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Perceptual Characteristics of Buzz-Saw Aircraft Noise and Its Relationship to Noise Unpleasantness

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Summary

The term buzz-saw noise describes a physical and acoustic phenomenon occurring in high-bypass turbofan aircraft engines at high fan rotational speeds (e.g. during an aircraft take-off). In this situation, buzz-saw noise presents a component of noise emitted by the aircraft and can form a component of environmental noise around airports. Data from a listening test and signal analysis are used in the study to explore the perception and sound quality of the noise and its signal parameters. The results show an association between perceptual attributes and signal characteristics attributed to buzz-saw noise, and also show an association of the noise with unpleasantness. Verbal attributes describing sound quality related to the signal characteristics are also presented.

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1. Introduction

The term *buzz-saw* or *multiple-pure-tone* noise is used to describe a physical and acoustic phenomenon occurring in turbo-machinery and in high-bypass turbofan aircraft engines of some currently operated aircraft under high load conditions and at high fan rotational speeds, at which the front fan blade tips exceed the speed of sound (e.g. during an aircraft take-off). This results in the production of non-linear acoustic waves which propagate through the engine inlet duct and radiate as a saw-tooth-like pressure waveform forward of the aircraft engine. The buzzsaw phenomenon has been shown to occur in engines of modern turbofan passenger aircraft and presents a component of the aircraft noise during an approach of an aircraft towards a listener [1, 2]. The noise has been acoustically linked to the presence of multiple closely-located tonal components which occur at frequencies that are multiples of the rotation frequency of the engine fan shaft [3, 1, 4]. The tonal components have been used previously to indicate the presence of buzz-saw noise in aircraft noise [4].

Aircraft engine noise is a dominant source of noise *sound pressure level* in departing aircraft [5] and presents a significant source of noise exposure in communities along flight pathways of larger airports, which has been linked to negative effects on health and well-being in numerous studies (e.g. [6]). The negative effects have been causally linked to *annoyance* and *noise reaction* (e.g. [7, 8]) and

noise exposure is therefore subject to various reduction attempts [5] and regulatory measures (e.g. [9]), in which the concept of *annoyance* is used as a response metric [10]. *Annoyance* represents a complex concept which has been shown to feature affective components associated with unpleasantness of the perceived sound [7, 11, 12, 13, 14, 6], which has also been causally linked to the perceived sound quality of the noise [15, 16]. The sound quality of a noise may influence its on-ground annoyance and dose-response relationship and is therefore of concern to aircraft noise engineering and research [17].

An increase in annoyance due to aircraft noise with the same sound pressure levels has been reported in recent decades [18, 19, 20]. While several factors have been presented to explain the increase [20, 21], further causes, such as changes to sound quality of the noise due to changes in engine technology may also be proposed and buzz-saw noise subjected to further study.

Association of aircraft buzz-saw noise (and noise with non-linear waveforms) with unpleasantness has previously been discussed in qualitative and synthesis based studies [2, 22, 23, 3]. The noise has also been described in previous aircraft noise studies as *perceptually distinct* [3] and has been associated with a perceptual dimension in aircraft noise [22]. This implies the noise could be associated with noise annoyance on-ground and its perception may be associated with distinct sound qualities (which are therefore subject to this research). Multiple perceptual factors represented by such *distinct* sound qualities were found in environmental noise of departing aircraft [22], and have been associated with annoyance in Gille *et al.* [23] and also in the author's own research (a study of the relationship of

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perceived sound quality with unpleasantness of departing aircraft noise¹ [24]). A follow-up study of the data suggested a prominent perceptual factor could be associated with the occurrence of closely located tonal components in the frequency spectrum which have been attributed to buzz-saw noise [4].

In response to the conclusions above, the present study aimed to explore the sound quality, signal characteristics, and unpleasantness of the noise as perceived at exposed locations².

