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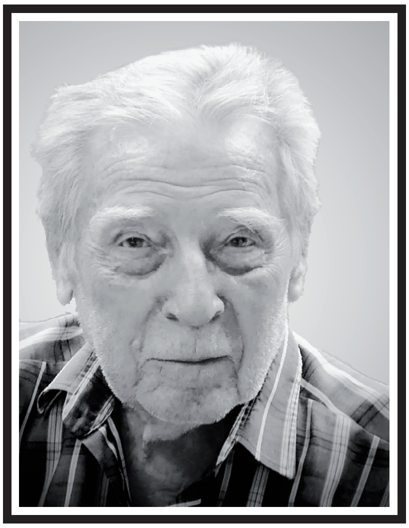
ročník 26, číslo 1–4 prosinec 2020

Obsah

ČESKÁ AKUSTICKÁ SPOLEČNOST

Vážené kolegyně, vážení kolegové,

je to již drahně let, kdy byl otištěn poslední prezidentský sloupek. Mým cílem není tuto tradici obnovit, nicméně současná situace si nějaký vzkaz žádá. Především se musím zmínit o 100. akustickém semináři. Vzhledem ke kulatosti čísla jsme se snažili dát semináři důstojný formát, zařadit přednášky jak odborné, tak vzpomínkové a také zvolit odpovídající doprovodný program. Když nás jarní vlna pandemie přinutila seminář posunout, říkali jsme si, že alespoň bude více času na přípravu a na podzim bude vše ještě propracovanější. Nyní máme připravený termín na jaro 2021, ale při sledování zpráv si nejsem jist, že je definitivní, stejně tak lokalita se může kvůli krizi podobných zařízení změnit. Sledujte prosím webové stránky společnosti, kde se budeme snažit uveřejňovat aktuální informace, a pokud máte nějaký odborný příspěvek, nezapomeňte jej přihlásit.



V tomto roce jsme měli slavit *Mezinárodní rok zvuku* (International Year of Sound 2020). Mezinárodní akustické společenství věnovalo této akci enormní úsilí, nyní se ale můžeme jen smutně dívat, jak jsou jednotlivé akce přesouvány, rušeny nebo převáděny na on-line verze. Tak například největší evropská konference *Forum Acusticum*, která se měla konat v Lyonu, je přejmenována na *e-Forum Acusticum* a organizátorům teď nezbývá než se snažit zachránit, co se dá. Doufejme jen, že to neznamená konec sociální role takovýchto akcí, která je mnohdy srovnatelně důležitá jako ta vědecká.

Koronavirová krize zasáhla i do naší členské základny. Kvůli zrušeným seminářům totiž mnoho členů nezaplatilo své členské příspěvky, a tím *de jure* vypadli z řad členů společnosti. Doplaťte prosím své členské příspěvky a my vám za to slibujeme, že se od příštího roku budeme snažit vrátit vše do původních kolejí.

I v této době běží život neúprosně dál, a tak mám bohužel smutnou povinnost vám sdělit, že česká akustická komunita přišla o dva významné členy. Prvním byl Ing. Zdeněk Kešner, CSc., který zesnul 21. dubna 2020 ve věku 88 let. Jeho akustická pouť vedla od Výzkumného ústavu zvukové, obrazové a reprodukční techniky (VÚZORT), kde strávil většinu svého odborného života, do Paláce kultury, kde vedl zvukové oddělení až do odchodu do důchodu. V rámci České akustické společnosti dlouhá léta předsedal odborné skupině Elektroakustika. Neméně významné bylo jeho působení v české pobočce Audio Engineering Society. Pod hlavičkou obou společností uspořádal Ing. Kešner řadu seminářů a pozval i několik významných odborníků k přednášce pro české akustiky.

Dne 10. května nás ve věku 83 let opustil Ing. Alois Melka, CSc., klíčová osobnost české psychoakustiky. Ing. Melka započal svoji vědeckou dráhu ve Výzkumném a vývojovém ústavu elektroakustiky, kde pod vedením prof. Merhauta začal se systematickou prací v tehdy mladém oboru psychoakustiky. Již v té době bylo jeho doménou subjektivní hodnocení různých typů zkreslení při přenosu zvukového signálu. Později přešel do Výzkumného ústavu sdělovací techniky, kde se věnoval hodnocení kvality zvuku reproduktorových soustav. Významnou část svého profesního života strávil ve Výzkumném ústavu zvukové, obrazové a reprodukční techniky, kde pracoval na hodnocení akustické kvality předních pražských koncertních sálů poslechovými testy a později se věnoval hodnocení zvukové kvality žesťových nástrojů a následně i houslí. V devadesátých letech přešel do Akustiky Praha, kde pokračoval v systematické práci na hodnocení kvality různých zdrojů zvuku včetně těch rušivých. Jeho stopu lze nalézt také ve Zvukovém studiu Hudební fakulty AMU, kde vedl výzkum percepčních účinků digitálních prostorově akustických efektů, které se používají při finálních úpravách studiových nahrávek. Jeho služeb využívali i ve vývoji Škoda Auto, a. s., kde připravoval experimenty pro hodnocení vnitřní akustiky automobilů. Ing. Alois Melka je autorem desítek výzkumných zpráv a článků. Svoje znalosti pak shrnul v knize *Základy experimentální psychoakustiky*, která je nejen vynikající učebnicí, ale představuje také téměř úplný popis principů a metod používaných v hodnocení kvality zvuku.

V obou pánech ztrácí česká akustika velké osobnosti, které se podílely na rozvoji akustiky v Čechách. Čest jejich památce!

Klidné vánoční svátky a hodně zdraví do nového roku přeje

Ondřej Jiříček

Akustické listy, **26**(1–4), prosinec 2020, str. 5–9

Extension of the Simplified Method for Estimating Sound Insulation between Rooms in Buildings

Rozšíření zjednodušeného způsobu odhadu zvukové izolace mezi místnostmi v budovách

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The new simplified method for estimating the flanking airborne and impact sound transmission between rooms in residential buildings was published in 2014. It is based on the theoretical models described in parts 1 and 2 of the technical standards ČSN EN ISO 12354. This method enables quick estimation of *in situ* sound insulation in buildings with common building elements. Recent activities have extended its possible use to include walls and floors with acoustic linings (both on separating or flanking elements). This paper describes the principle of extension and provides examples of its application to typical building situations. It is shown that the resulting theoretical airborne or impact sound insulation improvement by additional lining depends dramatically on the degree of flanking transmission in the original situation. This finding would provide particularly important information for an accurate design when the laboratory data of improvement are used.

