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RETROSPECTIVE REVIEW OF THE DEVELOPMENT OF THE CONCEPTS OF CONSONANCE AND DISSONANCE: ON THE PROBLEM OF MUSICAL AND AESTHETIC AS WELL AS PHYSICAL AND MATHEMATICAL INTERPRETATION

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SUMMARY. The research aimed at a comprehensive retrospective analysis of the development of "consonance and dissonance" as a musical and aesthetic category in physical and mathematical interpretation; defining the notion of consonance as a musical theoretical and aesthetic category, confirming the relevance of its use in physical and mathematical terminology to explain acoustic phenomena. Research methodology is based on the use of the retrospective method (or the retrospection method), which allowed identifying the theories of consonance and dissonance in the historical retrospective. The periodization method was used to find out individual stages in the development of science in order to discover the leading directions of scientific thought, identify new elements relating to various aspects of "consonance" and "dissonance". The study of the retrospective review of the development of the notions of consonance and dissonance in the physical and mathematical interpretation involved an interdisciplinary method a way of organizing research work, providing for the interaction of music and mathematics in the study of consonance and dissonance. Scientific novelty. This study is the first to reflect the general tendency towards the mathematization of the humanities and the humanitarization of the physical and mathematical areas of modern culture. Some provisions of musical acoustics were clarified in the context of creating a harmonious conceptual structure. The article presents the author's concept of clarifying the notion of phase in relation to the spectral structure of an audio signal based on the notion "slightly mistuned consonance". Conclusions. A retrospective review of the development of the notions of consonance and dissonance in the physical and mathematical interpretation was carried out and presented as a comprehensive description and review of the formation of concepts in the temporal sequence of their creation. Retrospectiveness through a review of

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significant discoveries and achievements in music and natural science allowed tracing the formation of the theories of consonance and dissonance from the standpoint of the interdisciplinarity of modern knowledge in the humanities. The further process of the development of sound musical art technologies requires a significantly higher scientific level of their study, the creation of a coherent conceptual system based on modern physical and mathematical sciences as well as computer science to explain sound acoustic phenomena.

Keywords: consonance, dissonance, mistuned consonance, overtone, harmonics, beats, phase, spectral component

Research topicality. Problem statement

Modern science and practice in the field of musical activity and sound technologies urges several problems related to the introduction of new definitions and notions into the terminological framework. The ambiguous semantics of their interpretation from the point of view of the musical theoretical as well as physical and mathematical sciences requires new research approaches to clarify them and coordinating their understanding.

Modern scholars who use the terminology of physical, mathematical and computer science to explain some sound musical phenomena involve the musical theoretical notions "consonance" and "dissonance" into their theoretical framework. As Neihauz[3] said, 'Mathematics and music are at the opposite poles of the human spirit. These two antipodes confine and determine the entire creative activity of a human being'. This approach reflects a deeper use of physical and mathematical terminology and the general modern trend of mathematization of the humanities. In this regard, the problem of the retrospective review of development of the notions of consonance and dissonance in the physical and mathematical interpretation is considered urgent.

Review of research and publications

Studies related to the musical theoretical side of the phenomenon of consonance and dissonance usually relate to the theory of music set forth in various musical dictionaries, encyclopaedias, in textbooks on music theory, in chapters that deal with the intervals, chords, and the musical

[3] Neihauz, Henrikh. *On the art of piano playing*. Iskustvo, 1982.

temperament in general, textbooks on harmony and polyphony, as well as methods of teaching musical theoretical subjects. Basically, these are the works of musicologists and educators of the middle of the 20th century.

The historical paradigm of the notion of consonance is presented in studies on musical aesthetics, which allowed us to cite in this work the statements of scholars from antiquity to the 18th century on the issues of consonance as a consistent sound[4] [5] [6] [7] [8] [9] [10].

