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Dlouhodobá studie věkově závislých akustických charakteristik řeči

Longitudinal Study of Age-related Changes in Acoustic Characteristics of Speech

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In this paper a longitudinal study is presented of age-dependent speech acoustic characteristics from the utterances of Czech actresses, acquired from movie databases recorded in the years from 1985 to 2014. The age dependence of phonation is analyzed using the parameters fundamental frequency, jitter, and shimmer. For assessment of articulation, the formant-based voice area index of vocals and the length of the burst from a palatal stop consonant is used. For prosody, no characteristics were found that were applicable to the analysis of film archives. The results of age dependencies described by the phonetic categories are consistent with the assumptions and conclusions presented in the literature. This pilot project also confirms the possibility of creating valuable studies from publicly available sources.

1. Úvod

1.1. Věková závislost lidské řeči

Podobné změny, ke kterým dochází u lidského těla v důsledku stárnutí – kdy ubývá svalů a síly, přibývá tělesného tuku, zpomaluje se pohyb, dochází k degeneraci tkání –, ovlivňují také hlas. Ve stáří se hlasivky stávají tužšími a tenčími, což může vést k slabšímu a dyšnějšímu hlasu. Menší pružnost hlasového ústrojí může mít za následek redukci hlasového rozsahu a v důsledku změn v respiračním ústrojí se řeč může stát obtížnější. Řeč seniorů tak může provázet pomalejší tempo spojené s prodlužováním slabik a slov a větším počtem nádechových pauz. Ke snížené hlasitosti se může přidat hlasový tremor. Stárnutím se hrtan mužů mění více než u žen a tyto změny nastávají dříve. Základní perioda hlasu starších mužů má tendenci s věkem stoupat, zatímco základní perioda ženského hlasu zůstává stejná, případně se mírně snižuje. Ztráta sluchu u starších lidí může mít za následek hlasitější projev, který zpětně ovlivňuje stav hlasivek.

Změny v řeči během stárnutí a v závislosti na pohlaví stále nejsou dostatečně prozkoumány a publikované studie se rozchází. Naprostá většina studií věkové závislosti akustických charakteristik byla hodnocena na tzv. „příčných“ databázích, u kterých se porovnávají starší a mladší věkové skupiny. Ačkoliv takové studie ukazují obecné trendy, tak dlouhodobé (podélné) studie, které jsou však poměrně vzácné, zobrazují vývoj akustických charakteristik jedince v závislosti na věku bez vlivu statistického průměrování a jsou vhodné pro studium intraindividuálních hlasových změn v čase. Dlouhodobé studie však bývají ovlivněny změnami nahrávacího prostředí, nahrávacího zařízení a kompresí zvuku.

Studium závislosti akustických charakteristik na věku přispívá k porozumění a odlišení přirozených systematických neuromuskulárních změn v důsledku stárnutí, oproti případným patologiím vznikajícím vlivem progrese neurodegenerativních onemocnění (například vlivem Parkinsonovy choroby nebo ALS). Pro tyto analýzy řečových charakteristik osob s různými nemocemi a poruchami je také potřebné vytvoření normativních dat. Nová poznání o věkové závislosti by mohla být využita v klinické praxi a jsou rovněž využitelná pro řečové technologie, jakými jsou syntéza a automatické rozpoznávání řeči.

1.2. Dlouhodobé studie

Práce [1] zkoumá vliv stárnutí na hlasech u dvaceti nizozemsky mluvících novinářů, kteří četli stejný text po třiceti letech. Analyzuje věkovou závislost střední hodnoty základní frekvence F0 a délky neznělých explozív. Další dlouhodobá studie [2] se věnuje věkově závislým změnám hlasu u 11 zdravých dobrovolníků (mužů), ve věku od 50 do 81 let po dobu pěti let na průbězích základní frekvence a její frekvenční a amplitudové nestability. Experimentální dlouhodobá studie [3] sleduje, zda změny v hlase žen mohou být slyšitelné a měřitelné již po pěti letech, a také hledá vhodné věkově závislé akustické parametry. Výsledky ukázaly, že věková diference je velmi dobře určitelná i měřitelná jak ve spontánních promluvách, tak i u samohlásek s prodlouženou fonací (/i/ a /u/), především na základě měření rychlosti promluvy a základní frekvence a její frekvenční a amplitudové nestability. Studie [4] se zabývá dlouhodobou akustickou analýzou nahrávek čtyř smluvčích ve věku jejich 29 let a poté v 50 letech. Analýza se zaměřuje na změny v základní frekvenci a ve formantech. Dlouhodobá studie [5] se věnuje rovněž analýze

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základní frekvence a formantů v samohláskách u každoročních vánočních vysílání britské královny Alžběty II. během uplynulých padesáti let. Studie [6] porovnává hodnoty základní frekvence ve skupině 8 žen s hodnotami stejných mluvčích naměřených o 25 let později.

Práce [7] prezentuje dlouhodobou analýzu věkové závislosti základní frekvence F0 a formantových frekvencí F1, F2 a F3 u pěti mluvčích (britské královny Alžběty II., bývalé britské ministerské předsedkyně Margaret Thatcherová, britské herečky, rozhlasového reportéra a novináře Alistaira Cooka). U britské královny a u novináře byla provedena analýza promluv z období padesáti let, u ostatních z období trvajícího více než 30 let. Velmi zajímavou prací je podélná studie [8], která analyzuje promluvy (základní frekvenci a počet slov na jeden nádech) v nedělních kázáních amerického pastora nahrávané po dobu 50 let (ve věku od jeho 48 až do 98 let). Ve studii [9] byly analyzovány formanty a základní frekvence od osmi mluvčích (šesti mužů a dvou žen) z televizního dokumentu „7 Up“ natáčeného po 28 let (po sedmi letech, ve věku 21, 28, 35, 42 a 49 roků).

1.3. Cíl práce

Cílem této studie je především ověření možnosti využití veřejně dostupných databází pro výzkum věkové závislosti akustických charakteristik popisujících fonaci, artikulaci a prozódii a také porovnání věkově závislých akustických charakteristik v českých promluvách s experimenty na dlouhodobých studiích publikovaných zahraničními autory.

2. Vybrané věkově závislé akustické parametry

Sledované vybrané akustické parametry jsou pro účely této studie rozděleny do tří fonetických kategorií: 1) fonace, 2) artikulace a 3) prozódie.

2.1. Fonace

Fonací se nazývá proces, při kterém je vytvářen zvuk. Představuje výdechový proud z plic, který pokračuje jícnem a prochází hlasivkami, které jsou normálně otevřené. Při mluvě jsou však pomocí svalu hrtanu uzavřeny a proudem vzduchu rozechvívány. Parametry, které popisují fonaci, bývají odvozovány od základní frekvence F0 a hodnotí kmitočtovou a amplitudovou nestabilitu.

Základní frekvence Jedním z nejčastěji sledovaných parametrů závislých na věku je střední hodnota základní frekvence F0. Změny v F0 ovlivňuje kalcifikace chrupavek hrtanu a u žen také hormonální změny po menopauze či kouření. Z výsledků studie [1] vyplývá, že základní frekvence F0 v mužských čtených promluvách s přibývajícím věkem klesá. V práci [6] popisují autoři významný pokles F0 pro muže i pro ženy. V práci [2] byla u kuřáků pozorována nižší hodnota základní frekvence řeči, která se však u mužů zdála být reverzibilní. Práce [12] popisuje pro ženy trend, kdy je základní frekvence prakticky konstantní až do menopauzy a poté klesá, zatímco u mužů je uváděn trvalý pokles F0, po kterém následuje zvýšení F0 (přibližně od 60 let věku). Výsledky studie [6] také potvrdily klesající trend hodnoty základní frekvence u žen. V dlouhodobé studii [7], ve které byly nasbírány vzorky promluv od muže a ženy za padesát let, je dokumentováno, že trend základní frekvence v závislosti na věku má u muže tvar písmene „V“ (po dlouhodobém poklesu následuje nárůst) a u ženy setrvalý pokles. Další „padesátiletá“ studie [8] potvrzuje trend „V“ pro muže. Studie [9] uvádí pokles základní frekvence u mužů během 28 let v produktivním věku jako velmi mírný (pouze o 3 %). U jedné ženy byl pokles F0 o 8 % a u druhé, silné kuřačky, dokonce o 23 %. Nedávná příčná studie [13] u mužů nepozoruje vůbec žádný trend (ani ve vysokém věku), avšak u žen mezi roky 20 až 50 uvádí velmi výrazný pokles F0, který je ve vyšším věku už pouze velmi nepatrný.

Z literatury vidíme, že v obecném popisu průběhu časové závislosti základní frekvence F0 není dosud úplná shoda.

Shimmer a jitter U starších mluvčích bývá slyšitelný třes a zvýšený chrapot. Uvedené vlastnosti souvisí se změnou základní frekvence F0 a s její amplitudovou (shimmer) a kmitočtovou (jitter) nestabilitou. Tyto charakteristiky ukazují na stabilitu hlasu a mají tendenci se s věkem zvyšovat [10], [14].

Shimmer má poměrně silnou korelaci s věkem. [10] uvádí, že střední hodnota parametru shimmer u starších hlasů je 5,43 %, zatímco pro mladší mluvčí je 2,21 %. Hodnoty parametru shimmer se zvyšují s věkem nezávisle na celkovém zdraví, a mohou proto sloužit jako indikátor stárnutí hlasu.

S přibývajícím věkem je u mužů i u žen pozorováno také chvění hlasivek projevující se zvýšenou hodnotou parametru jitter, což potvrzuje řada studií [11]. Jitter nemusí být jednoznačným ukazatelem chronologického věku, neboť bývá závislý na celkovém zdraví, určitou indikaci stárnutí však může poskytovat. [10] uvádí, že střední hodnota jittru u starších hlasů je 2,06 % a u mladších je 0,62 %.

2.2. Artikulace

Artikulace neboli tvorba hlásek je tvořena změnou tvaru a pozice mluvidel během průchodu zvuku dutinou hrdelní, ústní a nosní. Artikulace bývá nejčastěji hodnocena na samohláskách, které se popisují a hodnotí v rovině prvních dvou formantů. Lze ji však také hodnotit např. na délce jednotlivých fází exploziv.

Formantové frekvence Práce [4] a [7], zabývající se věkovou závislostí ve vztahu k formantům a k základní frekvenci, ukázaly, že změny související s věkem v F1 mohou být kompenzovány fyziologicky vyvolaným poklesem F0, čímž je udržována relativně konstantní sluchová vzdálenost mezi F0 a F1. Studie [9] ukazuje na mírný pokles prvních třech formantů (F1 pokles 8,5 %, F2 pokles 3,7 %, F3 pokles 2,2 %) během 28 let. Práce [13] na příčné databázi nenalézá u mužů statisticky významné změny formantů. U žen ano, ale změny jsou pozorovány jen u některých samohlásek a spíše v mladším věku.

Délka explozív Práce [1] analyzuje délku počátku znělosti (*VOT* – Voice Onset Time), která u neznělých explozív s věkem roste.