1. Introduction

In 2014, the new theoretical method for estimating the corrections for *in situ* flanking transmission of airborne and impact sound was presented in Reference [4]. The idea was to propose a design procedure significantly easier for practical use than the complex calculation models according to ČSN EN ISO 12354-1 and -2 [2, 3], but still general and accurate. The empirical values given in ČSN 73 0532 [1] are representative only for a small number of typical building situations.

As described in Reference [4], the weighted apparent sound reduction index R'_w can be estimated from the weighted (laboratory) sound reduction index R_w of the separating element according to formula

$$R'_\mathrm{w} = R_\mathrm{w} - k_{R_\mathrm{w}}, \tag{1}$$

where k_{R_w} is the correction in decibels for flanking sound transmission (via all paths), calculated from equation (new method)

$$k_{R_\mathrm{w}} = 10\lg\left[(1-n) + \sum_{i=1}^{n} 10^{k_{R_{\mathrm{w},i}}/10}\right], \tag{2}$$

where n is the number of flanking paths (usually $n = 4$) and $k_{R_{\mathrm{w},i}}$ is the correction of weighted (laboratory) sound

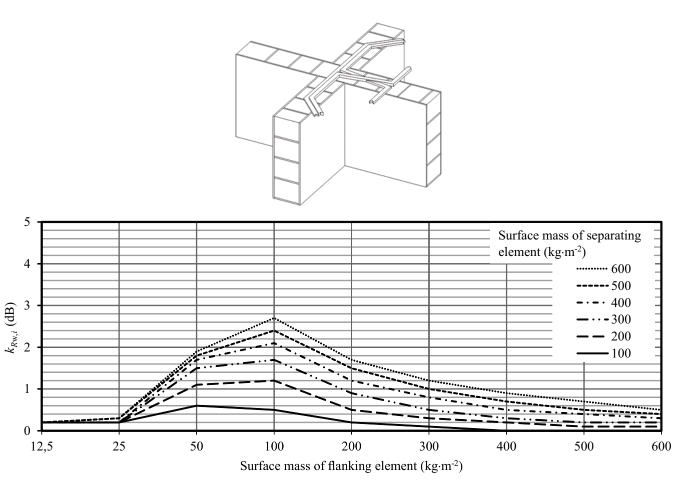

Figure 1: Correction $k_{R_{\mathrm{w},i}}$ (dB) of the weighted sound reduction index R_w for a rigid X-juction (*example*)

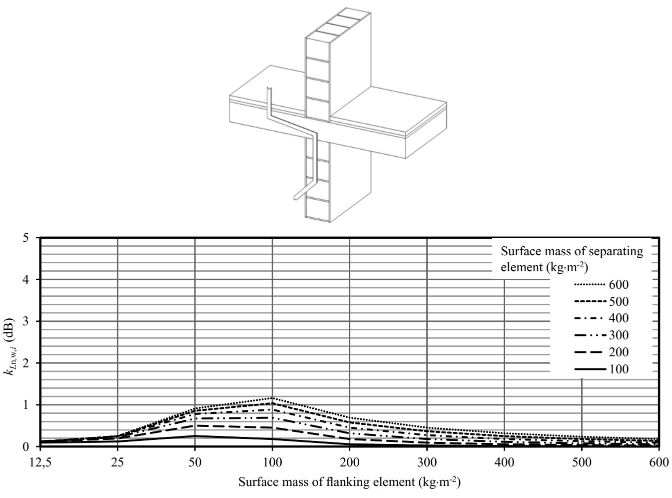

Figure 2: Correction $k_{L_{n,\mathrm{w},i}}$ (dB) of the weighted normalized impact sound pressure level $L_{n,\mathrm{w}}$ for a rigid X-juction (*example*)

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reduction index R_w caused by flanking path i. In Reference [4], theoretical values of $k_{R_{\mathrm{w},i}}$ for two examples of rigid X- and T-junctions were presented in tables. However, for easier work it is more convenient to provide them graphically as shown here in Figure 1.

Similarly to the sound reduction index, for the weighted normalized impact sound pressure level $L'_{n,\mathrm{w}}$ it follows that

$$L'_{n,\mathrm{w}} = L_{n,\mathrm{w}} + k_{L_{n,\mathrm{w}}}, \tag{3}$$

where $k_{L_{n,\mathrm{w}}}$ is the correction in decibels for flanking impact sound transmission (via all paths), calculated from equation (new method)

$$k_{L_{n,\mathrm{w}}} = 10 \lg \left[(1-n) + \sum_{i=1}^{n} 10^{k_{L_{n,\mathrm{w},i}}/10} \right], \tag{4}$$

where n is again the number of flanking paths (usually $n = 4$) and $k_{L_{n,\mathrm{w}}}$ is the correction of the weighted (laboratory) normalized impact sound pressure level $L_{n,\mathrm{w}}$ caused by flanking path i.

2. Improvement of airborne sound insulation by additional layers

In the following text, the term *additional layer* is used for layers resiliently mounted to basic single structural elements. Such layers are plasterboard wall linings or suspended ceilings. The improvement of the sound reduction index could either be measured in the laboratory or calculated. In principle, it is different for flanking and separating elements and depends on the sound reduction index of the basic structure. As an estimate, according to Reference [2] the improvement for flanking transmission can be assumed as equal to that for direct airborne transmission. If it is not available from laboratory measurements, it can be estimated for the resonant frequency f_0 between 30 Hz and 160 Hz using formula

$$\Delta R_\mathrm{w} = 74{,}4 - 20 \lg(f_0) - R_\mathrm{w}/2, \tag{5}$$

where R_w is the weighted sound reduction index of a homogeneous basic element (wall or floor). For common one-sided plasterboard additional layers with air cavities at least 50 mm thick and filled with porous absorbing material ($r' \geq 5$ kPa·s·m^{-2}), calculated ΔR_w reaches values between 15 dB and 25 dB.

2.1. Acoustic linings on separating homogeneous elements

From the acoustical point of view, a combination of single building elements with lightweight lining can be very effective. Increasing the thickness of the structure by several centimeters may lead to an improvement in the direct weighted sound reduction index of more than 15 dB as described in Section 2 (compared to an approximate increase of 6 dB when the thickness of the basic element is doubled). However, although the effect of the lining on direct sound transmission is strong, the question is how it may change the apparent sound reduction index R'_w, in which flanking transmission is also included.