2. Method

The study is based on data collected using a method of subjective evaluation of recorded stimuli of aircraft noise in a listening test (the main listening test in section 2.5.). The test was performed with 23 respondents and 16 stimuli. The task of the respondents was to evaluate the sound quality and unpleasantness of the stimuli on rating scales, and also to evaluate the sound quality of the stimuli using verbal description (section 2.5). In addition to the main test, the method also entailed two listening pretests at the stage of stimuli processing (sections 2.1. and 2.4.). Statistical methods of text analysis [26], correlation, factor analysis, and regression analysis were used to analyse the data from the listening test, to associate the results to parameters from signal analysis of audio signals used as stimuli, and to test the hypotheses (section 3.2.).

2.1. Stimuli

Sixteen stimuli were used in the main listening test and as sound signals in the signal analysis. The stimuli are based on trims selected from a set of 87 binaural aircraft recordings which were binaurally recorded during 16 hours of recording time at two locations (Prague - Suchbát and Unhost, Czech Republic) in the axis of Prague Václav Havel International Airport (7.2 km distance from the runway threshold; no reflecting surfaces in a 4 m radius, grassland, wind speed below 5 m/s, no precipitation). The duration of the samples was 1 second. The beginning of the trim of the recording was defined for every sound event by a first average sound pressure level rise above 65 dB_A. It was confirmed by measurements made during the recording sessions that the elevation angle of the aircraft-observer line at this level remained below 60°. The aircraft are therefore expected to be in positions at which buzz-saw noise emission occurs [1].

The samples had to meet the condition of a quasi-stationary character within the selection (absence of foreign noises or abrupt changes in sound recognised by a sound engineer performing the selection). A selection in a broader 1.5 s range was attempted for samples not meeting the condition. Thirty-four samples met the conditions

(were mainly without bird tweets or various noises) and were processed for use as stimuli with a 100 ms linear fade-in and fade-out. The stimuli were also adjusted in amplitude (to attain better loudness consistency relative to the initial dB_A selection) following to the results of a listening pretest. A median value of the individual amplitude shifts was used for the adjustment. Equal loudness of the stimuli was also further confirmed by all respondents of the main listening test. The average SPL change of the stimuli due to the adjustment of amplitude was 1.66 dB_{rms} (1.74 dB_A) with max. adjustment of 2.99 dB_{rms} (2.77 dB_A).

The final stimuli for the main listening test (16 stimuli) were selected from the samples based on multiple criteria of similarity to other stimuli, which was evaluated in a listening pretest (see Sections 2.3. and 2.4.). The aim was to reject similar stimuli while conserving the range of dissimilarity variance in the sample set. Only stimuli that had simultaneously met the following conditions were not selected³: The greatest number of pair proximities below 1.8 (below the verbal anchor for *small difference*). An absolute agreement of all listeners on proximities with values below 2. The highest correlations of dissimilarity values to another sound.

2.2. Apparatus

The recordings were performed using a Neumann KU100 binaural recording head (1.8 m at height) and a Steinberg UR44 audio interface (96 kHz, 32 bit, PCM). The pretests and the listening tests were performed in a soundproof and acoustically treated room of the Musical Acoustic Research Centre in Prague using calibrated HE-60 electrostatic headphones [27] and a computer interface (programmed in LiTEd listening test editor software [28]). Average stimuli sound pressure level in the headphones was adjusted to the average level at the recording site within the time frame of the samples.

2.3. Participants

The loudness matching and stimuli selection pretests were performed with 3 expert participants⁴ (sound engineers, 28–50 years) and the main test was performed with 23 participants (age 20–60 years). All subjects were volunteers, reported normal hearing and were instructed by the supervisor of experiment regarding the aim and duration of the test, and the possibility of an intermission.

2.4. Listening pretest

Prior to the main listening test, two listening pretests of loudness matching and stimuli dissimilarity evaluation were performed in the stage of stimuli processing. The pretests, performed with 3 experienced listeners (sound

¹ A study of precepts related to unpleasantness of aircraft noise. The *cutting, buzzing, screeching, narrow, high* sound qualities were found as related to unpleasantness.

² Testing and validating the results of previous studies.

³ Conservative criteria (e.g. an absolute agreement) were practiced to limit the effects of listener variance.

⁴ Number of participants in the selection test was limited by the duration of the test (6 hours for 561 pairs).