2.3. Prozódie

Prozódie představuje vyšší úroveň jazyka. Popisuje melodii, rytmus a přízvuk. Často se hodnotí z rychlosti promluvy, či délky trvání a časových poměrů jednotlivých řečových segmentů.

věk	počet	F0	jitter	*VAI*	*VOT*
22	39	14	5	18	1
23	18	8	2	0	1
24	14	5	2	6	0
25	3	0	1	8	0
26	94	8	11	14	3
27	35	2	6	9	1
28	0	0	0	0	0
29	70	5	11	14	2
30	57	0	11	8	0
31	17	5	2	12	0
32	0	0	0	0	0
33	0	0	0	0	0
34	18	0	2	16	0
35	76	6	6	29	3
36	27	7	4	21	1
37	45	5	5	18	1
38	27	5	2	12	0
39	64	7	4	16	1
40	0	0	0	0	0
41	0	0	0	0	0
42	63	5	8	18	2
43	0	0	0	0	0
44	105	5	12	18	0
45	45	3	2	8	5
46	5	2	2	5	0
47	0	0	0	0	0
48	125	7	33	21	0
49	2	0	1	0	0
50	3	1	1	7	1
51	10	0	6	14	0
celkem	962	100	139	292	22

Tabulka 1: Počty vzorků v databázi použitých pro analýzu

Rychlost řeči Řeč starších lidí bývá charakterizována pomalejší rychlostí. Ke snížení rychlosti může docházet v důsledku degenerace svalů, či úmyslného zpomalení spojeného s přesnější artikulací a zvýšením srozumitelnosti. Rychlost řeči souvisí také s délkou segmentů, či počtem segmentů za jednotku času a délkou a frekvencí pauz. Počet řečových jednotek (slabik, hlásek, sub-fonémů apod.) za časovou jednotku klesá s věkem [12] a prodlužuje se trvání souhlásek, samohlásek a pauz [14, 15, 12]. Některé práce ukazují výraznější pokles rychlosti promluvy u mužů než u žen. Percepční testy rozpoznání věku [16] ukázaly, že rychlost čtení se používá jako významná charakteristika pro rozlišení mladších mluvčích od starších.

3. Dlouhodobá studie akustických parametrů na databázi z filmových archívů [16]

Pro účely analýz věkově závislých akusticko-fonetických parametrů hlasu a řeči byla vytvořena databáze filmových záznamů české herečky (narozena 1963). Ze záznamů byly nastříhány její promluvy, od slov až po velká souvětí, a analyzovány v jednotlivých kategoriích.

3.1. Databáze

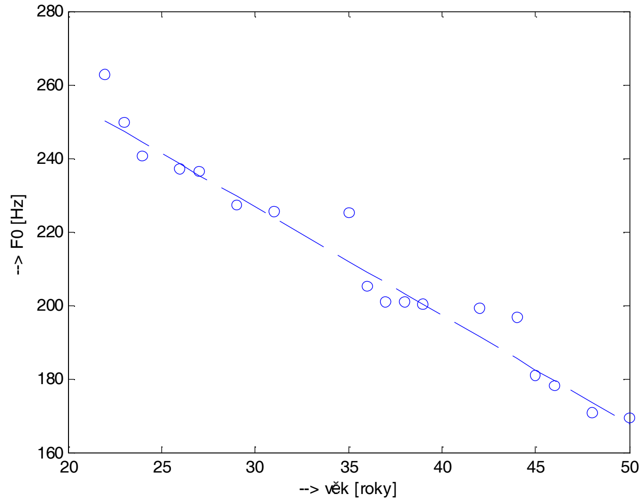
Filmové záznamy z období let 1985–2014 byly získány z internetových stránek www.hellspy.cz a www.youtube.cz ve formátu avi. Pomocí nástroje Any Video Converter byly nahrávky z filmů převedeny do formátu wav, dále pomocí softwaru Cool Edit Pro 2.0 bylo extrahováno celkem 962 záznamů (vět). Pro analýzu byly vybrány promluvy bez šumového pozadí a pasáže bez emocí, které byly analyzovány v prostředí Praat.

Ve sloupci „počet“ v tabulce 1 je uveden počet vět v databázi z příslušného kalendářního roku a v dalších sloupcích je počet vzorků, které dále byly použity pro vyhodnocení jednotlivých akustických charakteristik.

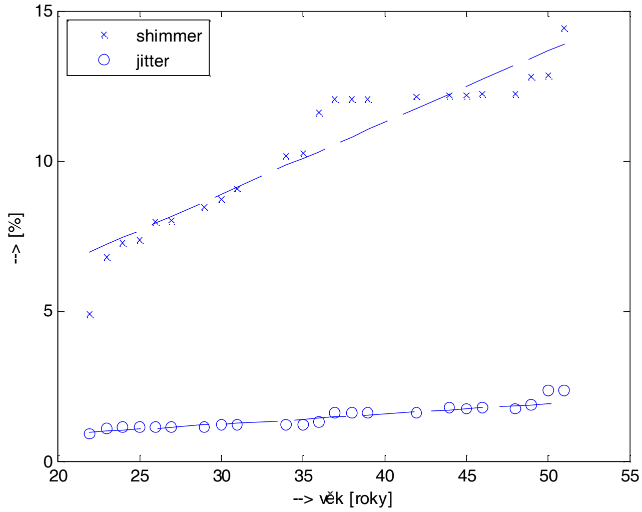
3.2. Fonace

Základní frekvence byla analyzována z prodloužených realizací samohlásky /a/ z jednotlivých záznamů bez rozdílu pozice samohlásky ve slově. V tabulce 1 (sloupec F0) je uveden počet vokálů použitý pro získání průměrné hodnoty základního hlasivkového tónu v jednotlivých letech. Analyzovány byly pouze vzorky bez velkého rušení hudebním pozadím a bez přehnaných emocí. Výsledné hodnoty F0 byly vypočteny detekčním algoritmem v Praatu a jsou zobrazeny v obrázku 1.

Dále byly vypočteny parametry frekvenční a amplitudové variability základní frekvence, které byly určeny rovněž z prodloužených realizací vokálu /a/ v Praatu. Jitter i shimmer určují kvalitu fonace, ale jsou také hodně citlivé na kvalitu použitých nahrávek pro analýzu. Kvůli tomu byly některé nahrávky vyřazeny a průběh průměrných hodnot obou parametrů byl počítán z menšího počtu dat. Na obr. 2 jsou uvedeny věkové závislosti hodnot lokálních parametrů jitter a shimmer v procentech.



Obrázek 1: Věková závislost střední hodnoty základní frekvence F0



Obrázek 2: Věková závislost shimmeru a jitteru samohlásky /a/

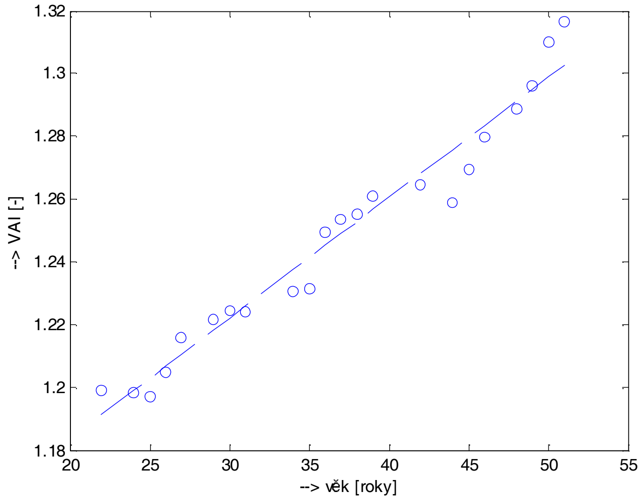
3.3. Artikulace

V práci byly analyzovány první dva formanty z prodloužených realizací samohlásek /a/, /e/, /i/, /o/, /u/. Pro jednotlivé samohlásky byly v Praatu nastaveny jejich typické rozsahy. Pro detekci /u/ byly hledány dva formanty do 1 000 Hz, pro /i/ byly nastaveny dva formanty do 3 000 Hz a pro /a/ byly nastaveny tři formanty do 3 000 Hz. V každém roce záznamu byl pro výpočet průměrné hodnoty použit rozdílný počet prodloužených realizací vokálů, viz tabulka 1, sloupec *VAI*.

Z výsledků vyplývá, že první formant u všech samohlásek s rostoucím věkem klesá, což také potvrzuje většina studií zabývajících se věkovou závislostí prvního formantu. Zatímco druhý formant F2 s věkem klesá pouze u samohlásek /a/, /e/, /o/, tak u samohlásek /i/, /u/ dochází s rostoucím věkem k jeho nárůstu. Pro vyhodnocení věkové závislosti artikulace byl použit parametr *VAI* (vowel articulation index) podle vztahu (1)

$$VAI = \frac{F_1(\mathrm{a}) + F_2(\mathrm{i})}{F_1(\mathrm{i}) + F_1(\mathrm{u}) + F_2(\mathrm{u}) + F_2(\mathrm{a})}\,. \qquad (1)$$

Obecně, s méně výraznou artikulací hodnota *VAI* narůstá, což odpovídá tzv. centralizaci formantů. Z obrázku 3 vidíme, že s rostoucím věkem hodnota artikulačního indexu rovněž roste.



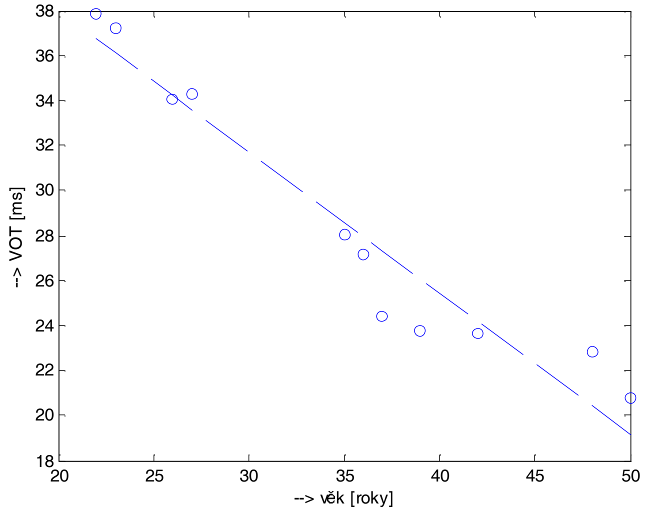
Obrázek 3: Věková závislost charakteristiky *VAI*

Délka znělé exploze byla zkoumána na spojení samohláska-explozíva-samohláska (/u-ď-e/ nebo /e-ď-e/) v databázi slov /udělat/ a /nedělat/, neboť tato slova byla nalezena u většiny roků. Pro analýzu byla použita slova z co nejklidnějších promluv bez emocí a velkého rušení hudbou, okolím. Některá slova byla řečena důrazněji (rychleji) v rámci dané filmové role. Jak je možné vidět na obrázku 4, doba exploze se s rostoucím věkem zkracuje.

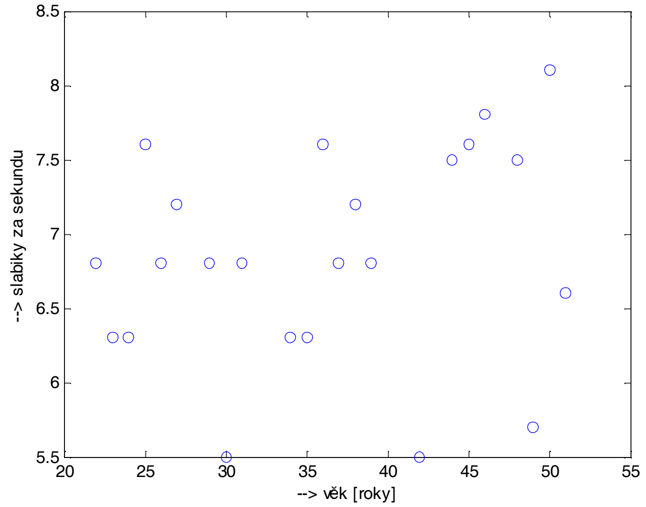
3.4. Prozódie

Z prozodických vlastností řečového signálu byla v této práci zkoumána věková závislost rychlosti řeči. Jednotkou tempa byl počet slabik za sekundu, viz obr. 5. Změny trvání slabik jsou ovlivněny trváním samohláskových segmentů mnohem více než trváním souhlásek, proto je důležité vybrat věty s podobným složením samohlásek. Experimentální data z filmů jsou omezená danou hereckou rolí a nalezení stejných vět pro všechny roky je prakticky nemožné. Z analýzy rychlosti řeči musel být vyloučen také čtený projev herečky z jednoho filmu, neboť čtení bývá doprovázeno pomalejší rychlostí.

