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REFLECTIONS ON SOUND TIMBRE DEFINITIONS

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The article is concerned with systematic classification of concepts and terms in acoustics. Special attention is attached to definitions of timbre. The article presents a review of definitions of timbre published in the literature. Inadequacy of the currently used IEC definition is shown and a new definition of timbre is proposed. Discussed are advantages of the new definition and the prospects for common acceptance of this definition in acoustics.

Keywords: sound timbre, systematics of sound notions, standards, objective and subjective definitions.

1. Introduction

Forty years have just passed since Professor Andrzej Rakowski published in *Archives of Acoustics* his classical paper entitled *Remarks on the Systematics of Sounds* [36]. In that paper he presented a review of basic acoustical notions used in German, American, English and French terminology. He pointed at various inconsistencies of the then used terms and proposed a system of notions based on two, consequently discerned approaches: an objective, i.e. physical approach, and a subjective, i.e. psychological approach.

Professor Rakowski's 50-year jubilee of scientific activity is an excellent opportunity to present reflections on the far-reaching consequences of his article [36]. The article helped Polish acousticians determine proper meaning of important terms and concepts and eliminate various misunderstandings and ambiguities. Professor Rakowski's article was particularly useful in teaching acoustics and related subjects at universities and other academic schools.

The article came out at the time when the authors of the present paper were just introducing their newly developed teaching programme, under the name of Electrophony, for students of the Faculty of Electronics specialized in sound engineering, at the Gdańsk University of Technology [44]. A systematic classification of sounds was essential as

basic knowledge for those students so the systematics presented in RAKOWSKI's article [36] was entirely incorporated into the programme and used during various specialization lectures.

RAKOWSKI [36] distinguished two possible categories of attributes of sound: objective and subjective attributes, and consequently formulated two different definitions of sound. This dualistic definition, although sometimes overlooked or disregarded by certain acousticians, allows to systematize precisely the attributes of sound. Rakowski's definitions, however, did not include the concept of timbre therefore special attention has been devoted here to the problem of an appropriate definition of this attribute of sound.

2. Definitions of sound

Although the two definitions of sound presented in Rakowski's article have been broadly known, it may be useful to quote them here. (1) Sound (from an objective point of view) is a wave disturbance in an elastic medium, able to cause an auditory sensation. (2) Sound (from a subjective point of view) is the auditory sensation caused by a disturbance in a surrounding medium. The contents of both definitions, despite some differences in wording, fully agree with the definitions adopted by IEC [17]. RAKOWSKI [36] pointed at considerable discrepancies and lack of consistency between definitions used earlier in the USA, in United Kingdom, France, Germany, Poland and other countries. It may be interesting to review here the definitions published in the literature.

Considering sources anterior to Rakowski's publication one finds both examples of inconsistencies mentioned above and examples of well systematized systems of acoustical concepts and terms. The approach of their authors was based on physical rather than physiological description of sound, i.e., they were formulated from an objective standpoint.

Among others, BERGTOLD [5] has emphasized in his textbook that sound (*Schall*) is a fundamental notion in acoustics. His approach assures the necessity for systematization postulated later by Rakowski. Many prominent authors considered a systematized terminology an important topic. The duality of the definition of sound was supported by BERANEK [3] and other authors. SACERDOTE [43], rather than formulating a definition of sound, has referred to source theories of Lord RAYLEIGH [39] and HELMHOLTZ [15] and has given a systematic overview of well-defined attributes of musical sounds.

RAYLEIGH's *Theory of Sound* [39] is a presentation of its author's scientific achievements and does not contain basic definitions usually needed in a didactic textbook. The work has been written by a physicist and deals with objective descriptions of the nature of acoustic phenomena. However, it is interesting to note that the beginning words of its first chapter were: "The sensation of sound is ..." [39]. In LINDSAY's opinion [26], Lord Rayleigh's seminal work was "apparently stimulated by his reading of Helmholtz's famous work *On the Sensations of Tone* in its original, German version". In a section titled *Definitions of the terms employed*, HELMHOLTZ's treatise [15] contains a system-

atic classification of definitions. Unfortunately, the systematics proposed by Helmholtz suffers from inconsistencies in translation of the terms from German into English.