Table I. Title, method, design and task instructions used in the listening pretests.

(1) Loudness matching test	
Method:	Loudness matching (matching of stimuli to a reference stimuli)
Design:	Respondents adjusted the amplitude of the stimuli to match a reference tone (1kHz tone), followed by fine adjustment of all stimuli presented simultaneously; each respondent participated in 10 tests.
Task:	Please match the loudness of the stimuli to the reference stimuli. Please fine-adjust the loudness of the stimuli to equal to all other stimuli
(2) Dissimilarity evaluation test	
Method:	Paired comparison (rating of dissimilarity between stimuli pairs).
Design:	Stimuli were presented in pairs in a sequence of screens (561 pairs), Ross stimuli order [32]. Respondents rated dissimilarity between the stimuli on labelled numerical scale (0-5). Scale points were labelled (0) <i>no</i> (1) <i>slight</i> (2) <i>small</i> , (3) <i>medium</i> , (4) <i>large</i> and (5) <i>considerable</i> difference.
Task:	Please evaluate the dissimilarity between the stimuli

Table II. Title, method, design and task instructions in individual tasks of the main listening test. The tasks used in this study are shown in bold.

(1) Evaluation of a difference between stimuli in unpleasantness	
Method:	Paired comparison [30]
(2) Stimuli unpleasantness ranking and rating test	
Method:	Ranking and rating (ranking of stimuli in a quality followed by a rating of the ordered stimuli on a rating scale [31])
Design:	Ordering of randomized stimuli according to unpleasantness followed by a rating on a verbal-anchored scale; not at all unpleasant (0) and maximum unpleasantness imaginable (100).
Task:	Please rank the stimuli by the extent of unpleasantness (from low to high) and then rate the unpleasantness on 0–100 scale.
(3) Evaluation of a difference between stimuli in sound quality	
Method:	Paired comparison [30]
(4) Spontaneous verbal description of sound quality	
Method:	Paired comparison (unaided verbal description of the sound quality of each stimulus in a pair).
Design:	120 stimuli pairs were presented on a sequence of screens, Ross stimuli order [32]. Respondents typed adjectives describing each stimulus in a text box.
Task:	Please describe the adjectives you find appropriate to describe the perceived quality on each sound.
(5) Stimuli roughness ranking and rating test	
Method:	Ranking and rating [31]

engineers), were based on the methods of *loudness matching* [29] and *paired comparison* [30]. The tests and the tasks are depicted in Table I. The duration of the tests was 3 and 6 hours.

2.5. Listening test

The main listening test (16 stimuli, 23 participants) was part of a broader listening test on aircraft noise that entailed multiple tasks⁵ (Table II). Only data from 2 tasks are used in this research (tasks 2 and 4, which are shown

bold in Table II). The order of the tasks in the table reflects their order in the test⁶. The duration of the test was 3 hours (split into two 1.5 hour sessions). Methods of *paired comparison* [30], *ranking and rating* [31] and *spontaneous verbal description* were used in the test.

The adjectives in the verbal description task were collected in Czech language. Czech-English translation was done using a dictionary [33] and with the help of a native English speaker. For thesaurus [34, 35] descriptions of select adjectives, please see [25].

⁵ Data from this test are also used in [25].

⁶ The tasks were ordered so that respondent unpleasantness ratings remained unbiased by the sound quality focus of the test.

Table III. f_{adj} of attributes and stimuli in this study.

Stimuli No.:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Hissing	1	2	30	11	9	11	41	6	3	0	6	4	22	68	89	27
Cutting	65	49	1	7	19	4	0	14	29	48	1	10	0	0	0	16
Buzzing	15	21	3	2	12	8	0	20	28	26	1	6	2	1	0	7
Booming	0	0	12	4	3	2	66	1	1	0	6	9	6	6	7	0
Yelling	18	44	0	0	3	2	0	4	10	15	0	0	0	0	0	1
Tenebrous	0	0	11	1	3	2	23	1	0	1	7	10	10	8	6	5
Sharp	12	15	2	6	7	8	0	13	7	6	3	0	2	0	0	7
Dark	0	0	7	4	6	6	14	2	3	0	0	4	9	8	7	6
Narrow	19	16	3	0	2	2	0	7	9	5	1	0	0	1	1	6
Thundering	0	0	9	9	4	0	20	1	0	0	3	0	4	9	11	0
Screeching	11	8	2	3	7	3	0	9	3	7	11	0	1	0	0	1
High	8	8	2	6	2	3	0	8	10	5	5	2	3	1	1	2
Mute	0	0	10	3	3	4	10	0	1	3	3	4	1	12	5	2
Dense	0	0	3	4	0	0	8	2	0	0	5	1	7	7	8	1