Filmové záznamy, vzhledem k nehomogenitě vět, nejsou vhodným materiálem pro analýzu rychlosti řeči, ani pro



Obrázek 4: Věková závislost charakteristiky *VOT* znělé explozívy /ď/ v samohláskovém kontextu



Obrázek 5: Věková závislost rychlosti řeči

analýzu podílu pauz v promluvě, neboť není možné nalézt stejné, či alespoň podobné věty, na nichž by se daly parametry zkoumat. Prozodické stránky promluv jsou také příliš ovlivněny filmovou rolí.

4. Diskuse a závěr

Poměrně výrazný trend poklesu základní frekvence hlasivkového tónu herečky je přibližně 3 Hz/rok a koresponduje s trendem ženy-kuřačky ve studii [9]. Trend pro ženu nekuřačku v práci [9] odpovídá mírnějšímu poklesu F0 britské královny (z dostupných zdrojů také nekuřačky) ze studie [7] a je okolo 1 Hz/rok. Z rešerše literatury i z této dlouhodobé studie vyplývá, že při tvorbě normativních věkových charakteristik základní frekvence bude nutné uvažovat nejen rozdílnost pohlaví a větný kontext analyzovaných vzorků, ale zřejmě i charakteristiky typu kuřák/nekuřák.

Publikované trendy pro jitter a shimmer, např. [10], získané z příčných databází, jsou plně v souladu s našimi závěry z podélné databáze, které však byly získány na poměrně omezeném počtu vzorků. Potvrzují nárůst frekvenční a amplitudové nestability hlasivkového tónu s přibývajícím věkem.

Věková závislost formantových frekvencí není v literatuře popsána jednoznačně. V této práci byl použit parametr VAI, který se často používá při hodnocení artikulace u dysartrických pacientů, avšak pro hodnocení věkové závislosti nebývá používán. Parametr VAI velmi dobře ukázal s věkem rostoucí méně výraznou artikulaci samohlásek. Narůstající méně výraznou artikulaci v závislosti na věku potvrzuje také zkracující se délka exploze u palatálního /ď/.

Experimenty v této práci potvrdily možnost využití veřejně dostupných zdrojů pro výzkum akustických charakteristik popisujících fonaci a artikulaci. Naopak, experimenty ukázaly také na nevhodnost posuzování prozodických charakteristik z filmových databází.

Poděkování

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Reference

[1] Decoster, W., Debruyne, F.: Longitudinal Voice Changes: Facts and Interpretation, *Journal of Voice*, 184–193, 2000.

[2] Verdonck-de Leeuw, I. M., Mahieu, H. F.: Vocal aging and the impact on daily life: a longitudinal study. *Journal of Voice*, 18, 193–202, 2004.

[3] Brückl, M.: Women's Vocal Aging: A Longitudinal Approach. *Interspeech*, 4, 2856–2859, 2007.

[4] Harrington, J.: An acoustic analysis of 'happy-tensing' in the Queen's Christmas broadcasts, *Journal of Phonetics* 34(4), 439–457, October 2006.

[5] Harrington, J., Palethorpe, S., Watson, C. I.: Age-related changes in fundamental frequency and formants: a longitudinal study of four speakers, *Interspeech*, 2, 1081–1084, 2007.

[6] Xue, S. A., Hao, G. J., Xu, L., Moranski, T.: Frequency Changes in Women Over Time, *Asia Pacific Journal of Speech, Language, and Hearing*, 11(3), 189–194, 2008.

[7] Reubald, U., Harrington, J., Kleber, F.: Vocal aging effects on F0 and the first formant: A longitudinal analysis in adult speakers, *Speech Communication*, 52 (7–8), 638–651, 2010.

[8] Hunter, E. J., Kapsner-Smith, M., Pead, P., Engar, M. Z., Brown, W. R.: Age and speech production: a 50-year longitudinal study, *Journal of the American Geriatrics Society*, 60, 6, 1175–7, 2012.

[9] Rhodes, R.: Changes in the voice across the adult lifespan: Formant frequency-based likelihood ratios and ASR performance, *IAFPA conference*, Tampa, Florida, USA, 21–25 July, 2013.

[10] Xue, S. A., Deliyski, D.: Effects of aging on selected acoustic voice parameters: Preliminary normative data and educational implications, *Educational Gerontology*, 27, 2, 159–68, Mar 2001.

[11] Verdonck-de Leeuw, I. M., Mahieu, H. F.: Vocal aging and the impact on daily life: a longitudinal study, *Journal of Voice*, 18, 193–202, 2004.

[12] Schötz, S., Müller, C.: A study of acoustic correlates of speaker age. Speaker Classification II, *LNAI* 4441, Springer Verlag, pp. 1–9, 2007.

[13] Romenesko, E., Vorperian, H. K., Kent, R. D., Austin, D.: Aging Effects on Acoustic Characteristics of Adult Speech, *Undegraduate Symposium Madison*, Waisman Center, Wisconsin, April 14, 2016.

[14] Brückl, M, Sendlmeier, W.: Aging female voices: an acoustic and perceptive analysis. In: ISCA Tutorial and ResearchWorkshop on Voice Quality: Functions, Analysis and Synthesis, Proceedings of *VOQUAL'03*, Geneva, 2003.

[15] Linville, S. E.: *Vocal Aging*, Singular Thomson Learning, San Diego, 2001.

[16] Harnsberger, J. D., Shrivastav, R., Brown, W. S. Jr, Rothman, H., Hollien, H.: Speaking rate and fundamental frequency as speech cues to perceived age, *Journal of Voice*, 22(1), 58–69, 2008.

[17] Behenská, J.: Změny v akustických charakteristikách řeči související s věkem, *Diplomová práce*, ČVUT FEL, 2015.

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Voice Effort of People Present in Different Acoustic Environments (an Overview)

Namáhanie hlasu v rôznych akustických prostrediach (prehľad)

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During the last few decades guidelines, requirements, acoustical norms or recommendations for schools were made by several countries within Europe. Most of the documents focuses on speech intelligibility and on background noise levels necessary for the sufficient concentration of students during the educational process. We have to keep in mind that overall acoustical comfort in the teaching environment includes more aspects related to acoustics, e.g. vocal effort of teachers and health problems connected with it. Previous research has shown that teachers belong to a large social group with chronic laryngeal fatigue and therefore this topic has become more often discussed at conferences and acoustic forums. The main research questions have been addressed to issues such as "how acoustic conditions in classrooms affect the vocal load of teachers". Typical research methods use monitoring of the teacher's vocal load over several days and compare the results with in-field measurements of background noise, room acoustic parameters and self-reports of teachers and students followed by the investigation of speech production accommodations due to changes in the acoustic environment. When speaking about vocal effort we have to keep in mind also other types of acoustic environments, such as restaurants, cafés or student canteens. This article reviews available information on so called voice – room interaction. The first part of the paper deals with different teaching environments and discusses how the vocal effort of teachers should be taken into account in acoustical guidelines.The second part of the paper shows recent outcomes in studying vocal effort in restaurants and eating facilities.

1. Introduction

Acoustical conditions inside a room always depend on architectural solutions, such as the shape and volume of the room, absorptive and scattering properties of the interior surfaces, on one hand, and on the function of the room on the other hand. In schools, the educational process is influenced by the level of education, age of the students, and other factors which impact on the acoustic situation, demands and requirements.

Between 50–80 % of teachers in Europe complain about voice problems. Studies in North America report that more than 18 % of teachers missed their lessons at least once a year due to voice problems and had problems with teaching because of their voice dysfunction. The vocal effort of teachers differs according to the taught courses. Teachers of mathematics, history or languages, etc. are forced to speak with increased voice almost the whole working time. On the other hand, teachers of physical education use their voices in a different way. They experience short intense periods when they have to shout. These periods are interrupted with quiet periods with sufficient time to rest and recover the voice [1, 2].

Schools can be sorted into different categories, such as primary, secondary, high schools, universities, universities of the third age, special schools etc. In these schools different teaching methods are applied (traditional plenary teaching, Montessori, etc). The acoustical conditions therefore vary from case to case and from country to country. Nevertheless, it is well known that acoustical comfort in the classroom strongly influences the educational outcome and most of the studies refer to delay in the learning process due to decreased speech intelligibility [3–5].

In the past, classroom acoustics have been mainly researched from the point of view of speech intelligibility and noise levels, so that students could learn in the most convenient, efficient and comfortable way. In recent years more and more focus is given to problems of the teachers' voice. A good vocal quality of teachers is important for the learning process of pupils, too [6]. Based on several research studies, which have investigated subjective complaints among teachers, Vilkman [5] reported that most of the teachers have or had vocal problems during their lifetime. For many of them the voice problem had an impact on their teaching [7–9]. Teachers also complained that their performance was strongly influenced by their vocal capacity [3], and there are also studies which report that students' understanding at school is negatively affected by the teachers' dysphonic voice [6, 10, 11].

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The overall factors, which negatively affect the vocal load, are related to the voice use, room acoustics, background noise, air quality, stress and psychological factors, and the lack of time for rest and recovery [12–14].

2. Quality of indoor environment

2.1. Reverberation time

Reverberation Time is a well-known and widely used quantity in room acoustics [15]. Most of the literature suggests an optimal reverberation time in the range of 0.7–0.9 s at mean frequencies, for an average classroom with volume of about 200 m^3. Pekkarinnen & Viljanen proposed a reverberation time between 0.6–0.9 s and this latter range was also reported as optimal by MacKenzie & Airey [16, 17]. It has been also confirmed that values of Speech Transmission Index (STI) higher than 0.75 can be obtained only in classrooms (of a typical size) with RT $<$ 0.6 s. Several series of intelligibility tests and acoustical measurements in occupied primary classrooms were performed by Bradley (1986), who proposed optimal RT values in the range 0.4–0.5 s [18]. A study of Vargová et al also reported the importance of decreasing the unwanted reverberation time values, as well as keeping few early reflections by application of an optimal amount of sound absorption [19]. In the study from Pelegrín-García et al, it is shown that variations of voice levels in spaces with different acoustic properties are rather associated with the room gain level or the voice support than with the reverberation times [20]. Several experiments have confirmed that in the case of long reverberation times, teachers have the tendency to raise their voices as well. Hodgson et al showed that a longer reverberation time increases the activity noise level and, due to the Lombard effect, teachers are forced to raise their voices [21].

2.2. Typical speech and noise levels in classroom and signal to noise ratio

Typical speech levels in primary and secondary school during classes were measured by many authors [22, 23]. A study by Houtgast showed that the average long-term speech level in the classrooms was 57 dB(A) and the effect of traffic noise on speech intelligibility in classrooms was perceivable when the indoor level exceeded a critical value of 42 dB [22]. Analysis of spectral components of long-term speech and noise in the classroom was reported in the work of Cornelisse et al (1991) and Byrne et al (1994), based on broad international information. Speech spectra typically peak at 500 Hz with a 15–20 dB drop at low and high frequencies [24, 25].

An external and internal noise survey of 142 London primary schools reported that 86 % of schools were exposed to noise from traffic [26]. The relationship between voice increase and background noise level in room is described in the international standard ISO 9921:2003 Ergonomics-Assessment of Speech and Communication [27].

Speech intelligibility depends not only on RT, but also on signal-to-noise ratio. Too short reverberation times can logically lead to an over-dampened place, which can influence the absolute strength of the teachers voice in the back row. A teachers voice has its limits, and the students activity level will almost never drop under 40 dB in average [23]. However, Nilson & Hammer [28]and Ruhe [29] refuted this opinion for classrooms not longer than 9 m, and suggested that students behavior in rooms with more absorbing materials compensates for lower signal levels at back rows.

Based on detailed acoustical measurements made in 41 working elementary schools, Sato & Bradley estimated that the average signal-to-noise ratio of 11 dB appears during teaching activities, with an average speech level around 60 dB(A) and noise level of 49 dB(A). Reverberation time in the occupied classrooms was averagely 0.4 s (10 % more than in the empty rooms) [30].