TREMAINE's *Audiocyclopedia* [48] presents at its beginning a uniform definition of sound formulated objectively, with a mention of a respective auditory sensation. Such definitions, based on physical description of the phenomenon of sound, and containing a condition of resulting auditory sensation, have been recently employed by a vast majority of authors. Among them, a proposal from a team of German acousticians [12] is worth to be noted here, namely, to treat objective sound definitions as definitions "in a broad sense of word", while subjective ones as those "in a narrow sense of word".

In some publications, definitions of sound are neither uniform nor sufficiently systematized [32], sometimes single-oriented, i.e., objective only [19, 20]. On the other hand, valuable publications that appeared in the meantime, contained definitions compatible with those mentioned above. Such definitions were presented, for example, by ŻYSZKOWSKI, the author of an outstanding Polish textbook on acoustics [51]. ROSSING [41] began the preface to his well-known textbook with the two definitions of sound, in reversed order. Reversed order, i.e., starting with the subjective notion of sound, was also preferred by JEAN-LOUIS [18].

Definitions given by PUJOLLE [35] in his Lexique-Guide resemble closely the English ones: "*Dans la domaine physique un son est une vibration acoustique capable d'éveiller une sensation auditive. Dans la domaine physiologique, c'est la sensation auditive engendrée par une vibration acoustique.*" Recently published textbooks also contain similar definitions [2, 12, 33].

The need for systematic classification of acoustic notions is also evident when one compares interlingual dictionaries of acoustical terms, such as those compiled by REICHARDT [40], CLASON [9], PUJOLLE [35], SZLIFIRSKI [46], and also glossaries included in some books on acoustics [47, 50]. In those publications, numerous inconsistencies between various terms may be found. For example, *acoustician* has been translated into German either as *Akustiker* or *Toningenieur*, in French as *acousticien* or *ingénieur de son*, while in Polish as *akustyk* and in Russian as *акустик*, only [40]. Another example of inconsistent terminology may be found in Elsevier's Dictionary where *sound quality* was translated into *qualité acoustique* or *Qualität der Akustik*, while the term *timbre* was omitted [9].

3. The notion and definitions of timbre

The word *timbre* stems from the ancient Greek *tymbanon* [42] or Latin *tympanum* [14], denoting a drum, a kettle, or a similar kind of a musical instrument. It is important to note that there have been difficulties in the interpretation of this word in various languages. For example, the term *sound quality* is used in English as an equivalent of German *Klangfarbe* [9, 15]. *Klangfarbe* has been preferred by German acousticians and also in other countries [4, 12, 41]. In French and German vocabularies, the word *tonalité* is sometimes advised in parallel to *timbre* [35, 50]. In Polish the term *barwa dźwięku*

(colour of sound) is mostly used, although the word *tembr* ('timbre' pronounced in Polish) has been known and used for a long time [42]. In Russian, the word *тембр* is used, in parallel to *окраска звука* (colour of sound) [2, 40]. In the light of such a variability of terms a question arises as to the source of all those terminological differences.

An interesting comment concerning the origin of the word *timbre* was made by Ellis, who translated over 130 years ago HELMHOLTZ's treatise *Die Lehre von den Tonempfindungen* into English [15]. Ellis mentioned that an earlier translator attempted to use the term *clangtint* as an English equivalent of *Klangfarbe*, due to its direct similarity. Ellis rejected this proposal because *clang* had a well-established meaning in English of a sharp, shrill, metallic sound. On the other hand, the word *timbre* was in use in France, where, among other meanings, it denoted a postage label or stamp. For this reason, Ellis conceived the term *quality of tone* which later evolved into *sound quality*. He argued that a translation from German into English ought to employ terms being thoroughly English and avoid the influence of German terminology. Those comments are worth to be quoted as they show how long may the effects of a scientific, yet inaccurate translation last.

The real cause of those terminological difficulties was probably the lack of a proper definition of timbre. The definition proposed by the authors of the ASA standard published in 1960 [2] was accepted 14 years later by the IEC [17], with almost no changes, as an international standard. That definition stated that timbre is "that attribute of auditory sensation in terms of which a listener can judge that two sounds, similarly presented and having the same loudness and pitch, are dissimilar".

An additional cause of terminological difficulties might be an unfortunate choice of the term *colour* (*Farbe*) used by Helmholtz in his original definition. Colour is a visual sensation associated with an appearance of a certain surface and is incompatible with the perceptual space of timbre which is multidimensional.

The duality of acoustical definitions results from the nature of perception. There are certain relations between the physical input signal and the perceptual output image. A similar scheme functions also in visual perception, in which there also is a dualistic system of objective and subjective notions [13]. The term *colour* was borrowed from visual perception and adopted in the domain of acoustics. This loanword should now be replaced by a specialized term *timbre*, preferably the same in all languages, for the sake of proper communication between acousticians in the international community.