The problem of dissonance and consonance was studied by foreign representatives of musical culture. In particular, Lahdelma and Eerola[11] [12], who considered consonance and dissonance in the context of cultural belonging and musical experience. McDermott, Schultz, Undurraga and Godoy[13] also associated these phenomena exclusively with cultural differences in the perception of music. In the theory of music and psychology, consonance and dissonance are considered as a dichotomy — Parncutt and Hair[14]. Arthurs, Beeston and Timmers[15] — in connection with acoustic descriptors and musical training. From the standpoint of neurophysiology — Bones[16].

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4 Losev, Aleksey. *Antique musical aesthetics*. Muzgiz, 1960.

5 Bieliavina, Nataliia. *Fundamentals of sound design: a textbook*. NAKKKiM, 2011.

6 Bieliavina, Nataliia. *Joint performance of "Concertini" and coordinated sound of "Consonantis" as aesthetic roots of the concept of "concert"*. Culture and modernity: Almanac, 1, 2012, pp. 119-122.

7 Bieliavina, Nataliia. *Methodology and methods of teaching professional art disciplines*. NAKKKiM, 2019.

8 Shestakov, Viacheslav. *Musical aesthetics of the Western European Middle Ages and Renaissance*. Music, 1966.

9 Shestakov, Viacheslav. *Musical aesthetics of Western Europe in the 17th-18th centuries*. Music, 1971.

10 Shestakov, Viacheslav. *Musical aesthetics of the Western European Middle Ages*. Musical Ukraine, 1976.

11 Lahdelma, Imre. *At the interface between sensation and emotion: Perceived qualities of single chords*. (Ph.D. thesis), Jyväskylän, University of Jyväskylä, 2017

12 Lahdelma, Imre; Eerola, Tuomas. *Cultural familiarity and musical expertise impact the pleasantness of consonance/dissonance but not its perceived tension*. Scientific Reports, 10, no. 8693, 2020, pp. 1-11.

13 Mcdermott, Josh, Schultz, Alan, et al. *Indifference to dissonance in native Amazonians reveals cultural variation in music perception*. Nature, 535, 2016, pp. 547-550.

14 Parncutt, Richard, and Hair, Graham. *Consonance and dissonance in music theory and psychology: Disentangling dissonant dichotomies*. Journal of Interdisciplinary Music Studies, 5, 2011, pp. 119–166.

15 Arthurs, Yuko, Beeston, Amy, et al. *Perception of isolated chords: Examining frequency of occurrence, instrumental timbre, acoustic descriptors and musical training*. Psychology of Music, 46, 2018, pp. 662-681.

16 Bones, Oliver; Hopkins, Kathryn; et al. *Phase locked neural activity in the human brainstem predicts preference for musical consonance*. Neuropsychologia, 58, no. 100, 2014, pp. 23-32.

The biological substantiation of musical consonance was presented by Bowling and Purves[17]. The phenomena of consonance and dissonance were studied in connection with the Western theory of harmony — Harrison and Pearce[18], through the psychophysics of harmony perception — Parncutt[19], as well as Prete[20], in studies related to passion and cognitive functions of music — Perlovsky[21], in connection with musical style and experience — Popescu[22] and others.

Studies of various aspects of the manifestation of consonance were reflected in the works of Ukrainian musicologists-theorists. Significant research potential lies in the works of Horiukhina[23] [24]. She considers the phenomenon of consonance in the context of a well-grounded scientific concept of an open form in music. Musicologist Herasymova-Persydska[25] studied the concept of consonance in the context of the history of the development of European music as an integral system. Moskalenko[26] reflected the understanding of consonance through the prism of the genesis and modern trends of the Ukrainian national musical language, as a semiotic system. In the studies of Kotliarevskyi[27] consonance is considered within the framework of the musical theoretical systems of European art history in their logical content and evolution. Various aspects of consonance were reflected in the studies of Kokhanyk[28] [29] [30] and Shyp[31] [32] in the context of the topic under consideration.

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[17] Bowling, Daniel, and Purves, Dale. *A biological rationale for musical consonance*. Proceedings of the National Academy of Sciences of the United States of America, 112, 2015, pp. 11155-11160.