3. Teachers voice problems

It is clear that bad acoustic conditions in classrooms negatively influence quality of speech communication and increases the vocal effort of teachers. There have been studies carried out which show that the quality of the indoor environment affects voice use and possibly leads to health problems with vocal chords. A few of the previous studies stated that teachers are the second largest social group suffering from chronical laryngeal fatigue [31]. Classrooms with bad acoustical properties cause a reduction in performance of students and make the teacher suffer from fatigue. Previous studies show that the percentage of time during the working day for which teachers speak is on average 21 % (13–31 %). This value is compared to office workers who speak 7 % of their working day [32, 33]. According to Durup et al, this can possibly cause severe voice problems. Results from their experiment showed that half of the tested subjects used their voices with high speech levels, although the subjects taught in rooms which fulfill the newest requirements for acoustical properties of classrooms [32].

In an experiment of Lyberg-Åhlander et al [34], which is based on a questionnaire answered by 467 teachers, the authors showed that there are lots of teachers who suffer from voice problems. The stronger reaction to vocally loading factors in the teaching environment very often leads to absenteeism from work. From the performed experiment it is clear that teachers with voice problems prefer longer room decay times while teaching in comparison with their healthy colleagues. But as the authors reported, more research is needed in this field.

In 2015 Puglisi et al [35] carried out experiments in real classrooms and reported that the vocal effort of the teachers can be classified as “raised” according to the standard ISO 9921 [27]. This can possibly lead to light or severe dysphonia [36].

An important finding about gender behavior in various acoustical environments is shown in a study by Hunter, where several differences between male and female teachers are shown [37]. In this study 57 teachers were monitored for 2 weeks. In environments with sound-absorbing panels a tendency of speakers to decrease the speech levels was reported. Fatigue problems occurred mostly for speaking loudly, especially with noise.

4. Influence of noise in restaurants

People in restaurants usually feel good when they are accompanied by friends, family or colleagues. Eating, drinking, talking and listening go together and from the acoustic point of view we consider people present in the room not only as listeners (e.g. sound receivers), but also as potential sound sources (e.g. speakers). All sounds from restaurant guests, ventilation systems, background music etc. are creating soundscape, which impacts on our feelings, mood, emotions and sometimes can even stimulate acoustic memories [38]. Noise in restaurants affects not only customers, but also employees of the restaurant, who are exposed to the given soundscape unwillingly and over longer time periods than customers.

B. Rohrmann studied acoustic conditions in several eating establishment from the point of view of social-psychology. He researched the opinions of customers through private interviews. The number of participants was 72 including employees and management staff. Besides the overall acoustic comfort assessment, he also took measurements of noise in several eating establishments and found out that the opinions of customers are very specific and a lot affected by music in the background. The measured values varied between 85 and 100 dB, but for most of the customers these values were acceptable [39].

Several researchers have investigated acoustic conditions in restaurants through measurements in situ. In Belgium, noise measurements in the student restaurant Alma in Leuven and in Trapistencafe in Westmalle were taken. This research was focused on observations of sound pressure level changes in a function in which a number of people were present. This publication reports the increase of sound pressure level by 5 dB in Trappistencafe and 6 dB in Alma when the number of people has doubled. Faster increases of sound level in Alma were probably caused by background music. But some values are higher than expected, which might be caused by the Lombard effect [40].

Similar experiments were performed by researchers in Hong Kong (Chinese restaurant, fast food and style of west restaurant). The results of measurements were within the range of 67 dB(A) to 89 dB(A). The aim of this research was to create a mathematic model of soundscape behaviour in a restaurant. The analysis has shown that the creation of a model is dependent on the density of seated people. The model was confirmed by measurements which showed that people increase their voices with the aim of achieving better speech intelligibility [41].

Also, White investigated the acoustic environment in a restaurant for gourmet foods in five eating establishments. The sound pressure level of unoccupied restaurants was within the range of 44–66 dB(A) and it was within the range of 66–80 dB(A) when 10–94 customers were present [42]. Christie researched objective possibilities (like the equivalent sound absorption of a room / equivalent absorption area of a room, reverberation time, the volume of a room, . . .) and possibilities of predicting acoustics which are acceptable environment in bars, cafes and restaurants. Her hypothesis states that noise in the sampled establishments is significantly affected by background noise. Average background noise level reached 57 dB(A) in bars, 58 dB(A) in cafes and 65 dB(A) in restaurants [43].

Lack of speech intelligibility is one of the reasons why people start to speak louder, and in doing so, noise levels in a room increase. Communication and conversation at the table in restaurants is known for its complexity. On the one hand, there are high noise levels, which can be considered as disturbing, but on the other hand, a certain noise level in the background is needed for providing speech privacy. High noise levels will support good speech privacy on the one hand, but they will disturb speech intelligibility on the other. Therefore, people will increase their voice when talking to people at the table in order to provide sufficient signal to noise ratio, but in doing so they will contribute to the overall noise in restaurant. In any case, providing good speech privacy in restaurant is a cumbersome task, since people can understand speech also in noisy environment thanks to the binaural unmasking phenomenon. This ability of the human auditory system is known as the cocktail-party effect [40].

The development of a method for prediction of speech intelligibility in noisy environments has been investigated by number of other authors. One of the most important references that can be found in the literature is the work of Lazarus [10, 11]. On the basis of his research, new general curves for the determination of speech intelligibility depending on distance between communicating persons and the signal interference level have been developed. This method serves for the description of quality of verbal communication, which includes the performance of a speaker and reduction of speech intelligibility in the position of a listener.

Assessment of verbal communication in pizzerias in Turin, Italy was the aim of research by Astolfi and Filippi. This research was based on questionnaires. The experiment aimed to assess verbal communication depending on the amount of sound absorption in a room, seating density, type of customers and on the influence of the Lombard effect [44].

Lena and Elaine dealt with comparison of speech intelligibility in four types of spaces (restaurant, cafe, metro, bus). The study was based on the spontaneous dialogue of 24 German speakers. The results have shown that the main influence of the Lombard effect [10] was seen in the increase of vocal effort. The Lombard effect has influenced the fundamental frequency of voices in both genders. The speed of the verbal communication stayed constant and so their conclusion was that noisy environment and influence of the Lombard effect didn't affect the speed of verbal communication [45].

Nahid and Hodgson investigated the quality of verbal communication and speech privacy in eating establishments by means of acoustic simulation (CATT-Acoustic), predicting the speech privacy and speech transmission index of existing eating establishments. The simulation took into account also the impact of the Lombard effect. By iteration of models and by the adding of barriers, sound absorption and dividing big places into smaller parts, it was possible to reach an optimal verbal communication and speech privacy [46].

Navarro and Pimentel researched interference of verbal communication with the aim of model creation for the prediction of noise in places for eating in shopping centers. The quality of verbal communication was assigned as poor in 12 eating areas where noise levels fluctuated between 66 dB and 70 dB. An increase of a speakers vocal effort did not suffice for achieving acceptable conditions for verbal communication. The impact of the position of sound absorption was also investigated, and it has been concluded that the most effective position for sound absorption placement in restaurant is the ceiling [47].

Kang compared basic characteristics of speech intelligibility by verbal communication in eating establishments with a lot of sitting places and with high levels of occupancy. Parametric study (performed in software that uses the radiosity method) has shown that with the raising of the amount of sound absorption it is possible to increase the values of the speech transmission index from 0.2 to 0.4. Acoustic absorbers can be situated differently in rooms with regular shapes. The strategic deployment of acoustic absorbers is needed for spaces with flat and long shapes [48].

The required size of the sound absorption area can be derived from values of acoustical capacity. A definition of acoustical capacity was developed by J. H. Rindel from his prediction models for average noise level depending on the number of present people. For estimating the number of present people, the parameter g (group size) was established. It was defined as a ratio of present people and active (speaking) people. Interestingly, in case of present people counted as possible sound sources, the noise level drops by 6 dB with doubling of sound absorption area (at constant sound source, without the Lombard effect, the noise level drops by 3 dB by the doubling of the sound absorption area) [49, 50].

5. Problems of sports teachers

Gymnasiums and sports halls are among such places with high background noise levels caused by internal sources, such as pupils playing, etc. Raising ones voice helps in speech understanding when there is background noise as a speech masking sound source. One can also increase the signal-to-noise ratio by decreasing the distance between the sound source (teacher) and receiver (student).

There is a difference in acoustical condition in rooms with long reverberation times (such as sports halls or gymnasiums where sound absorption is missing). In such spaces an increasing in speech level wont help understanding of speech. The stronger the signal sound is, the stronger the reflections will be. Therefore, the masking effect of reverberation remains the same [51].

There are two different acoustical environments for a physical education teacher to give their lessons: (1) Indoor environment, such as gymnasiums and sport halls and (2) Outdoor environment, such as football field, athletic stadium, basketball or any court.

The main problem of outdoor facilities for a speaking teacher is caused by law of sound attenuation in an open field, i.e. the voice level of teacher is decreased with distance by 6 dB for doubling the distance from the sound source (the teachers mouth). In general, talking to a large group of pupils without amplification outdoors is difficult in any case. Another problem can be caused if a school or courtyard is situated in a city center or close to a large road. In such case there might be a relatively high level of traffic noise or any other noise.

The background noise from traffic is partially blocked by building envelope during sport lessons performed indoors. However, there is the possibility of noise penetration because of naturally solved ventilation of such spaces since it is crucial to ensure an environment with fresh air for lessons. This means that windows might stay open for whole lessons; therefore levels of traffic noise will be acceptable or not-acceptable. Walls of the indoor environment can also help to support the teachers voice. However, speech intelligibility might be deteriorated by too much reverberation.

There is also the influence of the number of children/students present at a PE class. The noise from pupils will be increased because of reflections from interior constructions as well as different objects in the sport hall. This will force teachers to increase their voices also in an indoor environment [52].

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References

[1] Zelem, L.: The impact of acoustic properties of room and number of people present on psychoacoustics perception and verbal communication, *Advanced Building Construction and Materials*, 2015, 368–92.

[2] Thibeault, S. L., Merrill, R. M., Roy, N., Gray, S. D., Smith, E. M.: Occupational risk factors associated with voice disorders among teachers, *Annals of Epidemiology*, 2004, 14(10), 786–92.

[3] Roy, N., Merrill, R. M., Thibeault, S., Parsa, R. A., Gray, S. D., Smith, E. M.: Prevalence of voice disorders in teachers and the general population, *Journal of speech, language, and hearing research: JSLHR*, 2004, 47(2), 281–93.

[4] Connolly, D. M., Dockrell, J. E., Shield, B. M., Cox, T. J.: Students' perceptions of school acoustics and the impact of high noise on teaching and learning in secondary schools: Findings of a questionnaire survey, *Energy procedia*, 2015, 78, 3114–19.

[5] Lubman, D., Sutherland, L. C.: Classroom acoustics for the 21st century, 19th International Congress on Acoustics, Madrid, 2007.

[6] Lyberg-Åhlander, V., Haake, M., Brännström, J., Schötz, S., Sahlén, B.: Does the speaker's voice quality influence children's performance on a language comprehension test?, *Int J Speech Lang Pathol*, 2015, 17, 63–72.

[7] Roy, N., Merrill, R. M., Thibeault, S., Gray, S. D., Smith, E. M.: Voice disorders in teachers and the general population: effects on work performance, attendance, and future career choices, *Journal of speech, language, and hearing research: JSLHR*, 2004, 47(3), 542–51.

[8] Russell, A., Oates, J., Greenwood, K. M.: Prevalence of voice problems in teachers, *Journal of voice: official journal of the Voice Foundation*, 1998, 12(4), 467–79.

[9] Vilkman, E.: Voice problems at work: A challenge for occupational safety and health arrangement, *Folia Phoniatrica et Logopaedica*, 2000, 52(1–3), 120–5.

[10] Morton, V., Watson, D. R.: The impact of impaired vocal quality on children's ability to process spoken language, *Logopedics, phoniatrics, vocology*, 2001, 26(1), 17–25.

[11] Rogerson, J., Dodd, B.: Is there an effect of dysphonic teachers' voices on children's processing of spoken language?, *Journal of voice: official journal of the Voice Foundation*, 2005, 19(1), 47–60.