The IEC definition [17], although based on terminology used much earlier, was generally considered unsatisfactory. It attempted to define timbre with reference to a selected, particular case, whilst a vast area of the concept of timbre was left beyond its scope. The definition was applicable only to sounds having a defined pitch and loudness, and was therefore limited to steady-state sounds. The IEC definition was based on comparisons of auditory sensations, so it was purely subjective and unfit for use as an objective tool. It turned out to be useless in application to contemporary music, especially to synthetic sounds of electronic music, as well as to time-varying sounds. The ability to differentiate and describe timbre changes is a fundamental skill for musicians therefore special attention should be given to proper definitions and classification of

timbre in musical acoustics and musicians' listening abilities should be developed by special training [28].

The ASA definition was criticized by SACERDOTE [43] who indicated clearly its deficiencies. Also HOUTSMA [16] pointed at considerable problems in teaching students of composition, due to the lack of a comprehensive theory of timbre and a uniform nomenclature for description and classification of timbre. The ASA and IEC definitions were also criticised by MELKA [30] in the introduction to his paper in which he reported his investigations of musical timbre. Melka stated that the definitions do not comply with the needs of acoustical researchers and "fail completely". In this context he also criticized the use of "rather confusing terms", such as *tone colour*, *tonal quality*, *sound quality* and *Klangfarbe.*

Meyers Konversations-Lexicon [31] contains under the entry *Klangfarbe* the following statement: "*z.B. eine Trompete von Holz oder Pappe anders klingt als eine ganz gleich geformte von Metall. Diese letztern Unterschiede der Klangfarbe nennt man Timbre*". This definition, although old and incomplete, is contradictory to the IEC standard [17].

An example of ambiguity caused by using the word *quality* as part of the term *sound quality* is given in a paper published by the present authors [6], who presented a general concept of sound quality and discussed its dependence on various conditions in which sound signal is produced, propagated, transmitted, received and perceived. Comparisons of sound images at the input and at the output of the signal path can provide estimations of sound quality. Such a meaning of the word *quality* is in good agreement with its common sense, yet is contradictory with its use as an equivalent of the term *timbre*. In the case of ambiguities and inconsistencies mentioned above many authors either preferred to avoid the term timbre, or its foreign equivalents [3, 9], or used it in a less formal, traditional meaning [4, 5, 7, 8, 11, 18, 19, 25, 27, 37, 48].

Although RAKOWSKI [36] did not mention the term *timbre* in his article, he and his co-workers used it in further applied studies [28, 38, 46] devoted to various problems of pitch and timbre perception. More recently, many papers concerning the musical timbre were published [10, 24, 29, 30, 45, 49]. Their authors, however, refrained from discussing the definition of timbre and focused their attention on studying quantitative characteristics of timbre properties, mostly by the application of multidimensional scaling techniques. In other publications timbre was described as an attribute of sound, essential for identification and recognition of the sound source, e.g., a musical instrument or a talker [32, 33].

A valuable presentation of a variety of problems concerning the concept of timbre was recently given in a textbook by ALDOSHINA and PRITTS [1]. Althugh those authors quoted different Russian equivalents for the notion of timbre ("tone quality" – *качество тона*, *окраска тона*), they used consequently the term *timbre* (*тембр*) throughout the book. They cited the original ASA timbre definition published in 1960, the supplement added in 1973, and its completion resulting from PLOMP's [34] investigations. They also have discussed recent studies on timbre and this discussion may be a base for proper systematisation of notions and terms related to timbre. As the most

recent achievement, ALDOSHINA and PRITTS [1] mentioned soft computing methods applied by KOSTEK and CZYŻEWSKI [22, 23] for automated classification and recognition of musical sounds. In those methods, timbre has been employed as a set of qualitative properties describing sound by means of defined, quantitative parameters, resulting from applied computer processing. However, none of the authors mentioned above have formulated a new definition of timbre, a solution to a still existing problem, that seems to be unavoidable.

4. Systematized definitions

Terminological deficiencies discussed above have inspired the present authors to propose new, systematized definitions of timbre. First of all, this attribute of sound should be regarded dually, similarly as the concept of sound.