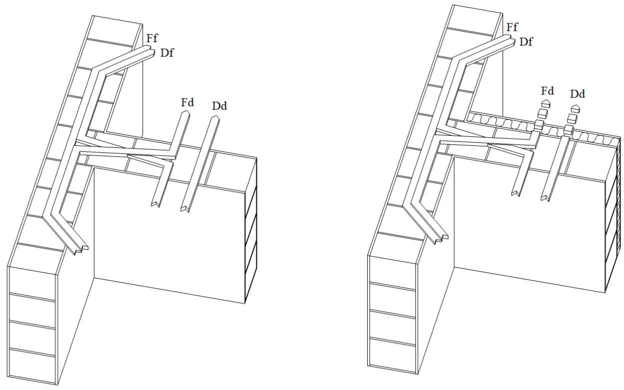

Figure 3: Sound transmission through a junction without and with acoustic lining on the separating (direct) element

First of all, it can assumed that the effect of lining on flanking transmission is negligible, because the flanking walls and floors remain unchanged. Although the assumption is not invariably true (as illustrated in Figure 3 for path Fd), it is useful for further steps.

According to Reference [4], the weighted apparent sound reduction index $R'_{\mathrm{w},i,\mathrm{A}}$ for sound transmission between two rooms via the direct path R_w and all three flanking paths through one junction "i", $R_{\mathrm{w},i}$, can be written as

$$R'_{\mathrm{w},i,\mathrm{A}} = -10 \lg \left(10^{-R_\mathrm{w}/10} + 10^{-R_{\mathrm{w},i}/10} \right) = R_\mathrm{w} - k_{R_{\mathrm{w},i,\mathrm{A}}}, \tag{6}$$

where the letter A in subscript means the situation without acoustic lining. Similarly, for situation B with acoustic lining the following applies

$$R'_{\mathrm{w},i,\mathrm{B}} \approx -10 \lg \left(10^{-(R_\mathrm{w}+\Delta R_\mathrm{w})/10} + 10^{-R_{\mathrm{w},i}/10} \right) = R_\mathrm{w} + \Delta R_\mathrm{w} - k_{R_{\mathrm{w},i,\mathrm{B}}}, \tag{7}$$

By combining equations (6) and (7), we obtain the following formula

$$k_{R_{\mathrm{w},i}} = k_{R_{\mathrm{w},i,\mathrm{B}}} = 10 \lg \left(1 - \frac{1 - 10^{k_{R_{\mathrm{w},i,\mathrm{A}}}/10}}{10^{-\Delta R_\mathrm{w}/10}} \right), \tag{8}$$

where $k_{R_{\mathrm{w},i,\mathrm{A}}}$ is the correction for flanking transmission calculated (or measured) for situation A (without acoustic lining) and ΔR_w is the weighted improvement of the sound reduction index of the separating element. This equation demonstrates that the acoustic lining is much more effective in such a situation A, where the direct sound transmission dominates (i.e. $k_{R_{\mathrm{w},i,\mathrm{A}}}$ is small).

Nevertheless, it needs to be mentioned that equation (8) systematically overestimates the flanking transmission, as a consequence of the initial simplification. In order to solve this problem, the detailed calculations of $k_{R_{\mathrm{w},i}}$ have been made with and without path Df for X- and T-shaped junctions, surface mass of building elements from 50 kg·m^{-2} to 600 kg·m^{-2} and ΔR_w from 2.5 dB to 25 dB (total 840 results). The ratio of $k_{R_{\mathrm{w},i}}$ with and without ΔR_w included in Df varied from 75 % to 92 % with the average value 84 %. Therefore, the formula (8) can be adapted to

$$k_{R_{\mathrm{w},i}} \approx 8\lg\left(1 - \frac{1 - 10^{k_{R_{\mathrm{w},i,\mathrm{A}}}/10}}{10^{-\Delta R_\mathrm{w}/10}}\right). \qquad (9)$$

Example 1

The separating wall is a single masonry wall with surface mass $m'_\mathrm{d} = 150$ kg·m^{-2} and $R_\mathrm{w} = 46$ dB. The floor is a concrete plate with surface mass $m'_\mathrm{f1} = m'_\mathrm{f2} = 500$ kg·m^{-2} (f2 with a heavyweight floating floor). Both inner wall f3 and facade f4 weight 250 kg·m^{-2}.

path No. 1 (X-junction, $m'_\mathrm{f1} = 500$ kg·m^{-2}):
$k_{R_{\mathrm{w},1,\mathrm{A}}} = 0.1$ dB
path No. 2 (X-junction, $m'_\mathrm{f2} = 500$ kg·m^{-2}):
$k_{R_{\mathrm{w},2,\mathrm{A}}} = 0.0$ dB
path No. 3 (X-junction, $m'_\mathrm{f3} = 250$ kg·m^{-2}):
$k_{R_{\mathrm{w},3,\mathrm{A}}} = 0.3$ dB
path No. 4 (T-junction, $m'_\mathrm{f4} = 250$ kg·m^{-2}):
$k_{R_{\mathrm{w},4,\mathrm{A}}} = 0.5$ dB

$$k_{R_{\mathrm{w},\mathrm{A}}} = 10\lg\Big[(1-4) + 10^{0.1/10} + 10^{0.0/10} + 10^{0.3/10} + 10^{0.5/10}\Big] = 0.9 \text{ dB}$$

$$R'_{\mathrm{w},\mathrm{A}} = R_\mathrm{w} - k_{R_{\mathrm{w},\mathrm{A}}} = 46 - 0.9 = 45.1 \text{ dB}$$

After applying an acoustic lining to the separating element, the laboratory sound reduction index is improved by $\Delta R_\mathrm{w} = 15$ dB. However, the apparent sound reduction index is controlled by flanking transmission as follows

path No. 1:
$k_{R_{\mathrm{w},1,\mathrm{B}}} = 8\lg[1 - (1 - 10^{0.1/10})/10^{-15/10}] = 1.9$ dB
path No. 2:
$k_{R_{\mathrm{w},2,\mathrm{B}}} = 8\lg[1 - (1 - 10^{0.0/10})/10^{-15/10}] = 0.0$ dB
path No. 3:
$k_{R_{\mathrm{w},3,\mathrm{B}}} = 8\lg[1 - (1 - 10^{0.3/10})/10^{-15/10}] = 4.1$ dB
path No. 4:
$k_{R_{\mathrm{w},4,\mathrm{B}}} = 8\lg[1 - (1 - 10^{0.5/10})/10^{-15/10}] = 5.5$ dB

$$k_{R_{\mathrm{w},\mathrm{B}}} = 10\lg\Big[(1-4) + 10^{1.9/10} + 10^{0.0/10} + 10^{4.1/10} + 10^{5.5/10}\Big] = 7.5 \text{ dB}$$

$$R'_{\mathrm{w},\mathrm{B}} = R_\mathrm{w} + \Delta R_\mathrm{w} - k_{R_{\mathrm{w},\mathrm{B}}} = 46 + 15 - 7.5 = 53.5 \text{ dB}$$

The results indicate that in situation A, the percentage of sound transmitted via direct path is 81 %, while for flanking it is only 19 %. When the acoustic lining is applied to a separating element (situation B), the ratio is almost opposite (18 % for the direct to 82 % for the flanking).