[12] Astolfi, A., Pellerey, F.: Subjective and objective assessment of acoustical and overall environmental quality in secondary school classrooms, *The Journal of the Acoustical Society of America*, 2008, 123(1), 163–73.

[13] Lassandro, P., Cosola, T., Tundo, A.: School building heritage: energy efficiency, thermal and lighting comfort evaluation via virtual tour, *Energy procedia*, 2015, 78, 3168–73.

[14] Tiesler, G., Machner, R., Brokmann, H.: Classroom Acoustics and Impact on Health and Social Behaviour, *Energy Procedia*, 2015, 78, 3108–13.

[15] Loreti, L., Barbaresi, L., De Casaris, S., Garai, M.: Overall indoor quality of a non-renewed secondary-school building, *Energy procedia*, 2015, 78, 3126–31.

[16] MacKenzie, D. J., Airey, S.: Classroom Acoustics, A Research Project, Summary Report, 1999.

[17] Pekkarinen, E., Viljanen, V.: Effect of sound-absorbing treatment on speech discrimination in rooms, *Audiology: official organ of the International Society of Audiology*, 1990, 29(4), 219–27.

[18] Bradley, J. S.: Speech intelligibility studies in classrooms, *The Journal of the Acoustical Society of America*, 1986, 80(3), 846–54.

[19] Vargová, A., Tirpáková, V., Rychtáriková, H.: Working conditions of sport teachers from Acoustical point of view, *Building and Environment*, Brno, Brno university of technology, 2010, 149–52.

[20] Pelegrin-Garcia, D., Fuentes-Mendizabal, O., Brunskog, J., Jeong, C. H.: Equal autophonic level curves under different room acoustics conditions, *The Journal of the Acoustical Society of America*, 2011, 130(1), 228–38.

[21] Hodgson, M., Rempel, R., Kennedy, S.: Measurement and prediction of typical speech and background-noise levels in university classrooms during lectures, *The Journal of the Acoustical Society of America*, 1999, 105(1), 226–33.

[22] Houtgast, T.: The Effect of Ambient Noise on Speech-Intelligibility in Classrooms, *Applied Acoustics*, 1981, 14(1), 15–25.

[23] Pekkarinen, E., Viljanen, V.: Acoustic conditions for speech communication in classrooms, *Scand Audiol*, 1991, 20(4), 257–63.

[24] Byrne, B. M.: Testing for the Validity, Replication, and Invariance of Causal Structure Across Elementary, Intermediate, and Secondary Teachers, *American Educational Research Journal*, 1994, 31(3), 645–73.

[25] Cornelisse, L. E., Gagnne, J. P., Seewald, R. C.: Ear level recordings of the long-term average spectrum of speech, *Ear and hearing*, 1991, 12(1), 47–54.

[26] Shield, B. M., Dockrell, J. E.: The effects of noise on children at school, *Journal of Building Acoustics*, 2003, 10(2), 97–106.

[27] Standardization I. O. f. ISO 9921: Ergonomics Assessment of speech communication. 2003.

[28] Nilsson, E., Hammer, P.: *Subjective Evaluation of Speech Intelligibility for normal hearing persons and for persons with simulated hearing loss*, 1995.

[29] Ruhe, C.: Barrierefreies Planen und Bauen, Klassenraumgestaltung fur die integrative Bechulung horgeschädigter Kinder, 2003.

[30] Sato, H., Bradley, J. S.: Evaluation of acoustical conditions for speech communication in working elementary school classrooms, *The Journal of the Acoustical Society of America*, 2008, 123(4), 2064–77.

[31] Rantala, L., Sala, E.: Associations between classroom conditions and teacher's voice production, *Energy procedia*, 2015, 78, 3120–5.

[32] Durup, N., Shield, B. M., Dance, S., Sullivan, R., Gomez-Augustina L.: How classroom acoustics affect the vocal load of teachers, *Energy procedia*, 2015, 78, 3084–9.

[33] Masuda, T., Ikeda, Y., Manako, H., Komiyama, S.: Analysis of vocal abuse: fluctuations in phonation time and intensity in 4 groups of speakers, *Acta otolaryngologica*, 1993, 113(4), 547–52.

[34] Lyberg-Åhlander, V., Rydell, R., Löfqvist, A., Pelegrin-Garcia, D., Burnskog, J.: Teachers' voice use in teaching environment. Aspects on speakers' comfort, *Energy procedia*, 2015, 78, 3090–5.

[35] Puglisi, G. E., Cantor Cutiva, L. C., Pavese, L., Castellana, A., Bona, M., Fasolis, S., et al.: Acoustic comfort in high-school classrooms for students and teachers, *Energy procedia*, 2015, 78, 3096–101.

[36] Astolfi, A., Bottalico, P., Accornero, A., Garzaro, M., Nadalin, J., Giordano, C.: Relationship between vocal doses and voice disorders on primary school teachers, *Proc. of Euronoise 2012*, Ninth Conference on noise control: European Acoustics Association, 2012, 55–60.

[37] Hunter, E. J., Bottalico, P., Graetzer, S., Leishman, T. W., Berardi, M. L., Eyring, N. G., et al.: Teachers and Teaching: Speech Production Accommodations Due to Changes in the Acoustic Environment, *Energy Procedia*, 2015, 78, 3102–7.

[38] Rychtáriková, M.: Psychoakusticke testy v stavebnej akustike, Bratislava: SAV, 2015.

[39] Rohrmann, B.: Soundscapes in restaurants, In: World Forum Acoustic Ecology (Eds.), *Proceedings of the International Symposium of Acoustic Ecolog*, Melbourne, 2003.

[40] Rychtáriková, M., Vermeir, G.: Soundscape in restaurants, *Fortschritte der Akustik – DAGA 2011*, 2011, 271–2.

[41] To, W. M., Chung, A. W. L.: Restaurant Noise: Levels and Temporal Characteristics, *Noise & Vibration Worldwide*, 2015, 46(8), 11–7.

[42] White, A.: The effect of building enviroment on occupants: the acoustics of dining Spaces, Robinson college, 1999.

[43] Christie, L. H.: Psycho-to-building acoustics: Are bars, cefes and restaurants acceptable acoustical eniromenments?, Wellington: Victoria University, 2004.

[44] Astolfi, A., Filippi, M.: Good acoustical quality in restaurants: a compromise between speech intelligibility and privacy, *Proc. of ICA*, Japan, 2004.

[45] Wong, L. L., Ng, E. H., Soli, S. D.: Characterization of speech understanding in various types of noise, *The Journal of the Acoustical Society of America*, 2012, 132(4), 2642–51.

[46] Hodgson, M., Razavi, Z., Steininger, G.: Evaluation of Acoustical Environments in Eating Establishments, *Building Acoustics*, 2009, 16(2), 125–48.

[47] Navarro, M. P. N., Pimentel, R. L.: Speech interference in food courts of shopping centres, *Applied Acoustics*, 2007, 68(3), 364–75.

[48] Kang, J.: Numerical modelling of the speech intelligibility in dining spaces, *Applied Acoustics*, 2002, 63(12), 1315–33.

[49] Rindel, J. H.: Verbal communication and noise in eating establishments, *Applied Acoustics*, 2010, 71(12), 1156–61.

[50] Rindel, J. H.: The Acoustics of places for social gatherings, *Proc. of Euronoise 2015*, Maastricht, 2015.

[51] Vermeir, G., Rychtáriková, M.: Invloed van de ruimteakoestiek op de spraakinspannig en op het Spraakverstaan, 7de Jaarlijks symposium "Bridging Voice Professionals", Leuven-Oss, 2010, 31–47.

[52] Cunha, D. S., de Abreu, L. C., Frizzo, A. C. F., Cardoso, M. A., Valenti, V. E.: Vocal complaint in physical education teachers and its association with the cardiovascular system, *International Archives of Medicine*, 2014, 7(7).

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Fan Noise Propagation in Hard-Wall and Lined Ducts

Šíření hluku ventilátoru potrubími s tuhými a pohltivými stěnami

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Acoustic transfer impedance (ATI) is proposed for use in investigating and describing noise propagation in ducts. A way of hybrid (analytical-numeric) computing ATI transfer functions in acoustically lined rectangular and cylindrical ducts is outlined, and some examples are shown of the ATI transfer functions computed in the proposed way. In the conclusion, further development is proposed of the ATI transfer function concept in application on fan noise in ducts.

1. Introduction

Let us recall first some basic terms that are used in this article. Acoustic transfer impedance (ATI or Z^{T}) is the designation for the complex ratio of sound pressure $p(f, X_0)$ at frequency f and in a point X_0 to the volume velocity $q(f, X)$ (also called volume flow and/or denoted by Q) generated by a sound source in a position X, where X and X_0 are the position vectors in the used coordinate system. As a result, we can write

$$Z^{\mathrm{T}}(f, X, X_0) = \frac{p(f, X)}{q(f, X_0)}. \tag{1}$$

Let us suppose first that the sound source has dimensions smaller than the respective wave lengths, or that it can be described or substituted by a bundle of small sound sources. In the case that $X = X_0$, we obtain the basic, "in place" acoustic impedance $Z(f, X)$ or also the acoustic load impedance, acting on a sound source. In a similar way, it is possible to extend the basic conception of acoustic specific impedance, which is defined as the complex ratio of sound pressure and particle velocity at a given point in a sound field.

Both acoustic impedances and acoustic-specific impedances are complex vectors, though using their complex amplitudes as functions of frequency is mostly sufficient. Acoustic transfer impedance is proposed for use instead of the sound pressure transfer function for fans, as fans are basically, or mostly can be assumed to be, sound sources with high internal acoustic impedance, and therefore to behave more as sources of (constant) volume velocity than sources of sound pressure.

An extensive amount of knowledge about noise generated by fans and its propagation in ducts has already been published, and is dealt with in numerous books and articles. Both fundamental and detailed information about noise in ducts and ductworks can be found e.g. in one well-known book [1], or in a comprehensive, freely accessible and recently updated university text [2], or even in a more condensed version in [3], to mention at least a few.

References [4–7] are another few examples of papers relevant to the topics of this paper, as is the modal concept of sound propagation in ducts [4, 5], or the acoustical lining of ducts [6], or the hybrid approach to simulating sound propagation in ducts [7]. In this paper, the concept of acoustic transfer impedance (ATI) is recommended to be used for describing noise propagation in ducts. Subsequently, a way of hybrid computing of ATI transfer functions in acoustically lined ducts is described.

The proposed way of computing ATI transfer functions is computationally less demanding than the methods of computational aeroacoustics or other methods based on FEM or BEM or similar principles.

The proposed way of using the ATI concept on fans and ducts is derived from the previous experience of the author with sources of known and/or constant volume velocity, and their use for measuring acoustic impedances [8–12], as well as later with measuring and computing acoustic load and transfer functions in rectangular rooms [14] and transient responses in rectangular rooms [15, 16].

The used way of computing acoustic load and transfer impedances in rectangular ducts emerges from the basic part of the older SW, formerly developed and used for simulation of acoustic transfer functions in rectangular rooms at low frequencies [15]. The last version of this SW can also simulate transient phenomena in rectangular rooms [16].

The basic parts of the mentioned earlier SW [15] have been used with only smaller modifications in the program DUCT_R [30], which is described briefly in the following section of this paper. Some problems arose with rewriting the mentioned earlier SW into cylindrical coordinates in the program DUCT_C, for cylindrical waveguides. Numeric generation of Bessel functions was solved by approximating the Bessel functions with trigonometric functions, available in all programming languages [17, 18].

2. Rectangular and cylindrical ducts

Let us first recall at least very briefly the basics of using the acoustic wave equation concept in application to rectangular and cylindrical ducts, supposing the presence of rigid, fully reflective walls and zero energy losses at sound wave propagation and reflection.

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2.1. Rectangular duct

Let us assume a simple rectangular duct situated in Cartesian coordinates as shown in Fig. 1.