Objectively, i.e., from a physical viewpoint, timbre denotes the shape of a sound object represented in a spectrum space, comprised of three orthogonal axes, that describe the sound by its intensity, frequency and elapsing time. Thus, an objective representation of timbre is a three-dimensional image, evolving in time, called the evolutive spectrum. In a particular case of a steady-state sound the evolutive spectrum is reduced to the form of a instantaneous spectrum, the surface of which represents the spectral characteristics of a stationary sound.

Subjectively, i.e., from a perceptual viewpoint, timbre requires a multidimensional space for representation of its properties. The three main axes described above change their scales into loudness, pitch, and elapsing time. Further axes and scales depend on possible diversity of perceived sensations produced by identical stimuli. This means that a given sound, having a particular objective timbre image, may produce an infinite number of different subjective timbre images, evoked in the listeners' brains.

Definitions of timbre may be expressed as follows:

1. Generally: Timbre of a sound is defined by a set of its properties which allow to classify and recognize sounds or identify their sources.
2. Objectively: Timbre of a sound is represented by the shape of a spatial object in a space consisting of time, intensity and frequency components of the sound.
3. Subjectively: Timbre of a sound is represented by a beyond-spatial object in a multidimensional space created on the base of the objective sound timbre, yet modified by the properties of the sound perception process.

5. Discussion

Below presented are a few examples that may illustrate possible applications of both definitions. The first example is a personal perceptual experience of auditory events occurring sometimes at the Baltic seaside. When one hears characteristic muffled bass roars, coming from a far distance, behind the horizon, it is difficult to tell whether they are sounds of an oncoming thunderstorm or sounds of artillery shots during military manoeuvres. The so-called "colour of sound" and the sound intensity are in both cases identical. There exists, however, a perceivable difference between those two kinds of

sounds. This difference depends on intensity changes of the characteristic time envelope of the sound and is a cue for recognising the sound source.

The next example is also a personal experience of sound perception. The co-author of this paper was listening to a sermon transmitted through a reinforcement system in a church interior of a unique shape (Władysławowo Church). While listening to the sermon, he repeatedly moved his head, either 20 cm back and forward, or 40 cm up and down. The results of such a head movement were in all cases the same: the apparent sound source was shifted from the left to the right ear, or inversely and the movements of the sound source were accompanied by respective changes in timbre. This simple experiment provides an example of subjective (i.e. depending on the listener) modifications of the timbre of a sound source in a case, when the objective properties of the sound source remain unchanged.

Many similar observations may be quoted, though they are rarely described in the literature. Worth to be emphasized here is the practical role of the general form of the definition of timbre. This definition is particularly useful in traditional applications, such as classification of musical instruments, in the case of which the differentiation between objective and subjective timbre is of utmost importance.

The difference between objective and subjective definition of timbre has important practical implications. An objective timbre is measurable. Then, it may be statistically averaged and serve as a generalization, specific for a particular sound source, e.g., a musical instrument or voice register. So far, such a differentiation has not been taken into consideration in the terminology. In most of the older publications timbre is treated as an objective notion, referring to steady-state sounds.

In recent publications, directed mostly towards the study of human sensory and psychological capabilities, timbre is treated as a subjective notion, referring to time-varying sounds, that are difficult to be represented in a multidimensional timbre space. The investigations and methods discussed here are valuable for the theory of sound perception, yet they do not have a practical application, such as providing distinctive marks for particular sound sources. Further studies and discussions are needed to fully appreciate the importance of the two – the objective and the subjective – notions of timbre.

In comparison to the definitions used so far, the systematized definitions proposed here are more general and may be useful in a variety of applications. The definitions are applicable to any kind of sounds, also sounds that vary in pitch and loudness, that were beyond the scope of previous definitions. The proposed definitions hold for all kinds of sounds and voices, natural and synthetic, heard in different time, recorded and live sounds, also sounds known only from a verbal description. The definitions may be applied in the theory of sound source identification, especially speaker identification, in cases when a human listener is replaced by a computerized analyser.

An advantage of the new definitions is their clear distinction between objective and subjective properties of timbre. The difference between the three-dimensional image of objective timbre and the multi-dimensional image of subjective timbre is an effect of the characteristics of human hearing.

Some additional light may be cast upon the above considerations by examples taken from investigations of timbre of organ and bell sounds [7, 8]. Figures 1 and 2 show the evolutive spectra of the two organ sound. They represent an analysis of the time sections of sound of the trombone register, of the church organs in St. Mary's Cathedral in Gdańsk (Fig. 1) and in St. Nicolaus Basilica in Gdańsk (Fig. 2). Although the organ registers were in both cases the same, a distinct difference in timbre is apparent in Figs. 1 and 2.