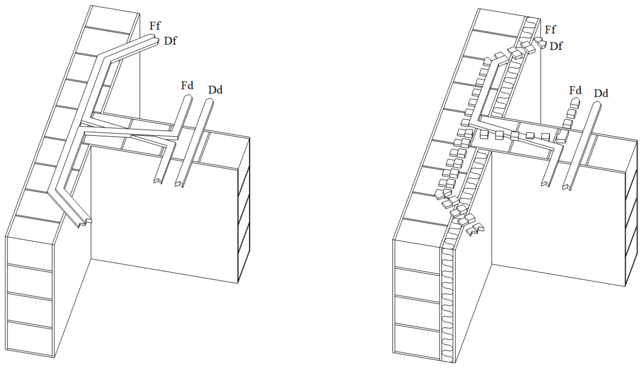

Figure 4: Sound transmission through a junction without and with acoustic lining on flanking elements

2.2. Acoustic lining on flanking homogeneous elements

Sometimes, the apparent sound reduction index between rooms is limited by flanking transmission. For example, this occurs when subtle homogeneous elements from the source room continue into the receiving room. In such cases, it may be advantageous to increase the sound reduction index of both flanking elements by applying an acoustic lining, as shown in Figure 4.

While in the original situation $R'_{w,i,A}$ follows equation (6), which can be rewritten to the following detailed formula

$$R'_{\mathrm{w},i,\mathrm{A}} = -10\lg\Big[10^{-R_\mathrm{w}/10} + 10^{-R_{\mathrm{w},i,\mathrm{Fd}}/10} + 10^{-R_{\mathrm{w},i,\mathrm{Ff}}/10} + 10^{-R_{\mathrm{w},i,\mathrm{Df}}/10}\Big] = R_\mathrm{w} - k_{R_{\mathrm{w},i,\mathrm{A}}}, \quad (10)$$

after application of an additional lining it changes to

$$R'_{\mathrm{w},i,\mathrm{B}} \approx -10\lg\Big[10^{-R_\mathrm{w}/10} + 10^{-(R_{\mathrm{w},i,\mathrm{Fd}}+\Delta R_\mathrm{w})/10} + 10^{-(R_{\mathrm{w},i,\mathrm{Ff}}+1.5\Delta R_\mathrm{w})/10} + 10^{-(R_{\mathrm{w},i,\mathrm{Df}}+\Delta R_\mathrm{w})/10}\Big] = R_\mathrm{w} - k_{R_{\mathrm{w},i,\mathrm{B}}}. \quad (11)$$

For homogeneous separating elements, all three flanking paths Fd, Ff and Df shall be taken into account, but the second lining for path Ff can be neglected without significant loss of accuracy (i.e. number 1.5 is then omitted in equation (11)). By combining equations (10) and (11), we obtain

$$k_{R_{\mathrm{w},i}} = k_{R_{\mathrm{w},i,\mathrm{B}}} = 10\lg\Big[1 + 10^{-\Delta R_\mathrm{w}/10}\Big(10^{k_{R_{\mathrm{w},i,\mathrm{A}}}/10} - 1\Big)\Big]. \qquad (12)$$

For the sake of completeness, it should be pointed out that without omitting the second lining for path Ff the flanking correction $k_{R_{\mathrm{w},i}}$ is on average 76 % of that one calculated using equation (12). This comes from the detailed 840 calculations similar to those described in Section 2.1. However, in the case of acoustic linings on flanking elements $k_{R_{\mathrm{w},i}}$ is very small and varies only between 0 dB and 0.5 dB for properly designed lining (let's say with $\Delta R_\mathrm{w} > 10$ dB), so the resulting effect of previous simplification on $k_{R_{\mathrm{w},i}}$ is negligible.

For lightweight multilayered separating elements (e.g. plasterboard walls) with homogeneous flanking elements, the dominant flanking path is Ff and the remaining two paths (Fd and Df) can be neglected [2]. In such a case, equation (12) is changed to

$$k_{R_{\mathrm{w},i}}=k_{R_{\mathrm{w},i,\mathrm{B}}}=10\lg\left[1+10^{-1.5\cdot\Delta R_\mathrm{w}/10}\left(10^{k_{R_{\mathrm{w},i,\mathrm{A}}}/10}-1\right)\right]. \qquad (13)$$

Example 2

The separating wall is a single masonry wall with surface mass $m'_\mathrm{d} = 300$ kg·m^{-2} and $R_\mathrm{w} = 57$ dB. The floor is again a concrete plate with surface mass $m'_\mathrm{f1} = m'_\mathrm{f2} =$ 500 kg·m^{-2} (f2 with a heavyweight floating floor). The inner partition f3 weighs 100 kg·m^{-2} and facade wall f4 has 300 kg· m^{-2}.

path No. 1 (X-junction, $m'_\mathrm{f1} = 500$ kg·m^{-2}):
$$k_{R_{\mathrm{w},1,\mathrm{A}}} = 0.2 \text{ dB}$$
path No. 2 (X-junction, $m'_\mathrm{f2} = 500$ kg·m^{-2}):
$$k_{R_{\mathrm{w},2,\mathrm{A}}} = 0.1 \text{ dB}$$
path No. 3 (X-junction, $m'_\mathrm{f3} = 100$ kg·m^{-2}):
$$k_{R_{\mathrm{w},3,\mathrm{A}}} = 1.7 \text{ dB}$$
path No. 4 (T-junction, $m'_\mathrm{f4} = 250$ kg·m^{-2}):
$$k_{R_{\mathrm{w},4,\mathrm{A}}} = 1.0 \text{ dB}$$

$$k_{R_{\mathrm{w},\mathrm{A}}} = 10\lg\Big[(1-4)+10^{0.2/10} +10^{0.1/10}+10^{1.7/10}+10^{1.0/10}\Big] = 2.6 \text{ dB}$$

$$R'_{\mathrm{w},\mathrm{A}} = R_\mathrm{w} - k_{R_{\mathrm{w},\mathrm{A}}} = 57 - 2.6 = 54.4 \text{ dB}$$