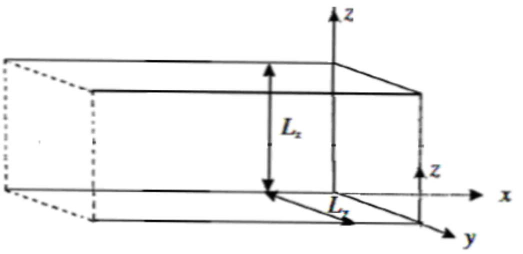

Figure 1: Rectangular duct in Cartesian coordinates

The wave equation for sound in air can be writen e.g. in its most often used version (explained thoroughly e.g. in [2, 3])

$$\frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} - \nabla^2 p = 0. \tag{2}$$

First, we need to find a single-frequency solution of the wave equation (2) with separated variables x, y and z as

$$p = A\mathrm{e}^{-\mathrm{i}(\alpha kx-\omega t)}Y(y)Z(z). \tag{3}$$

By substituting (3) into the wave equation and by separating the variables, it is possible to obtain the following equations for the two transversal wave modes

$$\begin{aligned} &\frac{\partial^2 Y}{\partial y^2} + k_y^2 Y = 0,\\ &\frac{\partial^2 Z}{\partial z^2} + k_z^2 Z = 0. \end{aligned} \tag{4}$$

The basic solution of the above set of second-order equations (4) can be written e.g. as

$$\left.\begin{aligned} Y(y] &= \begin{matrix}\sin(k_y, y)\\ \cos(k_y, y)\end{matrix}\\ Z(z] &= \begin{matrix}\sin(k_z, z)\\ \cos(k_z, z)\end{matrix} \end{aligned}\right\} k_y^2 + k_z^2 = k^2(1-\alpha^2). \tag{5}$$

In equation (3) and later on, k is the wave number. In the case of hard walls, it must be

$$\frac{\partial Z}{\partial z} = 0, \qquad \frac{\partial Y}{\partial y} = 0.$$

Therefore, also for the two transversal wave numbers k_{ny} and k_{nz} must be

$$\sin(k_{ny}L_y) = 0, \qquad \sin(k_{nz}L_z) = 0.$$

As a result, for the transverse angular eigen-frequencies ω_{nynz} we find the well-known formula

$$\omega_{nynz} = c\pi\left[(n_y/L_y)^2 + (n_z/L_z)^2\right]^{-1/2} \tag{6}$$

and it is possible to introduce a coefficient of dispersion for transversal wave modes

$$\alpha_{nynz} = \sqrt{1-\left[\left(\frac{n_y\pi}{kL_y}\right)^2 + \left(\frac{n_z\pi}{kL_z}\right)^2\right]}, \tag{7}$$

for which the following also holds:

$$\alpha_{nynz} = \sqrt{1-(\omega_{nynz}/\omega)^2}. \tag{8}$$

The coefficient of dispersion α_{mn} also equals the cosine of the angle φ between the modal wavefronts and the duct axis. It may be interpreted as well as an indicator of how a particular wave mode will propagate in the duct. Each mode propagates axially along the duct at their axial phase speeds. Hence, the axial speed of transverse modes will then be

$$c_{mn} = \frac{c}{\sqrt{1-(\omega_{mn}/\omega)^2}}. \tag{9}$$

The next well-known formula holds for eigen frequencies of all the particular wave modes in rectangular ducts as well:

$$f_{m,n,p} = \frac{c_0}{2}\sqrt{(n/L_x)^2 + (m/L_y)^2 + (p/L_z)^2}. \tag{10}$$

The resulting sound pressure in the duct is the weighted sum of the pressure patterns of the particular wave modes, and the sound pressure distribution in a rectangular duct can be expressed (e.g.) as

$$\begin{aligned} &\hat{p}(y,z,x) = \sum_{ny=1}^{\infty}\sum_{nz=1}^{\infty} A_{nxny}\Phi_{nxny}(y,z)\,\mathrm{e}^{-\mathrm{i}\alpha kx},\\ &\Phi_{nynz}(y,z) = \cos(k_{ny}y)\cos(k_{nz}z). \end{aligned} \tag{11}$$

Supposing excitation of the sound field in the duct by a point or very small sources of volume velocity, the coefficient A_{nxny} will also have to include the excitation weighting coefficients for the individual wave modes according to the position of the sound source. Let us just recall that for the propagation of an acoustic mode in a duct, its coefficient of dispersion α_{mn} must be real. Otherwise the wave decays exponentially (evanescent wave).

2.2. Cylindrical duct

Let us suppose a cylindrical duct situated in cylindrical coordinates e.g. as in Fig. 2.

The Laplace operator in the wave equation for sound in cylindrical coordinates can be written as [see again e.g. 2,3]

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2}{\partial\theta^2}. \tag{12}$$

Let us again find a harmonic, single-frequency solution of the wave equation in cylindrical coordinates with separated variables as

$$p = A\mathrm{e}^{-\mathrm{i}(\alpha kx-\omega t)}G(r)H(\theta). \tag{13}$$

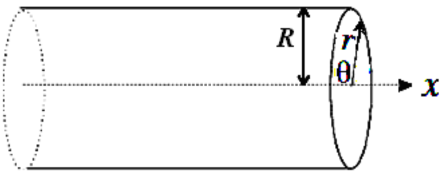

Figure 2: Cylindrical duct in cylindrical coordinates

By substituting (13) into the wave equation, and separating variables, we can – similarly as in rectangular coordinates – obtain two equations with separated coordinates

$$\begin{aligned} \frac{\partial^2 G}{\partial r^2} + \frac{1}{r}\frac{\partial G}{\partial r} + \left[k^2\left(1-\alpha^2\right) - \frac{m^2}{r^2}\right] G = 0, \\ \frac{\partial^2 H}{\partial \theta^2} + m^2 H = 0, \end{aligned} \qquad (14)$$

which are only slightly more complicated than the equations (4) in rectangular coordinates. The equations for transversal wave modes can be written as

$$\left.\begin{aligned} G(r) &= \frac{\mathrm{J}_m(\kappa r)}{\mathrm{Y}_m(\kappa r)} \\ H(\theta) &= \mathrm{e}^{-\mathrm{i}m\theta} \end{aligned}\right\} \kappa^2 = k^2\left(1-\alpha^2\right), \qquad (15)$$

where κ is the transversal wave number, J_m and Y_m Bessel functions. For more explanations see again e.g. [3, 4].

Bessel functions are mostly not available in the majority of programming languages; however, trigonometric approximations are available [17, 18]. The resulting sound pressure pattern in the cylindrical duct is again the weighted sum of pressure patterns of the particular wave modes. Sound pressure distribution in cylindrical ducts can be described similarly as

$$\begin{aligned} \hat{p}(r,\theta,x) &= \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} A_{mn}\Phi_{mn}(r,\theta)\,\mathrm{e}^{-\mathrm{i}\alpha_{mn}kx}, \\ \Phi_{mn}(r,\theta) &= \mathrm{J}_m(\kappa_{mn}r)\,\mathrm{e}^{-\mathrm{i}m\theta}. \end{aligned} \qquad (16)$$

If we suppose the excitation of the sound field by a point source of a known volume velocity, the coefficient A_{mn} will have to include the weighting factors for individual wave modes according to the shape of the mode and position of the sound source.

Examples of shapes or nodes of transversal wave modes in cylindrical ducts are shown in Fig. 3, where k is the wave number ($k = 2\pi f/c_0$) and a stands here for the radius of the duct. The transversal mode with the lowest eigenfrequency is the first circular one for which $ka = 1.841\,2$. The eigen-frequency of the lowest transversal mode will therefore be $f_{10} = 1.841\,2 \cdot c_0/(\pi D)$, where D is the inner diameter of the duct. Let us recall again that the acoustic mode mn propagates in a duct only if its coefficient of dispersion α_{mn} is real, which also means its frequency $f \geq f_{mn}$.

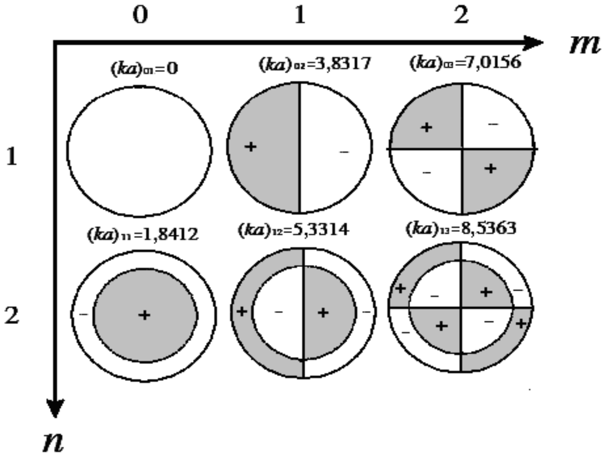

Figure 3: Transversal wave modes in cylindrical ducts

3. Computing transfer functions in ducts

In the previous chapter, we have seen a brief review of the wave theory basics of sound fields in rectangular and cylindrical ducts with hard walls and no energy losses. To obtain transfer functions, formulations (11) and (16) have to include an excitation of the sound field in the ducts.

In this paper, we recommend for acoustic transfer impedance (ATI) to be used for describing and investigation fan noise propagation in ducts, rather than sound pressure transfer functions. The way of computing acoustic transfer impedances in rectangular ducts proposed in this paper is derived from an older SW formerly developed for simulation of sound fields and sound transfer functions in rectangular rooms [14, 15]. The last version of this SW could also simulate transient phenomena in rectangular rooms [16].

The basic part of the mentioned earlier SW [14, 15] has been used with only small modifications in the program DUCT_R, [30], for computing transfer and acoustic load impedances in rectangular ducts with sound-absorptive walls. Several problems arose with transcription of the author's earlier SW from rectangular to cylindrical coordinates in the program DUCT_C, written for cylindrical ducts.

The numeric generation of Bessel functions in the program DUCT_C is solved using an approximation of Bessel functions by a trigonometric function [17, 18].

3.1. Rectangular ducts with rigid reflective walls

To obtain transfer impedance from the formulation (11), it has to be extended to include also a source of excitation of the sound field in the duct. In the contemporary state of development of the DUCT programs, an excitation of the ducts is supposed by a source of constant volume velocity having small or negligible dimensions. As a result, the relation for acoustic transfer impedance in a rectangular duct can be expressed e.g. as

$$\begin{aligned} Z^{\mathrm{T}}(y,z,x,y_0,z_0,k) &= \\ &\sum_{n=1}^{\infty}\sum_{m=1}^{\infty} A_{nm}\Psi_{nm}(y_0,z_0)\Phi_{nm}(y,z)\,\mathrm{e}^{-\mathrm{i}\alpha kx}, \\ \Phi_{nm}(y,z) &= \cos(k_n y)\cos(k_m z), \\ \Psi_{nm}(y_0,z_0) &= \cos(k_n y_0)\cos(k_m z_0). \end{aligned} \qquad (17)$$

In relations (17), Z^{T} is the acoustic transfer impedance from the point y_0, z_0 ($x_0 = 0$) to the point x, y, z, and $k = \omega/c_0$ ($\omega = 2\pi f$, c_0 is the speed of sound). It is assumed that the sound source is situated in the wall at $x_0 = 0$, and all the walls are rigid and reflective. The basic layout of the supposed rectangular duct and its position in Cartesian coordinates is shown in Fig. 4. The particular points 1 to 5 are discussed in a later section.