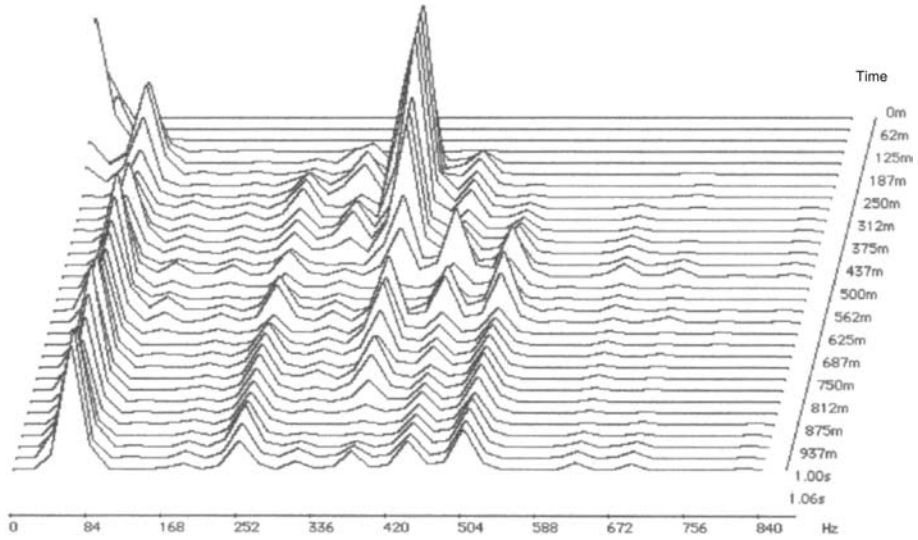

Fig. 1. Evolutive spectrum of the Trombone register of the organ at the St. Mary's basilica in Gdańsk.

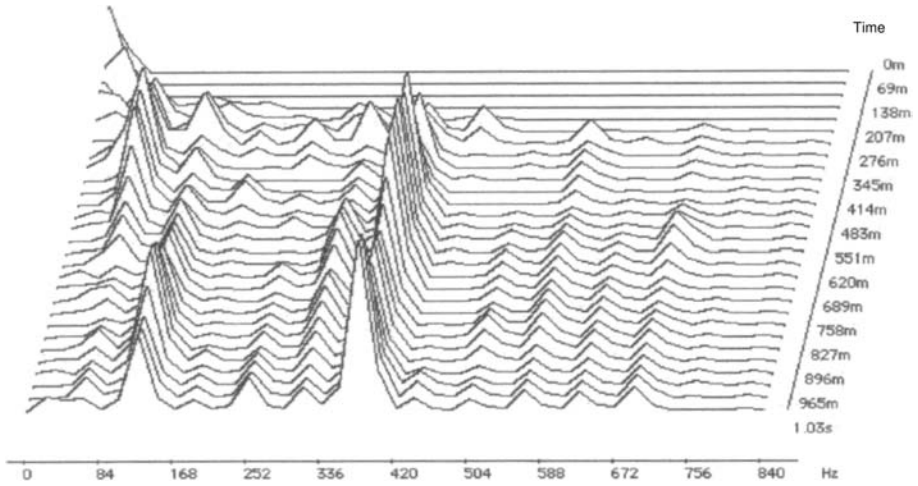

Fig. 2. Evolutive spectrum of the Trombone register of the organ at the St. Nicholas basilica in Gdańsk.

Figures 3 and 4 show the evolutive spectra of two bell sounds. The spectra represent two consecutive sounds of the same swinging bell (*Tuba Dei* at St. John's Cathedral in

Toruń). The sounds were produced by clapper hits at the same contact area; consecutive sounds produced by hits at opposite areas of the bell rim would be more differentiated. The objective timbre differences between consecutive sounds of the same instrument are distinctly evident in Figs. 3 and 4. The differences, objective of course, could be caused by imperfections of sound recording, by insufficient resolution of the analyzer, and by other factors, such as the irregularities of the swinging motion the bell and the clapper.