After applying an acoustic lining to the flanking element f3 with the laboratory sound reduction index improvement ΔR_w=15 dB, the correction $k_{R_{\mathrm{w},3}}$ changes to

path No. 3:
$$k_{R_{\mathrm{w},3,\mathrm{B}}} = 10\lg[1+10^{-15/10}(10^{1.7/10}-1)] = 0.1 \text{ dB}$$

$$k_{R_{\mathrm{w},\mathrm{B}}} = 10\lg\Big[(1-4)+10^{0.2/10} +10^{0.1/10}+10^{0.1/10}+10^{1.0/10}\Big] = 1.3 \text{ dB}$$

$$R'_{\mathrm{w},\mathrm{B}} = R_\mathrm{w} - k_{R_{\mathrm{w},\mathrm{B}}} = 57 - 1.3 = 55.7 \text{ dB}$$

In Example 2, the amount of direct and flanking transmission is almost the same (55 % and 45 %) for situation A. After application of the acoustic lining to the flanking elements (path No. 3) the percentage of flanking sound is reduced to 26 %.

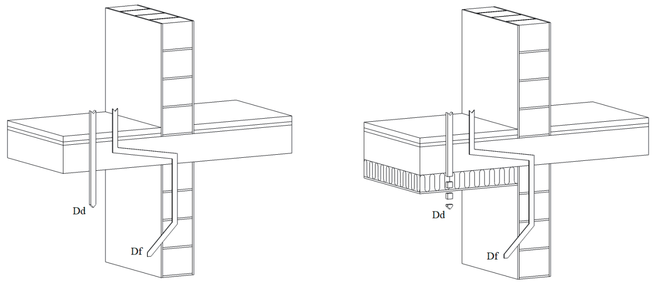

Figure 5: Transmission of impact sound through a floor without and with suspended ceiling

3. Improvement of impact sound insulation by suspended ceilings

The flanking transmission of impact sound in buildings is often considered insignificant compared with the airborne sound. Reference [1] recommends using the correction for flanking impact sound transmission between 0 dB and 2 dB. However, when the suspended ceiling is used below the floor, the importance of flanking transmission increases. This is due to the fact that with the suspended ceiling only the direct sound is suppressed, while the flanking sound remains almost the same. This process is illustrated in Figure 5.

In situation A without a suspended ceiling, the weighted normalized impact sound pressure level can be calculated using the formula

$$L'_{\mathrm{n,w,A}} = 10\lg\left(10^{L_\mathrm{n,w}/10}\sum_{i=1}^{n}10^{L_{\mathrm{n},i,\mathrm{w}}/10}\right) = L_\mathrm{n,w} + k_{L_\mathrm{n,w,A}}. \qquad (14)$$

After applying the suspended ceiling (situation B), equation (14) can be written as

$$L'_{\mathrm{n,w,B}} = 10\lg\left(10^{(L_\mathrm{n,w}-\Delta L_\mathrm{d,w})/10}+\sum_{i=1}^{n}10^{L_{\mathrm{n},i,\mathrm{w}}/10}\right) = L_\mathrm{n,w} - \Delta L_\mathrm{d,w} + k_{L_\mathrm{n,w,B}}, \qquad (15)$$

where $\Delta L_\mathrm{d,w}$ is the weighted reduction of impact sound pressure of an additional layer on the receiving side of the separating element, usually approximated by the sound reduction improvement index ΔR_w. By combining equations (14) and (15), we obtain

$$k_{L_\mathrm{n,w}} = k_{L_\mathrm{n,w,B}} = 10\lg\left(1+\frac{10^{k_{L_\mathrm{n,w,A}}/10}-1}{10^{-\Delta R_\mathrm{w}/10}}\right). \qquad (16)$$

Example 3

The separating horizontal element is a single concrete slab $m'_{\mathrm{d}} = 500\ \mathrm{kg{\cdot}m^{-2}}$ with a heavy floating floor ($L_{\mathrm{n,w}} = 40$ dB). All flanking structures are masonry walls with $m'_{\mathrm{f}} = 250\ \mathrm{kg{\cdot}m^{-2}}$ rigidly connected to the slab.

paths No. 1–3 (X-junctions, $m'_{\mathrm{f}} = 250\ \mathrm{kg{\cdot}m^{-2}}$):
$k_{L_{\mathrm{n,w,1-3,A}}} = 0.5$ dB
path No. 4 (T-junction, $m'_{\mathrm{f4}} = 250\ \mathrm{kg{\cdot}m^{-2}}$):
$k_{L_{\mathrm{n,w,4,A}}} = 0.9$ dB

$$k_{L_{\mathrm{n,w,A}}} = 10 \lg \Big[(1-4) + 10^{0.5/10} + 10^{0.5/10} + 10^{0.5/10} + 10^{0.9/10}\Big] = 2.0 \text{ dB}$$

$$L'_{\mathrm{n,w,A}} = L_{\mathrm{n,w}} + k_{L_{\mathrm{n,w,A}}} = 40 + 2.0 = 42.0 \text{ dB}$$

After applying a suspended ceiling below the concrete slab, the laboratory normalized impact sound pressure level is improved by approximately $\Delta R_{\mathrm{w}} = 15$ dB. However, the *in situ* impact sound pressure level is controlled by flanking transmission as follows

$$k_{L_{\mathrm{n,w,B}}} = 10 \lg \left(1 + \frac{10^{2.0/10} - 1}{10^{-15/10}}\right) = 12.9 \text{ dB}$$

$$L'_{\mathrm{n,w,B}} = L_{\mathrm{n,w}} - \Delta R_{\mathrm{w}} + k_{L_{\mathrm{n,w,B}}} = 40 - 15 + 12.9 = 37.9 \text{ dB}$$

The results show that in situation A, the percentage of impact sound transmitted via direct path is 63 %, while for flanking it is 37 %. After application of the suspended ceiling below the separating element (situation B), the direct path is almost canceled and the percentage of flanking impact sound rises up to 95 %.

4. Conclusions

Extension of the simplified method for estimating sound insulation between rooms in buildings described in this paper significantly improves its applicability to building elements fitted with acoustic linings.

It was illustrated that corrections for flanking transmission may be very high in such situations, which means that the flanking transmission dominates (for $k = 3$ dB flanking is 50 % of total). Therefore, it is particularly important for accurate design to focus on the prediction of all flanking paths with equal or greater care as that given to the direct path.