3. Results

In the opening of this section, the details of the procedures used to analyse the data are presented (Sections 3.1. to 3.2.). The results of the analysis are presented in Section 3.3. and are further discussed in Section 3.4.

3.1. Sound quality

The analysis of the subjective data involved the analysis of verbal descriptions of sound quality from the respondents and subsequent analysis using a correlation, factor analysis and regression which was used to link the perceptual variables to signal parameters associated with the phenomena studied.

The verbalisations had the form of single adjectives. The method of *text analysis* [26] could therefore be used to count the frequencies of adjectives (f_{adj}) in the corpus of the collected verbal data and to transform the data into quantitative form [36], see Table III. Adjectives used by at least two respondents and with $f_{\text{adj}} > 15$ were selected as perceptual attributes representing sound quality of the stimuli and the f_{adj} values were used to indicate the magnitude of the attributes. The attributes were correlated to parameters associated with the studied noise phenomena using Pearson r correlations. Since an assumption of normality for the Pearson correlation cannot be tested due to the low power of the tests on the stimuli count, Spearman ρ correlations were also used where appropriate and are presented along with the Pearson r correlations to supplement the results (especially for p -values < 0.01 [37]). The attributes with high and significant Pearson r and Spearman ρ correlations are presented in Section 3.2. The attributes and their f_{adj} are also shown in Table III.

A factor analysis was consecutively used to reveal the structure of sound quality of the stimuli. Factor analysis of the variance of f_{adj} values of the attributes was performed (see Section 3.3). Factors with high⁷ loadings of percep-

tual attributes highly correlated to the signal parameters presented in Section 3.2. were associated with the noise. The association of the perceptual attributes and the signal parameters is also used to explore their validity.

Since the attributes which were identified in the factor analysis form a single factor, they were combined into a novel *sound quality* variable according to their polarity on the factor axis. A percentage (f_{rel}) of f_{adj} of the attributes in the variable relative to total f_{adj} of all attributes in the variable is used as an indicator of their contribution to the variable (see Section 3.3). The variable was used to further confirm the relationship between the signal parameters and the sound quality using a correlation and a linear regression of the variable (dependent) and the signal parameters (predictor).

3.2. Signal parameters

In studies, buzz-saw noise (also known as *multiple pure tone noise*) was associated with an occurrence of multiple closely located tonal components in the frequency spectrum (which occur at frequency multiples of the engine fan shaft rotation frequency) [3, 4]. Signal parameters based on spectral analysis of the signals and detection of the tonal components were therefore used to indicate the extent of this noise.

Time-averaged frequency spectra were computed for every stimulus using FFT (125 ms window step, 125 ms windowing [Hanning], frequency resolution of 8 Hz) and a peak detection algorithm was used to detect tonal components in the 1365–3894 Hz frequency band (the band was determined by a visible occurrence of the tonal components)⁸. Levels of the peaks were used to compute a *tonal component level* (TCL) metric (Equation 1). The metric was computed as an average of the levels (L_{peak}) of the detected peaks (n) (see Figure 1 for an illustration of the parameters). The indicator represents an average of the levels of the whole series of tonal components⁹ and is used as

⁷ Factor loadings and correlations exceeding the value of 0.75 are regarded to be high

⁸ Peaks with relative levels < 1 dB were not detected to reduce detection of noise.