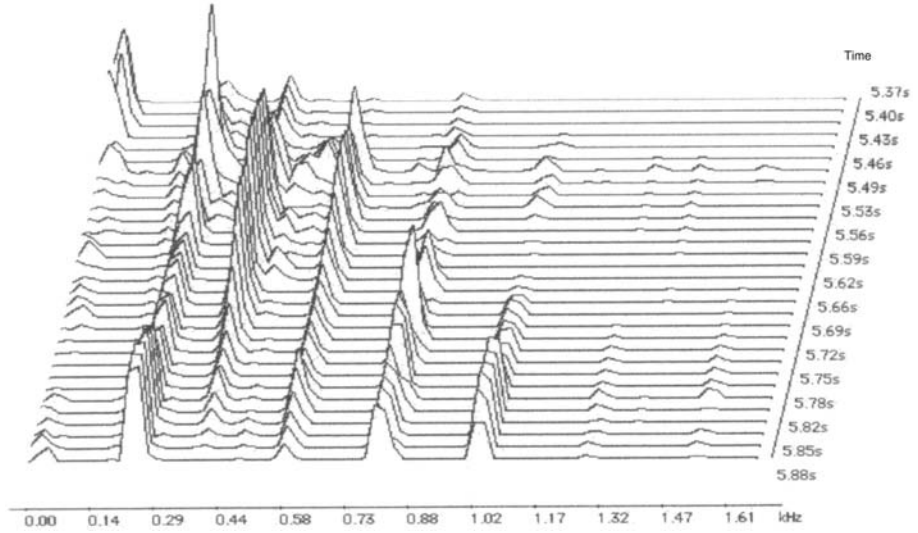

Fig. 3. Evolutive sound spectrum of the swinging bell Tuba Dei (at the St. John's Cathedral in Toruń).

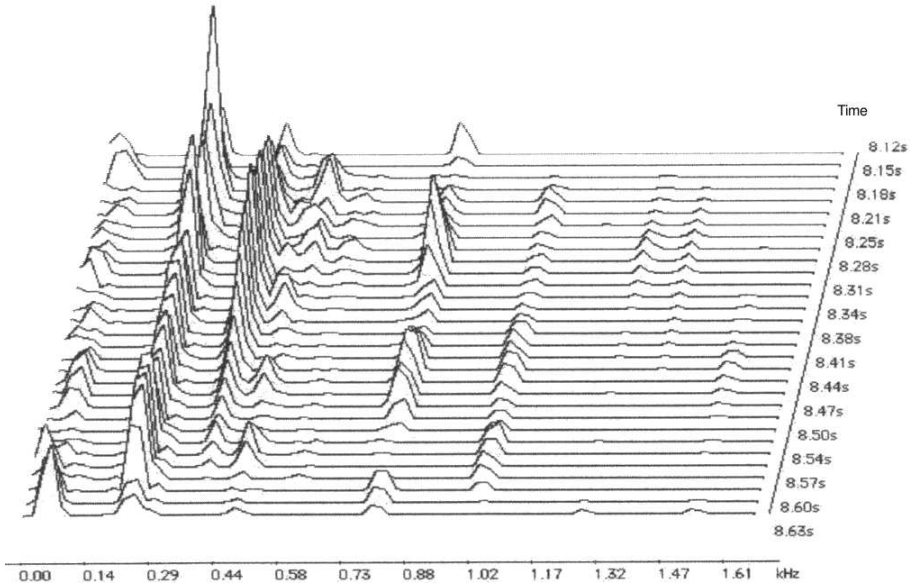

Fig. 4. Similar objective analysis (duration 0.5 s) of the next sound of the same bell. Subjective timbre differences between two sounds are almost unnoticeable.

Despite all these differences, a typical listener is able to memorize an averaged characteristic timbre, so specified, that it allows him to recognize, for example, the sound of *Tuba Dei*, among the recordings of other bell sounds.

The above examples show that it is not easy to define the characteristic objective spectra of musical instruments. Nevertheless, an attempt to find a solution of this problem is worth to be made by researchers who are interested in musical acoustics. Moreover, the examples shown above demonstrate that it is difficult, if not impossible, to present an image of subjective timbre, especially if the sound is non-stationary [1]. Such a presentation ought to be based on a statistical estimation of averaged responses obtained from listeners in an experiment.