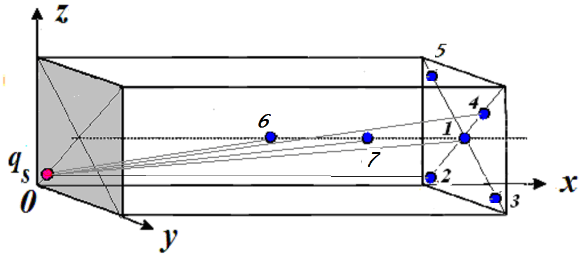

Figure 4: Rectangular duct with coordinates

The relations (17) have been derived for all the walls being rigid and reflective. As has already been mentioned, some energy losses can be introduced into the basic loss-free solution in the simplest way by assuming the sound speed or wave number to be complex, defined e.g. as

$$\underline{c}_0 = c_0\,(1+\mathrm{i}\eta)^{-1/2}$$

and

$$\underline{k} = k\,(1+\mathrm{i}\eta)^{-1/2},$$

where η is a coefficient of losses or a sound propagation loss factor. By introducing the complex wave number $\underline{k}$ into equations (17), rewritten with complex variables, it is possible to obtain the simplest solution of the wave equation with (equally) damped modal resonances. An example of an ATI transfer function with slightly damped modal resonances in a rectangular duct computed in this simple way is shown in Fig. 5.

Shown in Fig. 5 is the sound pressure (module) level at a point 1 inside of the rectangular duct outlined in Fig. 4, computed as a function of frequency for the source of constant volume velocity q_s placed in a base wall as marked in Fig. 4 by a red dot. The entered dimensions of the duct were: cross-section (0.5 × 0.5) m and length 5 m. The entered sound propagation loss factor was $\eta = 0.01$.

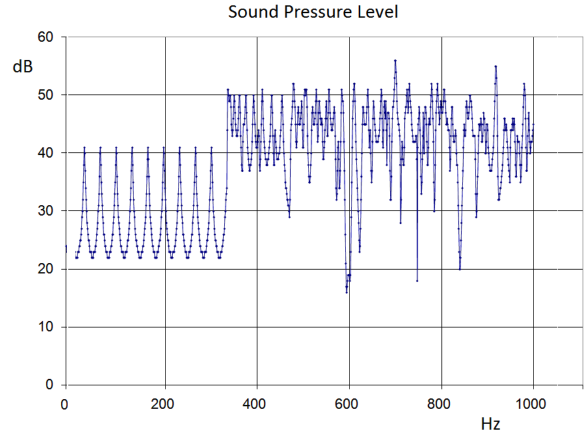

Figure 5: An example of a computed ATI transfer function in a rectangular duct

As can be seen from Fig. 5, up to about 340 Hz, only a simple axial wave propagates in the duct from the sound source, which then is reflected back from the closed hard and reflective end wall of the duct, and thus creates the axial standing wave. Beginning at 343 Hz, transversal waves start to emerge. In this simulation, all wave modes are damped equally.

The same way of introducing at least some sound propagation losses into the basic lossless relations can also be used for cylindrical ducts. Let us add that using complex wave numbers or a complex speed of sound is a highly frequent practice in describing the acoustic properties of porous or fibrous materials and sound propagation in spaces filled with such materials [19].

3.2. Ducts with sound absorptive walls

Walls or sections of ducts with sound-absorptive lining are very often used for noise damping in air-distributing ductworks. Terminating sections of ducts with sound absorptive walls is a method also used in standardized measuring facilities for measuring noise of fans radiated into ducts.

As has already been mentioned, computing ATI transfer functions in ducts is possible in different ways e.g. also by the now widely available SW using contemporary advanced numeric methods of computational aeroacoustics or by other numeric methods based mostly on FEM or BEM principles. For ducts, such methods are, however, computationally needlessly too demanding.

The way of computing ATI transfer functions in ducts with sound-absorbing walls proposed in this paper is derived from an analytical solution. An example of such a solution is equation (17). To get acceptable results for sound absorptive walls, the boundary task for non-zero boundary conditions has been solved using numeric iterations based on the Newton-Raphson iteration scheme [20].

The Newton-Raphson iteration technique proved relatively simple and fast even for transcendental functions.

An identical method based on the Newton iteration scheme was used by this author and referred to already in his previous paper [15]. It has been described in papers [21, 22], and is used in the DUCT programs. An example of ATI transfer function in a rectangular duct with sound-absorptive walls as computed by the program DUCT_R is shown in Fig. 6.

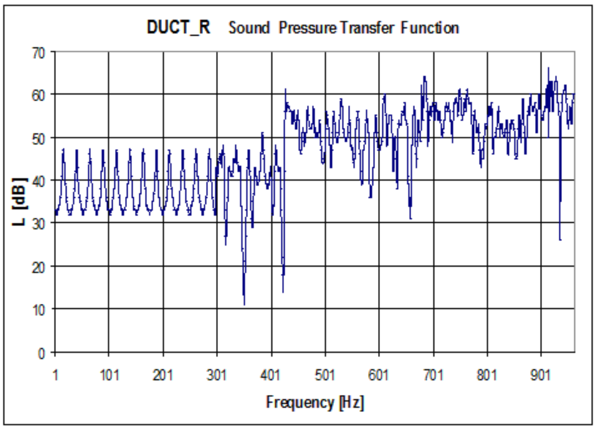

Figure 6: An example of ATI transfer function module computed by program DUCT_R

For the example of the ATI transfer function in Fig. 6, the figures entered were the duct cross-section dimensions (0.6×0.8) m and the duct length 7 m. The source of volume velocity (10^{-6} m^3/s) was near one corner in the wall at $x = 0$. The target point was in the opposite corner at $x = 6.9$ m, $y = 0.79$ m, $z = 0.59$ m. For all the walls, the sound absorption coefficient entered was $\alpha = 0.15$. The wall with the sound source is supposed to be rigid and to have zero sound absorption.

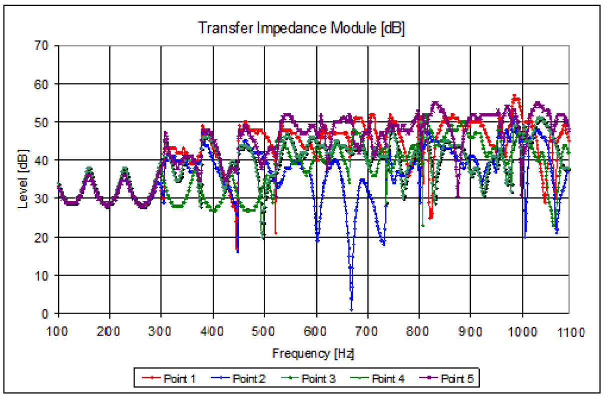

Figure 7: Set of ATI transfer functions in a rectangular duct as computed by the program DUCT_R

Another example of a set of ATI transfer functions in a rectangular duct as also computed by the program DUCT_R is shown in Fig. 7.

In this case, the basic dimensions of the duct were entered as: cross-section (0.8×0.5) m and length 3 m. Coefficients of the sound absorption entered were 0,2 for both the wider walls, 0.3 for the narrower walls and 0.4 for the terminating wall of the duct.

Again, the sound source was placed in one corner, as also marked in Fig. 4. The target points 1–5 were on, or very near to, the terminating wall, as they are marked (approximately) also in Fig. 7. Plotted in Fig 7 are again only the (relative) ATI moduli levels in dependence on the frequency or the sound pressure levels in dB for excitation by volume velocity 10^{-6} m^3/s.

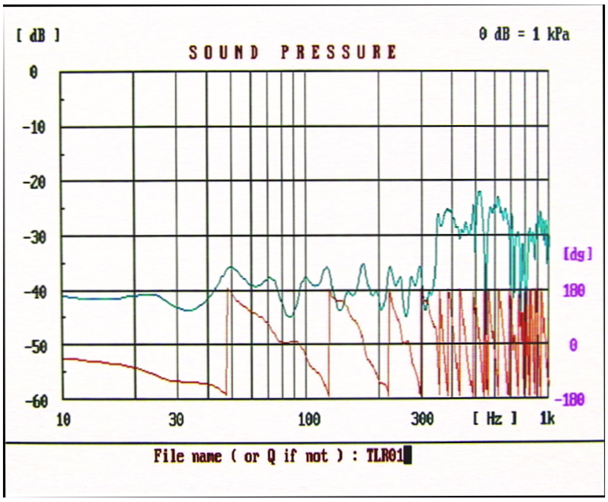

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Figure 8: An example of the output of program DUCT_C

In Fig. 8 is an example of a possible output of a DUCT program (DUCT_C this time) as displayed on a computer screen. Plotted in this case are the ATI modulus in dB and the phase angle in degrees. After the computation is completed, the results of computing can be derived or copied from the screen and saved for further use.

Shown in Fig. 8 is an ATI transfer function computed for a cylindrical duct with diameter 0.6 m and length 4 m. The ATI transfer function has been computed for the location of the sound source with radius $r_0 = 0.28$ m and at the azimuth angle $\theta = 0°$. The target point was set at a distance of 3 m from the sound source at the duct axis.

Other examples of the outputs of the programs DUCT_R and DUCT_C are shown in the Appendix.

3.3. Further development

First described in this paper were two versions of the DUCT programs. A supposition for further development is to make it possible to simulate excitation of the duct by a rotating line source of volume velocity, and subsequently as well with programmable volume velocity distribution and also for streaming air in the ducts. In the contemporary state of development, the DUCT programs are proved to give highly useable results for the velocities of the air streaming in ducts up to 15 m/s (as a similar limit also exists in EN ISO 11691).

The subsequent research was intended to aim first at further improving the simulation of the sound field in both rectangular and cylindrical ducts as derived from some recent papers such as e.g. [23–25] and then to add the simulation of the noise radiation from the open ends of pipes [26] and also a possible simulation of spinning waveform modes with flow [27, 28] in both circular and rectangular ducts. As of now, however, no continuance of the commenced development is foreseen.

4. Summary and conclusion

In this paper, acoustic transfer impedance (ATI) is recommended for describing and evaluating noise propagation in ducts and a method of hybrid computing for ATI transfer functions in acoustically lined ducts is described.

The proposed method of computing transfer functions in lined ducts is computationally much less demanding than the present fully numeric methods of computational aero-acoustics and/or general acoustics, or other methods based mostly on FEM or BEM or similar principles.

The proposed way of computing acoustic load and transfer impedances in ducts is derived from the previously developed and used routines for simulating acoustic load and transfer functions in rectangular rooms. The basic part of the mentioned older software has been used in the program DUCT_R, for rectangular ducts, and also in the similar program DUCT_C, for cylindrical waveguides.

The way of computing ATI transfer functions in ducts with sound-absorbing walls proposed in this paper emerges from the basic analytical solution of the wave equation with zero boundary conditions, an example of which is equation (17). To find the solution for sound-absorptive walls, the boundary task for nonzero boundary conditions is solved by an algorithm using the Newton-Raphson iteration scheme.

Some examples of ATI transfer functions computed by the two programs are shown and discussed in chapter 3. Further information about the use of the two programs with other examples of ATI transfer function is given in the Appendix. In the present article, only the two first versions of the two programs available now as finished executable computing programs are described.

In the contemporary state of development, the DUCT programs are expected to provide highly useable results of simulation for the air-streaming velocities up to 15 m/s, which also is a similar limit in EN ISO 11691. Further development should be targeted first towards making it possible to simulate excitation of the ducts by rotating line sources of volume velocity, and only subsequently with programmable volume velocity distribution and then for streaming air in the ducts.

Future work should also be aimed at further improving the simulation of the sound field in both rectangular and cylindrical ducts based on very recent findings, and in addition should also target the possible simplified simulation of spinning modes with flow. As of yet, however, no continuance of the commenced development is foreseen.

References

[1] Munjal, M. L.: “Acoustics of Ducts and Mufflers”, 2nd Edition, Wiley, March 2014.

[2] Rienstra, S. W., Hirschberg, A.: “An Introduction to Acoustics”, Ch. 7. Duct acoustics, Eindhoven University of Technology, 26 Jan. 2015. `http://www.win.tue.nl/~sjoerdr/papers/boek.pdf`

[3] Jacobsen, F.: Propagation of Sound Waves in Ducts, Tech. Univ. of Denmark. Lyngby. `http://web-files.ait.dtu.dk/fjac/p_home_page/notes/Duct_acoustics.pdf`

[4] Joseph, P., Morfey, C. L., Loqwis, C. R.: “Multi-mode sound transmission in ducts with flow”, Journal of Sound and Vibration, 264, 523–544, 2003.

