levels only. Moreover, they modelled overall WFN SPLs using ISO 9613-1 and ISO 9613-2, and thus the presence or otherwise of the special WFN characteristics discussed in Section 2 are unknown.

Jalali et al. (2016) assessed the effect of WFN on sleep using before and after wind turbine installation measurements. The objective sleep measurements (in terms of measured polysomnography) showed that the effect of WFN on sleep was insignificant, while psychological factors like the attitude to wind turbines were deemed responsible for negative subjective sleep measurements. Moreover, whole night sleep parameters only were considered in this study and it was not reported whether specific acoustic events could have an effect on sleep. These specific events may have an effect on the macrostructure and microstructure of sleep, which could result in the development of chronic insomnia over time (Micic et al. 2018). Frequent physiological activation responses and arousals could have an effect on the microstructure of sleep, while the reduced time of sleep affects the macro-structure of sleep.

Nevertheless, Smith et al. (2016) showed that WFN at high SPLs containing AM can have an effect on sleep in a more controlled environment of WFN characteristics through listening tests. However, the number of participants was limited to six. Furthermore, the sleep measurements due to different WFN characteristics were not quantified in a systematic way. Moreover, the development of WFN dose-response relationships for sleep has not been attempted before, meaning that further quantification studies in that area are needed.

4 DISCUSSION

The evidence regarding the potential effect of WFN on daytime annoyance and night-time sleep disturbance is still not well established (Council of Canadian Academies 2015). Establishing the exact effect of WFN on human response can help develop acceptable penalties regarding WFN. Although listening tests play an important role in the quantification of human response to WFN characteristics, far too little attention has been paid to quantification of some parameters that could have a different perceived human response. For example, the effect of modulated broadband spectra dominated by a frequency content below 200 Hz on human response still needs further research.

Moreover, further quantification methods of annoyance and sleep disturbance can be adopted. For example, separating WFN characteristics (i.e. LFN and infrasound, AM and tonality) systematically can be quite helpful to precisely investigate the relative effect of these characteristics on human response. Moreover, the absolute values of acceptable threshold levels (ATLs) such as those obtained by Moorhouse et al. (2005) can then be identified. Furthermore, combining these effects into one study allows identification of the most disturbing WFN characteristic or combination of characteristics.

In addition to WFN characteristics, other human modifiers including the visibility of wind turbine, sensitisation of participants, the existence of economic benefits, problems of recollection, and attitudes to wind turbines can affect human response to WFN (Janssen et al. 2011). Through listening tests, the most effective element of these human factors and each element contribution to perceived annoyance can be investigated through a systematic approach taking into account separating all of these factors. Szychowska et al. (2018) investigated how audio and visual stimuli can affect perceived annoyance. They found that the most significant factor was the SPL of stimuli; after that the visual effects; and then the audio sample characteristics (besides WFN, natural and transportation noise samples were included). However, many of the WFN characteristics were not tested systematically. Moreover, many other human factors such as sensory acuity and attitudes were not appropriately addressed as they only studied the effect of visual modifiers.

5 CONCLUSIONS

This paper has reviewed the human response quantification methods used in WFN listening tests. The results of this review indicate that further investigation and experimentation into the quantification of human response is recommended. A number of possible future studies using listening tests is suggested as follows,

- The human response due to AM LFN needs further work, especially at modulated spectra below 200 Hz.
- Further studies are needed for establishing the effect of tonality, LFN, and infrasound on human response.
- Additional studies are needed to investigate the WFN dose-response relationship for sleep disruption. Moreover, in future research, a greater focus on objective sleep measurements is recommended.
- Some methodological approaches such as isolating WFN characteristics and human factors can be adopted in listening tests to determine the potential effect of each factor on human response and the order of their impact.

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