In the face of the problems related to the definition of timbre, a concept of "computing with words" has gained considerable interest. In a recent publication, KOSTEK [21] summarized the state-of-art research oriented towards automatic musical timbre recognition and discussed its possible applications, aided by soft computing methods. The term *timbre* used by KOSTEK [21] is consistent with the systematized definitions given above. It is worth noting that the "computing with words" methods applied to timbre studies require verbal descriptions of timbre. Numerous publications have described attempts to find appropriate descriptors of timbre. Such studies were reported, for example, by MELKA [30] and RAKOWSKI [38]. All the investigations mentioned above referred to timbre defined as a subjective attribute, although this was not explicitly stated in none of the studies. To avoid ambiguities and misunderstandings, the systematised acoustical terminology requires a distinct differentiation of the objective and the subjective definition of timbre.

6. Conclusions

In the 1970s, Professor RAKOWSKI's classical paper [36] considered in this article resulted in a revision of the concepts and definitions used in acoustics, in Poland and in other countries. It had a strong impact on the syllabuses of courses in acoustics taught at Polish universities. Professor Rakowski's paper initiated the process of systematization of acoustical terminology which is now continued and further developed. Continuing this process, new definitions of objective and subjective timbre have been proposed in this article. It may be expected that the term *timbre* will be commonly accepted in English as well as in other languages, and the previous terms, such as tone colour, will no longer be used. The new definitions of timbre will contribute to a better and more clear systematic classification of acoustical terms.

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References

[1] ALDOSHINA I., PRITTS R., *Musical acoustics* [in Russian], Kompozitor, St. Petersburg 2006.

[2] *American Standard Acoustical Terminology*, American National Standards Institute S1.1 - 1960.

[3] BERANEK L. L., *Acoustics*, McGraw, New York 1954.

[4] BERANEK L. L., *Concert and opera houses – how they sound*, Acoustical Society of America, New York 1996.

[5] BERGTOLD F., *Schall und Klang*, R. Oldenbourg, München 1939.

[6] BUDZYŃSKI G., SANKIEWICZ M., *The definition of sound-image quality and its influence on sound engineering concepts*, Proceedings of the 86th AES Convention, Preprint 2747, Hamburg 1989.

[7] BUDZYŃSKI G., GUDEL J., SANKIEWICZ M., *Timbre of the Gdańsk historical bells and Carillons, Preservation of the industrial heritage – Gdańsk Outlook*, Technical University of Gdańsk, 1993.

[8] BUDZYŃSKI G., SANKIEWICZ M., SZYCHLIŃSKI G., *New timbres of St. Catherine's Carillon*, Archives of Acoustics, **25**, 2, 147–155 (2000).

[9] CLASON W. E., *Elsevier's dictionary of television and video recording (six languages)*, Elsevier, Amsterdam 1975.

[10] DONNADIEU S., MCADAMS S., WINSBERG S, *Caractérisation du timbre des sons complexes I*, Journal de Physique IV, **4**, C5 (1994).

[11] EVEREST F. A., *Master handbook of acoustics*, Polish translation by W. Kurylak, *Podręcznik akustyki*, Sonia Draga, Katowice 2004.

[12] FASOLD W., KRAAK W., SCHIRMER W., *Taschenbuch Akustik*, VEB Verlag Technik, Berlin 1984.

[13] FIOK A., *Television – general fundamentals* [in Polish], WKiŁ, Warszawa 1991.

[14] FOWLER H. W., FOWLER F. G. [Eds.], *The concise Oxford dictionary*, University Press/PWN, Warszawa 1956.

[15] VON HELMHOLTZ H., *Die Lehre von den Tonempfindungen als psychologische Grundlage für die Theorie der Musik*, F. Vieweg und Sohn, Braunschweig, 1863; English translation by A. Ellis, *On the sensations of tone*, Dover, New York 1954.

[16] HOUTSMA A. J. M., ROSSING T. D., WAGENAARS W. M., *Auditory demonstrations*, Acoustical Society of America, New York 1989.

[17] INTERNATIONAL ELECTROTECHNICAL COMMISSION, *International Electrotechnical Vocabulary*, 801-21-02-29-09, 2007.

[18] JEAN-LOUIS V., *L'Ingénieur du son*, Chiron, Paris 1955.

[19] JOSEPHS J. J., *The physics of musical sound*, Van Nostrand, Princeton 1967.

[20] KLINKE R., *Physiologie des Hörens I*, [in:] Hören, Stimme, Gleichgewicht, Urban & Schwarzenberg, München 1972.

[21] KOSTEK B., *Computing with words, concept applied to musical retrieval*, Electronic Notes in Theoretical Computer Science, **82**, 4 (2003).