[5] Bennett, G. J., O’Reilly, C. J., Liu, H.: “Modeling multi-modal sound transmission from point sources in ducts with flow using a wave-based method”, 16th International Congress on Sound and Vibration, Krakow, Poland, 2009.

[6] Sung-Hwan, K.: “Sound Attenuation in Lined Rectangular Ducts with Flow and its Application to Reduction of Aircraft Engine Noise”, J. Acoust. Soc. Am., vol. 50, 1971. `http://dx.doi.org/10.1121/1.1912784`

[7] Kirby, R.: “Sound propagation in acoustic waveguides using a hybrid numerical method”, School of Engineering and Design, Mechanical Engng., Brunel University, Uxbridge, UK. 2008, J. Acoust. Soc. Am., vol. 124(4), 1930–40, 2008. `http://core.ac.uk/download/pdf/335519.pdf`

[8] Salava, T.: “Sources of the Constant Volume Velocity and Their Use for Acoustic Measurements”, J. Aud. Eng. Soc., vol. 22, No 3, pp. 146–153, April 1974.

[9] Salava, T.: “Two Methods of Measuring Acoustic Impedances”, Transactions of 9th Internat. Congress on Acoustics, Madrid 1977.

[10] Salava, T.: “Acoustic Impedance Measurement Using Constant Volume Velocity”, J. Acoust. Soc. Am., vol. 67., p. 1831, May 1980. `http://scitation.aip.org/content/asa/journal/jasa/67/5/10.1121/1.384266`

[11] Salava, T.: “Measurements of the Input Impedance of Loudspeaker Horns”, J. Aud. Eng. Soc., vol. 29., p. 416., No. 6, 1981. `http://www.aes.org/e-ib/browse.cfm?elib=3903`

[12] Anthony, D. K., Elliott, S. J. A.: "Comparison of Three Methods of Measuring the Volume Velocity of an Acoustic Source", J. Aud. Eng. Soc., vol. 39, 5, pp. 355–366, May 1991, AES E-Library `http://www.aes.org/e-lib/browse.cfm?elib=5983`

[13] Dalmont, J. P.: "Acoustic impedance measurement, part I, A review", Journal of Sound and Vibration, vol. 243, No. 3, pp. 441–459, 2001. `http://www.aes.org/e-lib/browse.cfm?elib=7367`

[14] Salava, T.: "Acoustic Load and Transfer Functions in Rooms at Low Frequencies", J. Aud. Eng. Soc., vol. 36, p. 763, October 1988. `http://www.aes.org/e-lib/browse.cfm?elib=5130`

[15] Salava, T.: "Computer Simulation of Loudspeakers Performance in Rectangular Rooms", 102nd AES Convention, Munich 1997, preprint No. 4412 (B4).

[16] Salava, T.: "Low-Frequency Performance of Listening Rooms for Steady-State and Transient Signals", J. Audio Eng. Soc., vol. 36, p. 853, November 1991. `http://www.aes.org/e-lib/browse.cfm?elib=5960`

[17] Waldron, R. A.: "Formulas for computation of approximate values of some Bessel functions", Proceedings of the IEEE, vol. 69, 12, pp.1586–1588, 1981.

[18] Blachman, N. M., Mousavinezhad, S. H.: "Trigonometric approximations for Bessel functions", 1EEE Transact. on Aerospace and Electronic Systems, AES, 22, 2–7, 1986.

[19] Allard, J. F.: "Propagation of Sound in Porous Media", Elsevier Applied Science, 1993.

[20] The Newton-Raphson Method, UBC, Ca. `https://www.math.ubc.ca/~anstee/math104/104newtonmethod.pdf`

[21] Bistafa, S. R., Morrissey, J. W.: "Numerical solutions of the acoustic eigenvalue equation in the rectangular room with arbitrary (uniform) wall impedances", Journ. Sound Vibration, vol. 263, 1, pp. 205–218, May 2003.

[22] Buuren, Van G.: "Parametric studies on the low-frequency acoustics of listening rooms using a numerical wave model", (theses), May 2009. `http://www.whyverne.co.uk/acoustics/mscprojects/gil.pdf`

[23] Gorazd, L. at all.: "Modal Structure of the Acoustic Field in Hardwalled Cylindrical Duct", Forum Acusticum, Krakow, 2014. `http://www.fa2014.agh.edu.pl/fa2014_cd/article/RS/R21_3.pdf`

[24] Campos, L. M., Oliveura, L. M.: "On the Acoustic Modes in a Cylindrical Duct with an Arbitrary Wall Impedance Distribution", J. Acoust. Soc. Am., 116(6), December 2004.

[25] Silva, F., Guillemain, P. et all.: "Approximation formulae for the acoustic radiation impedance of a cylindrical pipe", J. Sound and Vibration, vol. 332, 1–2, 255–263, 2009.

[26] Newman, T. J., Agarwal, A., Dowling, A. P.: "Determination of the characteristics of a linear ducted sound source", Dept. Engng., Univ. of Cambridge, Submitted to J. Acoust. Soc. Am., 2014.

[27] Zhang, X., Chen, X., Monrfey, C. L., Nelson, P. A: "Computation of Spinning Modal Radiation from an Unflanged Duct", AIAA Journ., vol. 42, 9, September 2004.

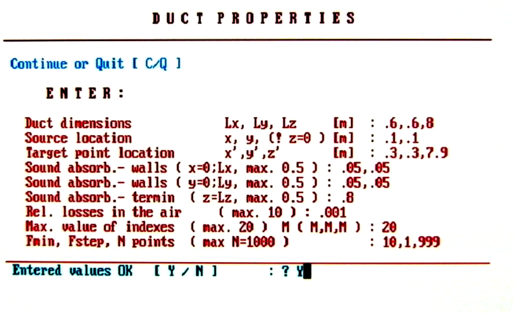
[28] Huang, X., Chen, X. at all: "Computation of Spinning Modal Radiation Through an Engine Bypass Duct", AIAA Journ., vol. 46, 6, June 2008.

[29] Salava, T.: "Noise Measuring and Control on Industrial Fans", Akustické listy, 20(3–4), 10–18, 2014. `http://www.czakustika.cz/listy/casopis/20-34.pdf`

[30] Salava, T.: Programy DUCT, Zpráva VZLÚ R-6192, 2015 – *In Czech.*

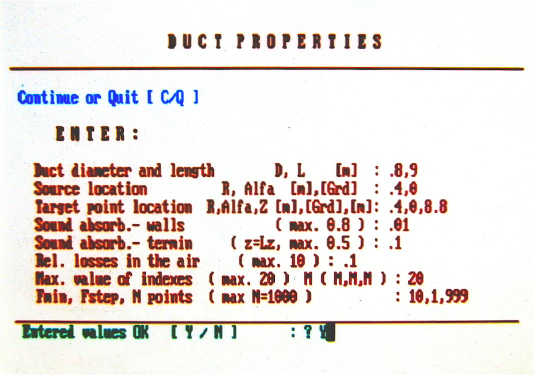
Appendix

Examples of the input and output screens of programs DUCT_R and DUCT_C.



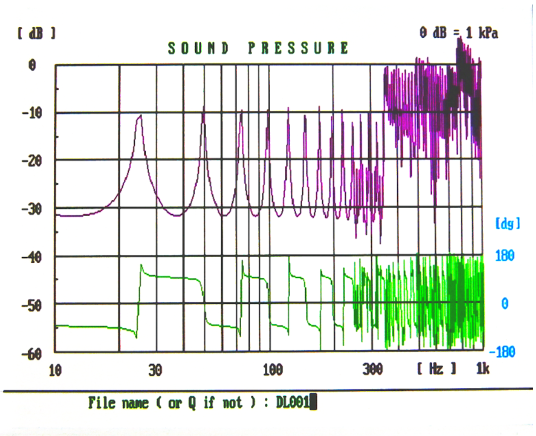
```
                    D U C T   P R O P E R T I E S

Continue or Quit [ C/Q ]

    E N T E R :

  Duct dimensions             Lx, Ly, Lz      [m]  : .6,.6,8
  Source location             x, y, (! z=0 ) [m]  : .1,.1
  Target point location       x',y',z'        [m]  : .3,.3,7.9
  Sound absorb.- walls ( x=0;Lx, max. 0.5 ) : .05,.05
  Sound absorb.- walls ( y=0;Ly, max. 0.5 ) : .05,.05
  Sound absorb.- termin  ( z=Lz, max. 0.5 ) : .8
  Rel. losses in the air      ( max. 10 ) : .001
  Max. value of indexes  ( max. 20 )  M ( M,M,M ) : 20
  Fmin, Fstep, N points  ( max N=1000 )            : 10,1,999

Entered values OK   [ Y / N ]        : ? Y
```

Figure 9: An example of the input screen of program DUCT_R with entered input values



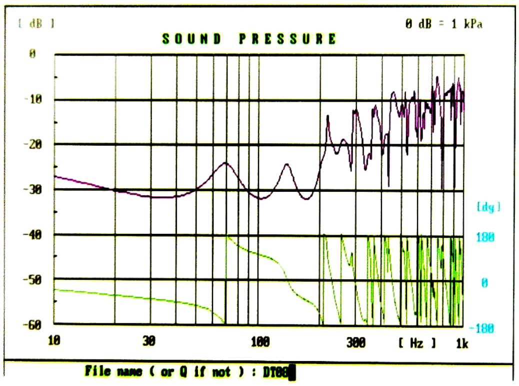
```
                    D U C T   P R O P E R T I E S

Continue or Quit [ C/Q ]

    E N T E R :

  Duct diameter and length        D, L    [m]  : .8,9
  Source location             R, Alfa  [m],[Grd]  : .4,0
  Target point location  R,Alfa,Z [m],[Grd],[m]: .4,0,8.8
  Sound absorb.- walls              ( max. 0.8 ) : .01
  Sound absorb.- termin       ( z=Lz, max. 0.5 ) : .1
  Rel. losses in the air      ( max. 10 ) : .1
  Max. value of indexes  ( max. 20 )  M ( M,M,M ) : 20
  Fmin, Fstep, N points  ( max N=1000 )            : 10,1,999

Entered values OK   [ Y / N ]        : ? Y
```

Figure 10: An example of the input screen of program DUCT_C with entered input values



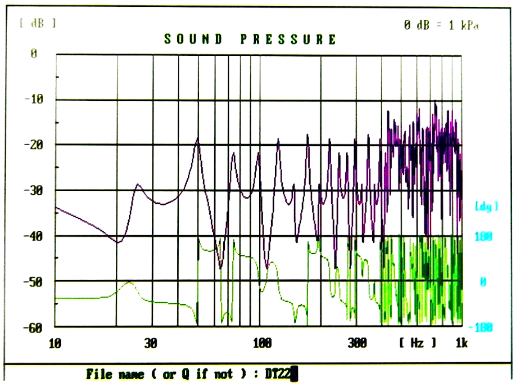
```
File name ( or Q if not ) : DL001
```

Figure 11: An example of an output screen of program DUCT_R



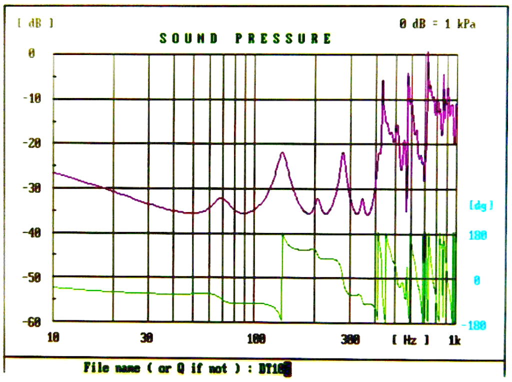
```
File name ( or Q if not ) : DT08
```

Figure 12: Another example of an output screen of program DUCT_R



```
File name ( or Q if not ) : DT22
```

Figure 13: An example of an output screen of program DUCT_C



```
File name ( or Q if not ) : DT18
```

Figure 14: Another example of an output screen of program DUCT_C

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