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A Comparison of Sharpness Evaluation Models

Porovnání modelů hodnocení ostrosti zvuku

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In this paper, the psychoacoustic quantity of sharpness is discussed and three models which can objectively evaluate it. The motivation for this research is to compare several methods of sharpness evaluation and find the differences as it is difficult to say which is the best. The models that were proposed by Fastl, the German standard and the method from Musical Acoustics Research Centre (MARC) in Prague were tested for this paper. Different sounds including bandpass noise, traffic, speech and non-sinusoidal waveforms were tested on each model in MATLAB. Narrowband noises rose in sharpness at a faster rate than broadband noises. The MARC method returned higher values of sharpness than the Fastl method throughout while the German standard gave the highest sharpness at high frequency bands. The MARC method appeared to give results closer to the standard. Comparisons were made between the algorithms and variations discussed so that we can gain a deeper insight into psychoacoustics and sound quality.

1. Introduction

Sharpness is one of the psychoacoustic metrics necessary for objective evaluation of sound quality of products from common tools, from noisy equipment to musical instruments. Models from varying authors will be investigated. The details and procedures of a relevant sharpness test will be discussed where three models were implemented in MATLAB. Various real world sounds and noises were input to the models so that comparisons could be drawn between proposed methods and the German standardised model for sharpness. The German standard has the advantage of being standardised for a relatively long time so has enough results for comparison, however, it is not exact. There are other possibilities and it is difficult to say which is best. Ultimately, this report aims at continuing work on comparing psychoacoustic models [1], providing a foundation for finding models for sharpness and delving deeper into an accurate representation of the quantity.

In order to understand the sharpness, loudness is a quantity that should be considered first. Loudness level is a quantity measured in phons. X phons means "as loud as X dB at a pure tone of 1000 Hz". The sone is a unit for loudness that describes a linear perception compared to the logarithmic scale of phon. In order to measure loudness, we must define critical bands, which is the minimal frequency band pass noise necessary for masking of the pure tone of the centre frequency. This makes it easier to analyse psychoacoustic relationships to frequency by transforming the frequency scale in Hz to the bark scale (critical band rate) so we can analyse loudness and sharpness.

The sharpness models that will be discussed later include an integration of specific loudness (sones/Bark) which measures the loudness over the transformed frequency scale.

2. Sharpness Models

The psychoacoustic quantity of sharpness describes a portion of higher frequencies in a sound. Generally, the more higher frequencies contained in a spectral envelope, the sharper it appears and therefore it is less pleasant to listen to. Sharpness does not have a global standardised unit of measurement, however Zwicker and Fastl coined the *acum* (Latin for sharp). 1 acum is defined as a narrowband noise, one critical band wide with a centre frequency of 1 kHz and a sound pressure level of 60 dB [2]. The sharpness of a sound can be thought to be similar to the spectral centroid of a sound, balanced by high and low frequencies [3]. Applications of this psychoacoustic quantity can be in automobile sounds as well as in domestic appliances like hair dryers or vacuum cleaners [4].

The main factors that decide the sharpness of a sound include the spectral content, (especially at higher frequencies) the centre frequency of a bandpass signal and the bandwidth.

Figure 1 shows the sharpness of three functions against the critical-band rate. Each function has a varying component such as the centre frequency, lower cut-off frequency or upper cut-off frequency. All functions exhibit a directly proportional relationship between sharpness and frequency. The critical band rate in Bark increases with frequency. Sensations of higher sharpness occur in the dashed function, where bandpass noise is a function of lower cut-off frequency and has a constant upper cut-off frequency of 10 kHz. Hence, it is evident that sharpness increases when higher frequencies are added to noise. Also, when lower frequencies are added to noise this will result in a decrease in sharpness as the higher end of the sound becomes less prominent.

Zwicker model for sharpness lays down the foundation for others to be built upon. Each model has its own weighting curve to make it unique. Zwicker method for

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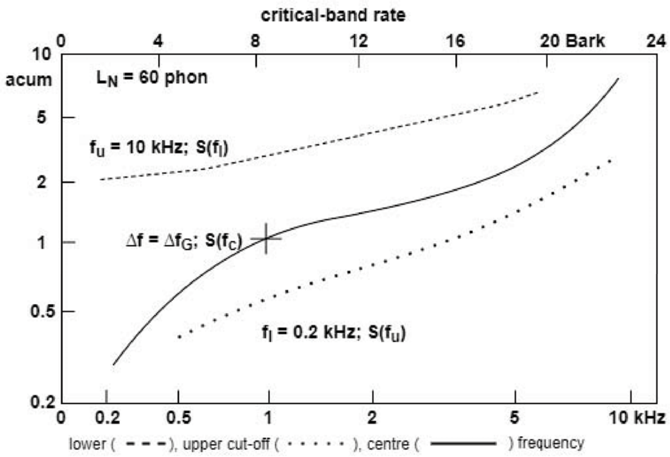

Figure 1: Sharpness of a) critical-band-wide narrow-band noise as a function of centre frequency (solid), b) band-pass noise with an upper cut-off frequency of 10 kHz as a function of the lower cut-off frequency (dashed) and c) band-pass noise with a lower cut-off frequency of 0.2 kHz as a function of the upper cut-off frequency (dotted) [2]. The cross marks the standard sound producing a sharpness of 1 acum

calculating loudness, identified in DIN 45631, includes three weighting curves. The first is the standard, the second is the Aures method and the third is the von Bismarck method. Aures and von Bismarck models differ in that the former takes absolute loudness into account [5]. Fastl created a slight variation on Zwicker method which was tested for this document – the corresponding results will be shown later. Moore and Glasberg created a model which allowed time-varying sounds to be tested, whereas the Zwicker and Fastl methods were better suited to stationary sounds [7].

Hales Swift and Gee combined the loudness models of the Moore-Glasberg standards 2007 and 2017 in their paper [3]. Both models use altered frequency scales; the critical band rate scale in Bark (Zwicker) and the equivalent rectangular band number in Cams (Moore-Glasberg). They also discovered that when narrowband noise and broadband noise were tested, broadband noise had a much more gradual increase in sharpness as the centre frequency of bands increased. Narrowband noise increased more rapidly as it was more tonal and each band consisted of less frequencies. Zwicker model is the German standard so it should be used as a reference to be compared to later on. The Fastl method and Musical Acoustic Research Centre (MARC) method have slight variations in the weighting curves of their model, so comparisons could be drawn between them and the German standard. The Moore-Glasberg, Aures and von Bismarck methods are more developed, therefore, it may be more suitable to investigate the lesser known approaches that do not appear in so much literature.