[22] KOSTEK B., CZYŻEWSKI A., *Representing musical instrument sounds for their automatic classification*, Journal of the Audio Engineering Society, **49**, 768–785 (2001).

[23] KOSTEK B., *Perception-based data processing in acoustics*, Springer, Berlin 2005.

[24] KRIMPHOFF J., MCADAMS S., WINSBERG S., *Caractérisation du timbre des complexes II*, Journal de Physique IV, **4**, C5 (1994).

[25] LEIPP E., *Acoustique et musique*, Masson, Paris 1971.

[26] LINDSAY R. B., *Historical introduction to the theory of sound*, Dover, New York 1945.

[27] LULLIES H., *Stimme und Sprache*, [in:] Hören, Stimme, Gleichgewicht, Urban Schwarzenberg, München 1972.

[28] ŁĘTOWSKI T., *Development of technical listening skills: Timbre solfeggio*, Journal of the Audio Engineering Society, **33**, 240–244 (1985).

[29] MALLOCH S. N., CAMPBELL A. M., *An investigation of musical timbre*, Journal de Physique IV, **4**, C5 (1994).

[30] MELKA A., *Methodological approach to the investigation of musical timbre*, Journal de Physique IV, **4**, C5 (1994).

[31] *Meyers Konversations-Lexikon*, Bibliographisches Institut, Leipzig 1897.

[32] MOORE B. C. J., *Introduction to the psychology of hearing*, 4th edition, Academic Press, London, 1997; Polish translation by A. Sęk and E. Skrodzka, *Wprowadzenie do psychologii słyszenia*, Wydawnictwo Naukowe PWN, Warszawa – Poznań 1999.

[33] OZIMEK E., *Sound and its perception* [in Polish], Wydawnictwo Naukowe PWN, Warszawa – Poznań 2002.

[34] PLOMP R., SMOORENBURG G. F. [Eds.], *Frequency analysis and periodicity detection in hearing*, Sijthoff, Leiden 1970.

[35] PUJOLLE J., *Lexique guide d'acoustique architecturale*, Eyrolles, Paris 1971.

[36] RAKOWSKI A., *Remarks on the systematics of sounds* [in Polish], Archiwum Akustyki, **2**, 73–92, 1967.

[37] RAKOWSKI A., *An analysis of factors governing the acoustical quality of concert halls* [in Polish], PWSM Scientific Reports, **3**, Warszawa 1968.

[38] RAKOWSKI A. [Ed.], *Studies on musical pitch and timbre* [in Polish], Fryderyk Chopin Academy of Music, Warszawa 1999.

[39] RAYLEIGH J. W. S., *The theory of sound*, 2nd edition, Macmilan, London 1874; reprinted Dover, New York 1945.

[40] REICHARDT W. [Ed.], *Technical acoustics – technical vocabulary* [in Polish], VEB VerlagTechnik, Berlin, WNT Warszawa 1978.

[41] ROSSING T. D., *The science of sound*, Addison-Wesley, London 1982.

[42] RYSIEWICZ Z. [Ed.], *Vocabulary of foreign words* [in Polish], PIW, Warszawa 1961.

[43] SACERDOTE G., *Acustica musicale*, Istituto Elettrotecnico Nazionale Galileo Ferraris, Vol. XXXVIII, Torino 1966.

[44] SANKIEWICZ M., *Specialization syllabus and review of diploma theses 1968–1974* [in Polish], Gdańsk University of Technology, Gdańsk 1975.

[45] SMURZYŃSKI J., HOUTSMA A. J. M., *Auditory discrimination of tone-pulse onsets*, Perception and Psychophysics, **45**, 2–9 (1989).

[46] SZLIFIRSKI K., *"Pro-Audio" English-Polish dictionary of sound recording terms* [in Polish], WNT, Warszawa 1996.

[47] THODEN U., *Neurophysiologische Terminologie*, [in:] Hören, Stimme, Gleichgewicht, Urban & Schwarzenberg, München 1972.

[48] TREMAINE H. M., *Audiocyclopedia*, H. W. Sams, New York 1959.

[49] VERSFELD N. J., HOUTSMA A. J. M., *Perception of spectral changes in multitone complexes*, Quarterly Journal of Experimental Psychology, **43**, 459–479 (1991).

[50] WINCKEL F. [Ed], *Klangstruktur der Musik*, Funk-Technik Bücher, Berlin 1955.

[51] ŻYSZKOWSKI Z., *Fundamentals of electroacoustics* [in Polish], WNT, Warszawa 1953.