Table IV. Statistics of TCL_{rel} and SEA scale components: Pearson r correlation, Cronbach α of the scale, Cronbach α if item removed, factor loadings, explained variance. Marked correlations are significant at: ** $p < 0.01$ level

	Correlation r	Cronbach α		Factor loadings		Variance %
		Scale	Item	f1	f2	
TCL_{rel}	0.69 **	0.82	0.74	0.93	0.37	84.68
SEA	0.69 **	0.82	0.71	0.37	0.93	15.32

a baseline indicator of the extent of multiple tones in the noise.

$$TCL = \frac{1}{n} \sum_{i=1}^n L_{peak} \quad (1)$$

It was found the validity relative to the perceptual data could be improved by adding other parameters from frequency spectra to the metrics. Three additional metrics with these parameters were computed and are explored: (1) *tonal component relative level* (TCL_{rel}), calculated as (Equation 2) an average value of levels L_{peak} of the detected peaks n with a subtracted level L_{loess} defined as a corresponding point on an envelope of a locally weighted regression of the analysed spectral envelope [38]. The smoothing bandwidth of the regression was $\frac{1}{4}$ of the fitted range (0.25 stiffness setting in Statistica software). The parameter is discussed as possibly representing the broadband aircraft noise which can psycho-acoustically mask the perception of the tonal components [29, 39]. (2) *spectral envelope area* (SEA) (Equation 3), calculated as an average of square-root values of levels in frequency bands in the analysed range $L_{envelope}$; the parameter closely represents a linearized measure of an area defined by the spectral envelope and is discussed to represent relative noise levels within the frequency band (noise between the tonal components).

$$TCL_{rel} = \frac{1}{n} \sum_{\substack{i=1 \\ L_{peak} - L_{loess} > 0}}^n L_{peak} - L_{loess} \quad (2)$$

$$SEA = \sqrt{\frac{1}{n} \sum_{i=1}^n L_{envelope}} \quad (3)$$

All of the metrics were 0-1 normalised relative to the highest value in the stimuli set. Select parameters used for calculating the metrics are illustrated in Figure 1 (spectra of stimuli with the highest differences of perceptual and signal data are shown for comparison).

A combination of the *tonal component relative level* and *spectral envelope area* had the highest correlation with perceptual attributes associated with *tonal component level* (TCL). The variables were therefore combined into a (3) *tonal component index* (TCI), which was computed using the formula shown in Equation (4)¹⁰ and is used along

⁹ Contrary to a level of an average of the peak energies (A_{peak}) which is sensitive to values of single peaks with high amplitudes.

¹⁰ The value of n is arbitrary and was selected so the index best represents the perceptual data (using a Monte Carlo method and the criteria

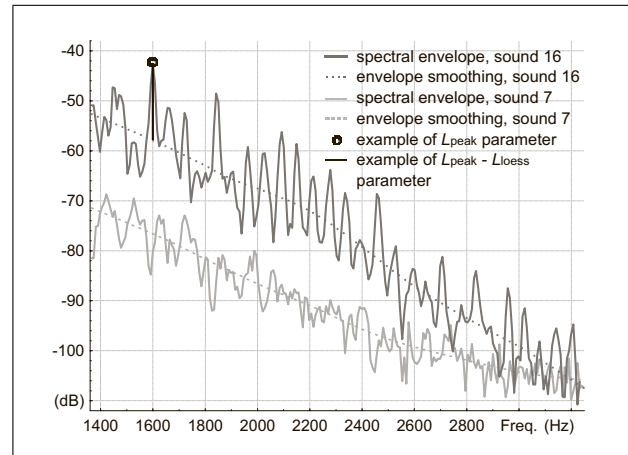


Figure 1. The spectra of sound 7 and 16; a visualisation of L_{peak} and $L_{peak} - L_{loess}$ of a single tonal component, used in calculating *tonal component level* and *relative tonal component level*. Level is shown in decibels relative to the full scale of the signal (dBFS).

with the other metrics (the complementarity of the components was tested using a scale consistency test, factor analysis and correlation; the results are presented in Table IV; the α if an item is removed is computed for a three item scale with two same items and is standardized relative to values of a two item α). The results suggest the components are consistent and measure unique qualities.

$$TCI = n * SEA + TCL_{rel}, \quad n = 0.4. \quad (4)$$

To explore the association of the noise with unpleasantness, the metrics were also correlated to average values of evaluated unpleasantness of the stimuli published in [25].