[18] Harrison, Peter, and Pearce, Marcus. *An energy-based generative sequence model for testing sensory theories of Western harmony*. Proceedings of the 19th International Society for Music Information Retrieval Conference, 2018, pp. 160-167

[19] Parncutt, Richard. *Commentary on Cook & Fujisawa's "The psychophysics of harmony perception: Harmony is a three-tone phenomenon"*. Empirical Musicology Review, 1, no. 4, 2006, pp. 204-209.

[20] Prete, Giulia, Fabri, Mara, et al. *The "consonance effect" and the hemispheres: A study on a split-brain patient*. Laterality, 20, no. 3, 2015, pp. 257-269.

[21] Perlovsky, Leonid. *Music: Passions and Cognitive Functions*. Elsevier, 2017.

[22] Popescu, Tudor, Neuser, Monja, et al. *The pleasantness of sensory dissonance is mediated by musical style and expertise*. Scientific Reports. 9, no. 1, 2019, p.1070.

[23] Horiukhina, Nadiia. *Dynamic Forms*. Essays on Musical Style and Form. Kyiv: Musical Ukraine, edited by A. Hokynska, 1985.

[24] Horiukhina, Nadiia. *Open forms*. Shape and style. LOLHK, 1990.

[25] Herasymova-Persydska, Nina. *Music. Time. Space*. Kyiv: Spirit and Litera, 2012.

[26] Moskalenko, Viktor. *Lectures on Musical Interpretation*. Kliaksa, 2012.

[27] Kotliarevskyi, Ivan. *Musical-theoretical systems of European musicology.* Musical Ukraine, 1983.

[28] Kokhanyk, Iryna. *Some features of the individual style of E. Stankovich (harmony as a style factor). Historical and theoretical problems of musical style.* Thematic collection of works, 1993, pp. 87-102.

Smahlii and Malovyk[33] also reflected on the theoretical generalization of consonance in their pedagogical works on the theory of music. The concept of consonance is associated mainly with figurative characteristics in the works of these and other musicologists dealing with the analysis of musical works and the history of music.

The issues of music theory have recently been presented in various publications related to users of musical computer technologies — in manuals “for dummies” and in various “tutorials”, which also deal with the elementary theory of music, without knowledge of which it is impossible to create musical works in sound computer programs.

Research related to audiovisual technologies for recording and processing sound, with the creation and use of acoustic engineering, takes a special place. These are the works of Ukrainian and foreign theorists and practitioners in the field of application of computer technology in the field of music composition, sound production, audio engineering. Ananiev[34] [35] presented fundamental developments in the field of musical acoustics. In the works of Belyavina[36] [37], Belyavin[38], the matter is about the study of auditory perception based on a mathematical model of the physical process. The technological aspect of the studied problem is reflected in the developments of: Bondarenko and Shulhina[39], who study application of computer technology in the field of music composition, Aldoshyna[40] in her works on psychoacoustics,

[29] Kokhanyk, Iryna. *A piece of music: the interaction of stable and mobile in terms of style*. Scientific Bulletin of the P. I. Chaikovsky National Music Academy of Ukraine: Musical work: the problem of understanding, 20, 2002, pp. 44-51.

[30] Kokhanyk, Iryna. *On the issue of the dialectic of style and non-style in the process of style formation*. Scientific Bulletin of the P. I. Chaikovsky National Music Academy of Ukraine: Style of musical creativity: aesthetics, theory, performance, 37, 2004, pp. 37-43.

[31] Shyp, Sergii. *Musical speech and the language of music. Theoretical research.* Publishing house of the A.V. Nezhdanova Odesa State Conservatory, 2001.

[32] Shyp, Sergii. *Theory of Artistic Styles*. Naukovetz, 2007.

[33] Smahlii, Halyna, and Malovyk, Liubov. *Fundamentals of music theory*. Fakt, 2005.

[34] Ananiev, Anatoliy. *Elements of musical acoustics*. Kyiv: Feniks, 2008.

[35] Ananiev, Anatoliy. *Acoustics for sound engineers: a guide*. Feniks, 2012.

[36] Bieliavina, Nataliia. *Fundamentals of sound design: a textbook*. NAKKKiM, 2011.