2.1. Zwicker Model

Zwicker was able to construct a model for sharpness from his findings from Psychoacoustic Facts and Models [2]

$$S = 0.11 \frac{\int_0^{24\,\mathrm{Bark}} N' g(z) z \,\mathrm{d}z}{\int_0^{24\,\mathrm{Bark}} N' \,\mathrm{d}z} \text{ [acum].} \tag{1}$$

In the above equation, N' is the specific loudness in Sone and $g(z)$ is the weighting function. The weighted partial first moment of loudness is given on the numerator as $N' g(z)\,\mathrm{d}z$. The weighting function increases from unity to 4 after 16 Bark. This stems from the non-linear increase in sharpness when higher frequencies are added. The integral on the denominator corresponds to total loudness. The three weighting curves that were tested for this report can all be implemented in this algorithm for sharpness.

2.2. Fastl, German standard and MARC Models

The three different models tested were the Fastl, German standard and MARC method. Each has its own weighting curve and stems from the Zwicker method for calculating loudness. The equation for the Fastl weighting curve [6]

$$g(z) = \begin{cases} 1 & \text{for } z \le 14\,\mathrm{Bark}, \\ 0.00012\,z^4 - 0.005\,z^3 & \\ \quad +0.1\,z^2 - 0.81\,z + 3.51 & z > 14\,\mathrm{Bark}. \end{cases} \tag{2}$$

This weighting curve is indeed very similar to what is shown in the book [2], the difference being that the curve begins increasing after 14 Bark. The German standard curve previously mentioned is similar but instead uses an exponential function after 15.8 Bark [7]

$$g(z) = \begin{cases} 1 & \text{for } z \le 15.8\,\mathrm{Bark}, \\ 0.15\,\mathrm{e}^{0.42(z-15.8)} + 0.85 & z > 15.8\,\mathrm{Bark}. \end{cases} \tag{3}$$

Finally the weighting curve from the MARC article [8]

$$g(z) = \begin{cases} 1 & \text{for } z \le 16\,\mathrm{Bark}, \\ 0.066\,\mathrm{e}^{0.171z} & z > 16\,\mathrm{Bark}. \end{cases} \tag{4}$$

This curve also takes the form of an exponential function, this time, after 16 Bark. These very slight variations in weighting curve will contribute to differences in calculations of sharpness. The curves begin to separate between 14 and 16 Bark. The German standard appears to rise at a higher rate compared to the other two. This may lead to sharper results when testing sounds. As previously mentioned, after 16 Bark, or more specifically 15.8 Bark there is a turning point where there is a significant increase in $g(z)$. The lower frequencies will be more closely related as the $g(z)$ remains constant. Yet at higher frequencies with the exponential increase in $g(z)$, small differences in $g(z)$ can give larger differences in sharpness. The implementation and testing of these weighting curves will be explained in the next section.

3. Implementation and Testing

The three weighting curves consequently contribute to three different sharpness models. These were taken forward for testing on technical and real world sounds. This subsection talks about the procedure involved, the MATLAB code and the results obtained for the test sounds.

In order to test sounds, MATLAB code was sourced from the University of Salford sound quality website [6]. Four MATLAB scripts were obtained which included functions for loudness, one-third octave filters, midbands and sharpness. It was important that each sound to be used in the experiment was separated into two 1-channel .wav files because, unlike mp3, wav format avoids compression. Additionally, the sampling frequency, F_s, always had to be 44.1 kHz to get the best output. The filters to obtain one-third octave spectrum and loudness metric are standardised by Zwicker. The sharpness metric used is Fastlf method. This is the part of the MATLAB code that can be varied to compare models.

When inputting sounds to the loudness section, the reference sound pressure level had to specified as an argument as $L_{p,\mathrm{ref}} = 94$ dB. The field coefficient is 0 as the sound is analysed in such close proximity, therefore a free field with no reflections can be assumed. The loudness function returns the loudness (sones) and the specific loudness (sones/Bark). The next step was to take the data from the specific loudness, just like the sharpness models earlier in the section, and input into the sharpness script. This returned the value of sharpness in acum of the sound that was input in to the original loudness function. In order to compare the methods, the weighting function within the sharpness script was changed for the German standard and the MARC model.

3.1. Results

A range of sounds were chosen to be analysed to show the different kinds of sources where sharpness can be found. One can recreate sounds like white noise (which can be band-limited), tones, sawtooth and square waves in MATLAB. These can be compared with real world sounds like speech and traffic noise to see how the complexity of tonal components affects sharpness. Table 1 shows some of the sounds that were tested by obtaining specific loudness and implementing in the sharpness metric.

Table 1: Table of Sharpnesses for Test Sounds

Sound Sample	**Sharpness S (acum)**		
	Fastl	**Standard**	**MARC**
Chimes	3.1745	3.4695	3.4735
Applause	1.5012	1.5517	1.5854
Sawtooth 50 Hz	1.4397	1.4976	1.5308
Sawtooth 500 Hz	1.7682	1.8442	1.8816
Sawtooth 1 kHz	2.0538	2.1486	2.1930
Sawtooth 5 kHz	3.0987	3.3406	3.4169
Square 50 Hz	1.4359	1.4957	1.5253
Square 500 Hz	1.9835	2.0759	2.1190
Square 1 kHz	2.3159	2.4458	2.4844
Square 5 kHz	3.2294	3.6149	3.4611
Male voice	1.5381	1.5882	1.6428
Female voice	1.5998	1.6871	1.6858
Traffic	1.4075	1.4474	1.4970

- ***Chimes*** – Initially, one can see that the chimes have a relatively high sharpness compared to the other sounds. The high frequencies of the metal being struck prove to be very sharp. As it is percussive there is no transient, only attack and release therefore it results in an unpleasant sound.

- ***Applause*** – The applause test sound, like the chimes, were sourced from Microsoft Office 2011 Media package. A three second clip of an audience applauding gives the impression of a sound with lower frequencies in the spectral envelope. This results in sharpness around 1.5 acum.

- ***Sawtooth*** – Created in MATLAB with 4 fundamental frequencies, the 50 Hz sawtooth wave has a sharpness similar to applause. The higher fundamental frequency of the sawtooth wave led to higher sharpness and becomes much more unpleasant.

- ***Square*** – Also done in MATLAB, the square wave generally had a higher sharpness than sawtooth for each corresponding fundamental frequency. It does not sound as clear as the sawtooth wave. Sawtooths tends to be modelled for stringed instruments, while the square wave is more like a wind instrument and is constructed of odd harmonics.

- ***Speech*** – The speech sounds, male and female, were sourced from a BBC podcast entitled, “The English We Speak”, where a man and a woman are talking. Men tend to have deeper voices compared to women so it is no surprise the male voice has a lower value of sharpness. Typically, men speak with a fundamental frequency between 85 and 180 Hz and women 165 to 255 Hz [9].