3.3. Results of the analysis

The values of the *tonal component level*, as well as the *tonal component relative level*, *spectral envelope area*, and *tonal component index* in the analysed (1365–3894 Hz) frequency range exhibit variance on different stimuli. The metrics are also significantly correlated to frequencies of occurrence of multiple perceptual attributes (Table V). The metrics with additional signal parameters (TCL_{rel} , SEA, TCI) are also correlated to the same attributes as the elementary TCL metric (Table V). Attributes with significant correlations to tonal component level (TCL) and high correlations ($r > 0.75$) to tonal component relative level

of a highest correlation to attributes otherwise highly correlated to TCL metric).

Table V. Correlations (Pearson r and Spearman ρ) of frequencies of sound quality attributes with *tonal component relative level* (TCL_{rel}), *spectral envelope area* (SEA), *tonal component index* (TCI) and *tonal component level* (TCL) (insignificant correlations are marked in grey). Marked correlations are significant at: * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$.

	TCL_{rel}		SEA		TCI		TCL	
	r	ρ	r	ρ	r	ρ	r	ρ
Sharp	0.87 ***	0.87 ***	0.69 **	0.67 ***	0.87 ***	0.87 ***	0.77 ***	0.67 **
Cutting	0.90 ***	0.91 ***	0.56 *	0.70 **	0.86 ***	0.91 ***	0.78 ***	0.79 ***
High	0.80 ***	0.82 ***	0.74 **	0.76 ***	0.83 ***	0.87 ***	0.65 **	0.62 *
Narrow	0.87 ***	0.73 ***	0.53 *	0.44	0.83 ***	0.75 ***	0.70 **	0.51 *
Buzzing	0.76 **	0.89 ***	0.56 *	0.62 *	0.75 **	0.88 ***	0.59 *	0.65 **
Yelling	0.76 **	0.90 ***	0.54 *	0.57 *	0.74 **	0.90 ***	0.66 **	0.69 **
Screeching	0.70 **	0.76 **	0.64 **	0.71 **	0.73 **	0.82 ***	0.60 *	0.54 *
Booming	-0.49	-0.85 ***	-0.64 **	-0.49	-0.57 *	-0.84 ***	-0.46	-0.71 **
Thundering	-0.69 **	-0.78 ***	-0.70 **	-0.45	-0.74 **	-0.74 **	-0.51 *	-0.51 *
Hissing	-0.71 **	-0.85 ***	-0.73 **	-0.73 **	-0.76 **	-0.88 ***	-0.54 *	-0.66 **
Tenebrous	-0.74 **	-0.88 ***	-0.70 **	-0.63 **	-0.78 ***	-0.91 ***	-0.67 **	-0.78 ***
Mute	-0.70 **	-0.73 **	-0.83 ***	-0.78 ***	-0.78 ***	-0.79 ***	-0.68 **	-0.73 **
Dark	-0.74 **	-0.78 ***	-0.78 ***	-0.71 **	-0.80 ***	-0.84 ***	-0.68 **	-0.65 **
Dense	-0.80 ***	-0.91 ***	-0.65 **	-0.55 *	-0.81 ***	-0.86 ***	-0.59 *	-0.59 *

Table VI. Pearson r and Spearman ρ correlation of *TCL correlation coefficients* (r and ρ) from Table V with TCL_{rel} , *SEA*, *TCI* correlation coefficients (r and ρ) from Table V. Marked correlations are significant at: *** $p < 0.001$.

	TCL_{rel} coefficients		SEA coefficients		TCI coefficients	
	r	ρ	r	ρ	r	ρ
TCL_{rel} coefficients	0.93 ***	0.93 ***	0.92 ***	0.92 ***	0.95 ***	0.94 ***

(TCL_{rel}), spectral envelope area (SEA) and tonal component index (TCI) are listed in Table V. The results are similar regardless of the correlation type¹¹.