[37] Bieliavina, Nataliia. *Joint performance of “Concertini” and coordinated sound of “Consonantis” as aesthetic roots of the concept of “concert”.* Culture and modernity: Almanac, 1, 2012, pp. 119-122.

[38] Belyavin, Viktor. *Mathematization as a basis for the formation of basic knowledge and competencies of a modern sound director*. Bulletin of the National Academy of Management of Culture and Arts, 3, 2019, pp. 196-201.

[39] Bondarenko, Andrii, and Shulhina, Valeriia. *Music informatics*. NAKKKiM, 2011.

[40] Aldoshyna, Iryna. *Basics of psychoacoustics*. https://nsk.jagannath.ru/users_files/books/Osnovy_psihoakustiki.pdf

Hryshchenko[41], who develops modern technologies for creating music, Kharuto[42], who studies computer analysis of sound in musical science, Belyavina[43] in connection with the methodology of teaching sound engineers, and others.

In modern Physics courses, more attention is paid to the musical side of sound theory. Thus, the American physicist, Nobel laureate Feynman[44] sets out these topics in separate chapters: Sound. Wave equation; Beats; Harmonics.

More attention is paid to the physical and mathematical theory of musical phenomena in textbooks on musical acoustics[45] [46].

In the chapter Auditory Analysis of Consonances and Dissonances, Aldoshina[47] considers this phenomenon from psychoacoustic positions: ‘the ability of the auditory system to spectral analysis and determination of frequency intervals between harmonics underlies the sensation of “consonance” or “dissonance” of the sound of various musical intervals and chords’. She introduces a quantitative assessment of the “degree of sensation of consonance”.

The effect of “slightly mistuned consonances” (according to Helmholtz, Rayleigh) is used by Harbuzov[48] in his presentation of the theory of consonance and dissonance of intervals to explain the effect of beats.

Such approaches reflect the modern trend of mathematization of the humanities and deeper use of physical and mathematical terminology in art technologies[49].

But, in spite of a significant array of works, a holistic retrospective of the physical and mathematical interpretation of the musical and aesthetic category of “consonance” and “dissonance” has not been presented.

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[41] Hryshchenko, Valentyn. *Composition and computer arrangement.* NAKKiM, 2016.

[42] Kharuto, Aleksandr. *Computer Analysis of Sound in Music Science*. P. I. Chaikovsky Moscow State Conservatory, 2015.

[43] Bieliavina, Nataliia. *Methodology and methods of teaching professional art disciplines.* NAKKKiM, 2019.

[44] Feynman, Richard, Leyton, Richard, et al. *Feynman Lectures in Physics*. Mir, 1965.

[45] Ananiev, Anatoliy. *Elements of musical acoustics*. Kyiv: Feniks, 2008.

[46] Belyavin, Viktor. *Mathematization as a basis for the formation of basic knowledge and competencies of a modern sound director*. Bulletin of the National Academy of Management of Culture and Arts, 3, 2019, pp. 196-201

[47] Aldoshyna, Iryna. *Basics of psychoacoustics.* https://nsk.jagannath.ru/users_files/books/Osnovy_psihoakustiki.pdf

[48] Harbuzov, Nikolaiy. *Musical acoustics*. Muzgiz, 1954.

[49] Belyavin, Viktor. *Mathematization as a basis for the formation of basic knowledge and competencies of a modern sound director*. Bulletin of the National Academy of Management of Culture and Arts, 3, 2019, pp. 196-201.

Aim of the research and research objectives

The research aimed at a comprehensive retrospective analysis of the development of "consonance and dissonance" as a musical and aesthetic category in physical and mathematical interpretation, as well as defining the notion of consonance as a musical theoretical and aesthetic category, confirming the relevance of its use in physical and mathematical terminology to explain acoustic phenomena.

Research objectives: study the notion of "consonance" and "dissonance" as a musical theoretical and aesthetic category; present their interpretation in physical and mathematical research using the mathematical terminology; clarify some provisions of musical acoustics in the direction of creating a harmonious conceptual structure and confirm the relevance of its use in physical and mathematical terminology to explain individual acoustic phenomena; state the author's concept of clarification of the notion "phase" in relation to the spectral structure of a sound signal on the basis of the concept of "slightly mistuned consonance".