- ***Traffic*** – This sample was taken from the sound effects website, Pachd.com, which is downtown traffic ambience. Naturally, the sound of vehicle engines has low frequency content so the sharpness calculated was not very high. To compare, we can look at traffic in different times and locations, in urban and rural areas [10].

Next, filtered white noise and pure tones were implemented in the MATLAB sharpness functions to show how different bandwidths and tones behave. Table 2 presents the results of four different types of sounds for each of the three sharpness methods.

Table 2: Table of Sharpnesses for Filtered Noises and Tones

Sound Sample Type	Centre Frequency	Sharpness S (acum) Fastl	Standard	MARC
Octave Band	250 Hz	0.4624	0.4626	0.4624
	500 Hz	0.6538	0.6538	0.6538
	1 kHz	1.0111	1.0089	1.0114
	2 kHz	1.6022	1.5909	1.6536
	4 kHz	2.6408	2.7360	2.8956
	8 kHz	3.6561	4.0504	3.9981
One-Third Octave Band	250 Hz	0.3826	0.3826	0.3826
	500 Hz	0.6472	0.6472	0.6472
	1 kHz	0.9502	0.9496	0.9497
	2 kHz	1.4397	1.4247	1.4575
	4 kHz	2.5344	2.5868	2.7986
	8 kHz	3.9731	4.4415	4.3176
White Bandpass Noise	100–1000 Hz	0.6304	0.6297	0.6301
	500–1000 Hz	0.7483	0.7481	0.7481
	1–3 kHz	1.4441	1.4308	1.4819
	2–4 kHz	1.9143	1.9099	2.0316
	4–8 kHz	3.0455	3.2145	3.3838
Tones	250 Hz	0.7160	0.7155	0.7200
	500 Hz	0.7160	0.7155	0.7200
	1 kHz	1.0652	1.0648	1.0724
	2 kHz	1.6252	1.6132	1.6665
	4 kHz	3.1075	3.2590	3.4633
	8 kHz	4.8890	5.5982	5.3073

- ***Octave Bands*** – A white noise function was created in MATLAB, where the frequency band could be selected. White noise has equal energy in all octave bands so has virtually no tonality. Six octave bands were created to investigate the sharpness of various bandpass noises. With the octave bands, there is a steady rise in sharpness. Fastl method is closer to the standard but the latter reaches a higher acum value with the higher octave bands.

- ***One-Third Octave Bands*** – In these tests, the bands are narrower which results in sharpness rising at a faster rate compared to the octave bands. This can be seen between the 4 kHz and 8 kHz band where there is a large jump in sharpness. The one-third octave bands are narrower, so they are slightly more tonal which results in a higher acum value as the centre frequencies of the bands increase.

- ***Band limited white bandpass noise*** – There is a large jump in sharpness from 500–1000 Hz to 1–3 kHz. The result was that the noise between 4 and 8 kHz gave the highest values of sharpness. This band is very wide but is not as noticeable as it is higher in the frequency spectrum, yet still gives a high acum value.

- ***Tones*** – Six pure tones were created in MATLAB as sine waves to test the sharpness. It can be seen that they have a higher sharpness value compared to the octave and one-third octave bands for the same centre frequency. The rise in sharpness is much steeper than the octave and third-octave bands due to the pure tonality. The MARC method has a higher sharpness than the Fastl method.

When comparing the methods, it appears that MARC consistently gives higher values of sharpness compared to the Fastl method. It also gives higher values of sharpness compared to the German standard, with the exception of highest one-third octave band results. When comparing the Fastl method to the German standard, Fastl returns much lower values of sharpness throughout, except from the mid-range frequency bands. For the majority of the tests, the Fastl method gave the lowest sharpness, with the exception of some of the bandpass white noises. The MARC weighting curve appears to be closest to the German standard on most sounds apart from the white bandpass noise tests.

Fastl weighting curve is the only one of the three that is not exponential, but quartic. Perhaps evaluating a curve at a higher order of polynomial would lead to more accurate results.

We have seen that bandpass noises increase with sharpness as the centre frequency increases, as expected. Narrowband noises increase in acum at a higher rate as they more closely resemble tonal components [3]. This is shown best when pure tones are tested. The broadband noises do indeed increase in sharpness as spectral content increases but not as rapidly. The bands contain more frequencies as they are wider so the rate of change of frequency content is not as steep. More testing in MATLAB should be done on a wider range of test sounds such as more white bandpass noises, other technical sounds and environmental sounds like different types of traffic. This will allow for more detailed comparisons of methods to see in which types of sounds each algorithm differs from one another. This could lead to comparisons with non-stationary sounds where the Moore-Glasberg method can be implemented. Measuring the sharpness of domestic appliances and industry sounds should be carried out more frequently so that one can evaluate harmful levels of sharpness. A threshold of pain could be calculated for sharpness similar to sound pressure level in equal loudness curves.

4. Conclusion

This article dealt with the psychoacoustics quantity of sharpness, three methods of evaluating sharpness and then compared these methods of measurement.

This led to the sharpness metric which uses the specific loudness pattern as a part in investigating the high frequency content of a sound. Sharpness proposals have been put forward, only one being standardised in Germany, each with a unique weighting function which treats the sounds in different ways. For this article, tests were run on three models for sharpness and the measurements involved have allowed for the comparison of two methods against the German standard. The model from MARC not only returned much higher values of sharpness compared to H. Fastl method but also appeared to be closer to the German standard.

The German standard is not exact so there should be a motivation to further research more adequate methods by observing where current proposals differ. The Fastl method was adjusted from the Zwicker method using a quartic weighting curve. Using a higher order polynomial or adjusting to an exponential function can provide a more accurate result. The weighting curves all increased from 1 after a certain value of Bark. This could be investigated further into an accurate point where the non-linear characteristics of the ear take over. Ideally, the Moore-Glasberg method for sharpness can be tested for further research to see the comparison with time-varying sounds, which could be a possible proposal for a sharpness standard. Additionally, for future testing, the sounds chosen can be expanded upon in order to investigate different types of sound and how accurately each model represents the true sharpness of a source.

Considering the next step, globalising the standard for sharpness in industry, there is always the demand for noise control and environmental acoustics, so finding ways of quantifying limits of sharpness would be a goal to aim for. Ideally, more investigation into the modelling of the ear's filter can be carried out to ensure more background information for understanding human perception.

There is still so much to be set in stone for sound quality evaluation and this report has attempted to understand the fundamentals and compared the advanced methods to pave the way for a better understanding of psychoacoustics.

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