The TCL_{rel} , SEA, TCI correlation coefficients from Table V all highly correlate to the TCL correlation coefficients from Table V (the correlations are shown in Table VI). The correlations of the metrics with the attributes are however the highest and most significant on the *tonal component relative level*, *spectral envelope area* and *tonal component index* metrics.

The results of a factor analysis of the variance of values of all perceptual attributes show that the unrotated 1st factor explains 33.4% of the total variance in the data, and the factor variance decreases on consecutive factors (see the eigenvalues in Table VII, bottom).

Perceptual attributes in both polarities of the 1st factor correlate to the tonal metrics (see the values in Table V), but correlate especially highly ($r > .70$) to *tonal component relative level* and *spectral envelope area* (and therefore also to the *tonal component index*). The perceptual attributes with high ($>.70$) factor loadings in both polarity axes of the 1st factor are shown in Table VII (top) along with the Pearson r correlation coefficients of the best correlating tonal component index metric.

Table VII. Top: Attributes with high 1st factor loading, 1st factor loadings, correlations of the attributes with TCI (Pearson r), relative percentage of f_{adj} of the attributes in the *sound quality* variable (f_{rel}). Bottom: Explained variance by the factors (only 1st to 4th factor is shown out of 15 factors in total). Marked correlations are significant at: *** $p < .001$ ** $p < .01$.

		1st factor load.	TCI (r)	f_{rel}
+	Sharp	0.88	0.87***	6.0
	High	0.87	0.83***	4.5
	Buzzing	0.85	0.75**	10.3
	Cutting	0.82	0.86***	17.8
	Narrow	0.76	0.83***	4.9
	Screeching	0.75	0.73**	4.5
	Yelling	0.71	0.74**	6.6
	Thundering	-0.76	-0.74**	4.7
−	Mute	-0.77	-0.78***	4.1
	Hissing	-0.78	-0.76**	22.4
	Tenebrous	-0.81	-0.78***	6.0
	Dense	-0.82	-0.81***	3.1
	Dark	-0.87	-0.80***	5.2
	Explained variance			
Factor No.	1	2	3	4
% variance	33.4	15.2	11.2	7.5

¹¹ The values significantly differ only on the booming and thundering descriptors that do not have high loadings in the 1st factor and are irrelevant to further results.

The attributes in Table VII were combined into a single *sound quality* variable; the relative percentage (f_{rel}) of the individual attributes in the variable is shown in Ta-

Table VIII. Linear regression statistics (R, R Square and F-change significance).

R	R ²	Adj. R ²	Std. Error	F.	Sig. F.
0.97	0.94	0.94	0.07	237.99	0

Table IX. Top: Regression coefficients B, Beta (β) and significance statistics for the regression of composite sound quality variable and TCI index. Bottom: an overview of the attributes combined in the sound quality variable.

	B	SE	Beta	t	Sig.
(Constant)	-0.05	0.04		-1.42	0.18
Sound quality	0.00	0.00	0.97	15.43	0.00
Verbal attributes in the sound quality variable: Sharp, cutting, high, narrow, buzzing, yelling, screeching (+) Dense, dark, mute, tenebrous, hissing, thundering (-)					

ble VII. Tables VIII and IX show the results of a regression of the variable and TCI. The regression is significant and explains 94% of the TCI variance.

The metrics (tonal component relative level, spectral envelope area and tonal component index) also highly (>0.90) and significantly correlated with the ratings of unpleasantness of the stimuli and with the sound quality variable (Table X). The results are similar regardless of the correlation type.

3.4. Conclusion of the results

The variance of multiple-tone content in the analysed signals (as indicated by the parameters) indicates that the extent of multiple-tone noise varied in the recorded aircraft noise. The multiple-tone content was associated with sharp, high, buzzing, cutting, narrow, yelling, screeching attributes (positively) and with dense, dark, tenebrous, hissing, mute, thundering attributes (negatively) (Tables V and VII). The attributes were also present in the most prominent factor of sound quality variance in the noise (explaining 1/3 of total variance in the perceptual data) (Table VII, bottom). The association of the attributes and the metrics that represent the tonal noise is further confirmed by the regression in Table VIII and Table IX and the correlations in Table X.