Materials and methods of research

The methodology of science describes the components of scientific research, the means necessary to fulfil the objective (solve the problem). The most common feature of modern science is the desire for theoretical synthesis, which allows combining objects or knowledge about them, that is, systematizing them. In this study, the retrospective method (retrospection method) made it possible. Retrospective analysis allowed identifying the theories of consonance and dissonance in a historical retrospective. The periodization method was used to single out individual stages in the development of science, to identify the leading directions of scientific thought, to identify new elements related to various aspects of "consonance" and "dissonance". An interdisciplinary method was applied to study the retrospective review of the development of the notions of consonance and dissonance in physical and mathematical interpretation. It is a method of organizing research work which implies interaction during a study of the same object between representatives of different subjects, music and mathematics in this case.

Author's conclusions were based on objective information, or the data obtained independently using scientific generally recognized methods, including comparison, which allowed identifying the peculiarities and establishing common features and differences, as well as generalities and patterns.

The research material is scientific and popular scientific literature on the research topic.

Results

The origins of the theory of "relationship between consonance and dissonance" in Antiquity

The ancient Greek philosophical school of the "Pythagoreans" united the most significant achievements of Greek thought of the most ancient period, including musical theoretical works. The Pythagoreans provided a completed theoretical doctrine of music in the 4th century BC in connection with the activities of the late Plato (about 427-348 B.C.), who, presumably, knew all the main representatives of this school[50].

Without citing the well-known theoretical musical heritage of the Pythagoreans in this work, we underline the historically reliable fact that the founder of "physical acoustics" is the Greek philosopher and mathematician, statesman Archytas (approx. 435/410-360/350 B.C.), Plato's contemporary. In general, Archytas bases his acoustics on the act of striking the air, which is a very advanced point of view for his time (according to the original fragment from Archytas' Harmonica)[51]. Archytas (Harmonica) is the author of the argument that "pitch of tone" is related to the speed of movement and the number of vibrations.

Archytas is also the creator of the theory of "the relationship of consonance and dissonance." Philosopher and art critic, Professor Losev (1893-1988) notes that this theory is very arbitrary and artificial in Archytas' presentation. It consists in the fact that the tones are the more consonant, the smaller their quantitative ratio. According to Archytas, consonance implies a ratio of whole numbers, since the exact half of an octave does not give a consonant tone. In addition to Archytas, the honour of this discovery also belongs to Eudoxus (408-365 BC), Greek astronomer and mathematician, student of Archytas and Plato[52].

So, the categories of "sound pitch", "consonance and dissonance" that were far from perfect and very ambiguous, in the modern sense, appeared for the first time in the 4th century B.C. As for the aesthetic essence of music, according to the historian and philologist Losev (1893-1988), the most general

[50] Losev, Aleksey. *Antique musical aesthetics*. Muzgiz, 1960.
[51] Idem.
[52] Ibidem.

principle of musical aesthetics of the Pythagoreans is expressed by the phrase: "Music is formation"[53]. There is no understanding that consonance and dissonance represent a musical aesthetic category.

Creation of the "theory of consonance" in the treatises of theorists and practitioners of the Middle Ages

In the treatises of music theorists and practitioners of the Middle Ages and the Renaissance, the problems of coordinated sounding of voices and the creation of a "theory of consonance" were being actively developed. In the early period of the Middle Ages, the so-called "Church Fathers" wrote about harmoniously coordinated sounds (Basil of Caesarea 330-379), about harmony and the measure of correlations of high-pitched and low-pitched sounds (Ambrose of Milan, approx. 340-397); and music was viewed as the science about "modulation" (Augustine Aurelius, 354-430).

The Roman philosopher and theorist Anicius Manlius Severinus Boetius (approx. 480-525) wrote that music is one of the four branches of mathematics and was virtually the first to talk about the relationships between sounds and the numerical theory of their relationship: "two sounds, one low-pitched and the other high-pitched taken simultaneously, combine into one pleasant sound". Another Roman Encyclopaedist Flavius Cassiodorus (490-593) also wrote about music as a science which is expressed in numbers and singled out the concept of "harmonics" as a science of low-pitched and high-pitched sounds[54].

Isidore of Seville (560-636) studied the etymology of scientific concepts and developed a rather harmonious system of harmonization of sounds: low-pitched and high-pitched sounds (acutum and gravem), symphony — 'a combination of melodies, which consists of coordinated sounds — high-pitched and low-pitched', diaphony — 'dissonant or discordant voices'; he also defined the concept of sound oscillations — 'a voice is rending the air by breathing'[55].

The famous musical figure Bede the Venerable (approx. 672-735) wrote that practical music is the teaching of low-pitched, medium-pitched and high-pitched sounds and that the instruments of practical music can be natural (naturale) sounds, and the instrument of theoretical music is research and an explanation of the relationship between sounds and voices. Scholars

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[53] Losev, Aleksey. *Antique musical aesthetics*. Muzgiz, 1960.

[54] Shestakov, Viacheslav. *Musical aesthetics of the Western European Middle Ages.* Musical Ukraine, 1976.

[55] Idem.

of the late Middle Ages developed the principles of early polyphony — "diaphony" on the basis of the "theory of consonance".

The musical theorist Aurelian of Rheome (9th century) designated the concept of consonance as a "symphony" of coordinated low-pitched and high-pitched sounds. The singing teacher Benedictine monk Hucbald (840-930) described intervals as follows: consonance is based on the joint sounding of two tones that do not belong to the same scale, unison is not an interval, calls consonance as organization and refers the fourth and fifth thereto.

The philosopher Johann Scott Eriugena (810-877) provides information on organum (organocum melos) and diaphony. Diaphony 'begins with a tone (in unison), then it passes in simple or complex intervals, and returns to its beginning — the tone (unison)', while in the organum 'voices either sound or separate from one another to a greater or lesser distance, according to reasonable laws and according to certain frets "[56].

Rationalistic studies of consonances and dissonances in the Renaissance

In the Renaissance, there is a turn towards empirical and dogmatic-free rationalistic research, including in music. Johannes Cotto (11th — early 12th century) declared that diaphony is a coordinated divergence of voices, which is created by no less than two singers. In subsequent treatises he attempted to differentiate intervals appear: consonances and dissonances.

The French theorist Johannes de Grocheo (approx. 1255 — approx. 1320) focused on the most perfect consonances diapason — octave, diapente — fifth, diatessaron — quart.

Flemish music theorist Joahannes Tinctoris (Tinctoris, 1435-1511) defines such notions as: "concordantia" — consonance is 'a mixture of different sounds pleasing to the ear'; "discordanta" — dissonance is a mixture of sounds that "distort the tone"; "concordantia perfecta" — perfect consonances that cannot be "taken up and down in a row" (unison, fifth, octave); concordantia imperfect - imperfect consonances that can be "taken up and down several times in a row" (third and sixth large and small); "armonia" — harmony as "a certain pleasantness obtained from the fact that one sound is combined with another"[57].

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[56] Shestakov, Viacheslav. *Musical aesthetics of the Western European Middle Ages.* Musical Ukraine, 1976.

[57] Shestakov, Viacheslav. *Musical aesthetics of the Western European Middle Ages and Renaissance.* Music, 1966.

The problem of consistency of intervals, consonances and dissonances became apparent during the development of the counterpoint technique. The Italian counterpoint theorist Gioseffo Zarlino (Zarlino, 1517-1590) wrote that 'counterpoint is consistency or consonance', which comes from the combination of voices 'that are in the cantilena and are formed by voices spaced apart from one another at appropriate and harmonic intervals'[58].

In the treatise Le Instituzioni Harmoniche, he carried out a mathematical calculation of the major and minor fret scale, developed the theory of interval reversal, put forward the acoustic theory of the "soniferous body", as well as the appearance of the "beat" effect. He wrote that in order to understand the essence of the musical interval, it is necessary to combine 'number and sound, and adding them together, we can say that the subject of music is the soniferous body'[59].