All of the metrics of tonal content (section 3.2.) correlate with the same perceptual attributes (see Table V and Table VI) and therefore represent similar perceptual quality in the setting of the stimuli (Table VI). The metrics which include additional signal parameters (Section 3.2.) have higher correlations to the attributes and to the main perceptual factor on the stimuli. It can be discussed whether the parameters in the latter metrics offer a better model of the perception of the noise relative to the basic metric (Section 4).

The extent of tonal content was also tested as significantly related to unpleasantness of the stimuli (Table X).

4. Discussion

The aim of this study was to explore the sound quality and signal characteristics of buzz-saw noise as perceived at noise-exposed locations and to test its relationship with unpleasantness of community noise.

The results of the analyses support the hypothesis buzz-saw noise is associated with distinct perceptual qualities and unpleasantness and forms a clearly defined factor in the noise. This supports and elaborates the conclusions on the perception and distinct character of the noise in [22, 2, 40] and supports a hypothesis of the studies that the noise contributes to community annoyance (a degree of validity relative to perceiving the noise at recording sites can be expected due to the used binaural method).

The perceptual qualities associated with multiple tone noise (presented in Table V and VII) likely represent its sound quality. A limited number of the adjectives (sharp, cutting, mute, high) are similar to adjectives in previous studies on perception of aircraft noise (sharp, strident, shrill, mute, high) [22, 24]. Since the cutting adjective is synonymous to the strident adjective in Czech language, the study supports the validity of the strident quality mentioned in the context of buzz-saw noise in Barbot *et al.* [22], though the diversity of attributes (Table VII) implies the perceived quality is complex and likely is not limited to a single attribute or dimension (the nature of the percept necessitates further studies).

Several of the presented attributes and signal parameters could relate to well established psychoacoustic and signal indices like sharpness, narrowness or roughness [29, 17, 41]. Although sharpness may seem like an obvious feature of its sound quality, it was not related to annoyance due to aircraft noise in Gille *et al.* [24] and even to unpleasantness of buzz-saw noise [22].

Signal parameters derived from the frequency spectrum were also explored in this study (Sections 3.2. to 3.4.), however their validity beyond the scope of this data needs to be further verified. The elementary TCL metric in this study is similar to the TETC₁₃₋₁₈ index. The index is a modified version of an index initially developed for tramway noise [42] which has been adapted to aircraft noise and related to its annoyance in Gille *et al.* [24]. The index represents the energy of tonal components in a similar frequency band to the one used here (this study therefore independently supports the relevance of the used frequency band). The parameters presented here (spectral envelope elevation and its area) might even be explored with regards to further improving this index. These parameters possibly represent a psychoacoustic masking of the tonal components due to broadband aircraft noise (regression curve in TCL_{rel}) [29, 39] and other noise levels within the frequency band (elevation of the spectral envelope in the frequency band) [4]. Further studies could also explore the suitability of using an average of the L_{peak} values in comparison with energy summation in frequency bands or barks.

To quantify aircraft noise, the concept of annoyance is currently used as a response metric, while energy-based

Table X. Pearson r and Spearman ρ correlations of tonal component relative level, spectral envelope area and tonal component index with the *sound quality* variable and unpleasantness ratings. Marked correlations are significant at: *** $p < 0.001$.

	TCL _{rel}		SEA		TCI	
	r	ρ	r	ρ	r	ρ
<i>Sound quality</i>	0.95 ***	0.97 ***	0.80 ***	0.72 ***	0.97 ***	0.98 ***
Unpleasantness	0.91 ***	0.92 ***	0.80 ***	0.75 ***	0.94 ***	0.96 ***

metrics are used as dose metrics [43]. Although they have been related to general unpleasantness of aircraft noise, the contribution of multiple tone noise to sound pressure level has been estimated between 1–5 dB_A [4, 5] and the findings in Barbot *et al.* [22] (which are supported by the results of this study on loudness matched stimuli) suggest that buzz-saw noise is not related to energy-based indices. These results therefore further support the necessity of a sound quality or annoyance-based approach in noise measurement and reduction, operational decisions, or engine engineering [17, 44, 45].

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