New time and the era of the Enlightenment as a stage in the harmonization of musical, physical, and mathematical and acoustic terminology

Further development of the theory of consonance and dissonance is associated with the rapid accumulation of new empirical knowledge. The Italian writer and aesthetician Ercole Bottrigari (1531-1612) first raised the topic of the consistency of instrumental ensemble playing, when during a concert one can hear 'confusion, and even complete discord', and emphasized that this is due to incorrect tuning of different types of instruments: strings (viols and lutes) and keyboards (cembalos and harpsichords).

Along with the theory of "affects", the concept of "consonantis" became one of the main topics of theoretical treatises of the 16th-17th centuries, namely, euphony and dissonance, coordination and inconsistency of consonances and dissonances.

Thus, the famous musical reformer, the Italian composer Claudio Monteverdi (1567-1643) saw the perfection of then contemporary music in attitude to consonances and dissonances. And the writer and composer Pietro Della Valle (1686-1652) wrote about concertini as pleasant consonances.

Ukrainian composer and music theorist Mykola Dyletskyi (1630-1690) pointed to the concept of "concordance" — consonance, triad composed on the basis of perfect intervals (third, fifth, octave). And the German philosopher

[58] Shestakov, Viacheslav. *Musical aesthetics of the Western European Middle Ages and Renaissance.* Music, 1966.
[59] Idem.

and mathematician Johannes Kepler (1571-1630) wrote that ‘there will be no harmony between the sounds until an exact sequence is established, which is determined by mathematically exact proportions’[60].

Anastasius Kircher (1601-1680) also studied the problems of “consoni et dissoni”, reflected on the magic of euphony and cacophony. He was one of the first to study the acoustic parameters of rooms for music performances.

The French philosopher and mathematician Rene Descartes (1596-1650) somewhat materializes these concepts and divides sounds according to their duration, as well as by “tension”, that is, by the pitch. He writes about the euphony of intervals, about the transition of unstable accords to stable ones.

The French philosopher and mathematician Marin Mersenn (1588-1648) made an attempt to classify the intervals into “natural” — diatonic and “artificial” — invented by musicians. Mersenne M. also writes about the “euphony of music”, which is the result of the correct correlation of consonances. From the same point of view, he explains such a phenomenon as “temperament” (Latin temperatio): ‘the temperament of sounds is necessary for the harmonious fusion of instruments, harmonization of dissonances and consonances’[61].

Mersenne M., as well as the music theorist and organist Andreas Werckmeister (1645-1706), were the first to calculate the 12-step temperament. They used the so-called “Pythagorean comma” (each perfect fifth was theoretically reduced by 1/100 of a whole tone), and were able to divide an octave into 12 equal parts (semitones).

Thus, the scholars approached virtually even temperament, anharmonicity and ordering of the musical tuning. In order to study individual acoustic phenomena, musicians of the 18th century began to approach their explanation not only from the point of view of music theory, but also through the prism of the natural sciences.

The German music writer and composer Johann Matheson (1681-1764) wrote that ‘mathematics has long made efforts to bring sound and its ratios to numerical order,’ but believed that ‘if the ratios of sounds are pleasant to the ear, the mathematical criterion should retreat’[62].

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[60] Shestakov, Viacheslav. *Musical aesthetics of Western Europe in the 17th-18th centuries*. Music, 1971.
[61] Idem.
[62] Ibidem.

Musical esthetician and teacher Friedrich Marpurg (1718-1795) also studied the nature of sound, supported the ideas of temperament. In works that dealt with the counterpoint theory he described the principles of the coordinated combination of several contrasting melodies and themes using certain counterpoint rules, where consonances play an important role.

The German music critic and composer Johann Scheibe (1708-1776) emphasized that 'music is a science that requires great knowledge, and at the same time is no less significant art', and 'realizing musical truths requires knowledge of logic, metaphysics, natural sciences and mathematics. Therefore, the composer must have an idea of all the laws of the world'[63].

Educational philosopher, writer, composer Jean-Jacques Rousseau (1712-1778) wrote that music is "the art of combining sounds in a way that is pleasing to the ear. When they want to find the principle of these combinations and the reasons for the sensations that art evokes, it becomes a science'[64].

In his Treatise on Harmony, the French composer and theorist Jean Philippe Rameau (1683-1764) was the first to reveal the phenomenon of oscillation of the "soniferous body", which creates a series of overtones (German oberton) from the main tone and developed the "doctrine of harmony" on this basis. He pointed out that 'music is a science that must have certain rules; these rules should follow from the corresponding principle, and this principle cannot be studied without the help of mathematics'[65].

French philosopher, encyclopedist, mathematician, acoustician physicist Jean d'Alembert (1717-1783) supported the theoretical foundations of the harmonic theory of J.F. Rameau and wrote that he was the first to 'reveal the resonance of the soniferous body': all bodies make it possible to hear, in addition to the main sound, the twelfth and septadecima of this sound. This complex resonance has been known for a long time and forms the basis of the entire Rameau's theory. He also supported the development of the Italian virtuoso violinist Giuseppe Tartini (1692-1770), who also wrote Treatise on Harmony, where he presented the concept of "combination tones", later called "Tartini tones"[66].

Prominent German musicologist Karl Wilhelm Julius Hugo Riemann (1849-1919) was actively engaged in the study of acoustics and formulated the essence of his doctrine of harmony based on some concepts. In the Musical Dictionary (1882) and in the work Acoustics from the Point of View of Musical Science (1898), he formulated the theory of "untertones" (German

[63] Shestakov, Viacheslav. *Musical aesthetics of Western Europe in the 17th-18th centuries*. Music, 1971.

[64] Idem.

[65] Ibidem.

[66] Ibidem.

unterton — subharmonic). It was proved that the sequence of sounds of the natural scale is the opposite of the sequence of overtones (harmonics) — 'untertones are a series of tones built down from the first overtone quite correspondingly, but opposite to the row of overtones built up from the first overtone"[67].

The concept of "harmonic untertone" was introduced by Helmholtz (1821-1894) back in 1863 — this is how he designated the first overtone of a sound source, a resonator. Subsequently, the term "undertone" was assigned to the concept of "combination tones". In parallel with the development of musical theory, acoustics and mathematicians studied musical sound phenomena. The possibility of studying various musical categories was predetermined by the formation of an understanding that a musical tone is mathematically modelled using such a concept as a "sinusoid function" with the parameters of "amplitude", "frequency", "phase". The artist and mathematician Albrecht Durer (1471-1528) presented its graph back in 1525.

The issues of harmonization of musical, physico-mathematical and acoustic terminology became relevant even before the appearance of natural science research, the development of which was determined by: the creation of the foundations of modern natural science — the creator of "classical" physics, English physicist and mathematician Newton; creation and further development of differential and integral calculus (mathematical analysis) — Newton, German mathematician Leibniz, Swiss mathematician and physicist Leonhard Euler, French scientist Fourier; the creation of the theory of sound phenomena, physiological and musical acoustics — the German scientist Helmholtz, the German physicist Georg Ohm, the English physicist Rayleigh[68].

The scientific study of sound phenomena became possible on the basis of the integral and differential calculus created by Newton (1643-1727) and Leibniz (1646-1716), the development of the foundations of "spectral analysis" by Jean-Baptiste Fourier (1768-1830) and Leonhard Euler (1707-1783), as well as the conclusion of Georg Ohm (1789-1864) about the ability of the human ear to perceive simple vibrations as separate tones, into which the sound vibration can be decomposed according to the Fourier theorem (Ohm's law, 1843).

As the physicist, Nobel Laureate John William Strutt (Lord Rayleigh, 1842-1919) noted, the work of the German physicist, physiologist,

[67] Riman, Huho. *Music Dictionary.* Direktmedia Pablishinh, 2008. http://biblioclub.ru/index.php?page=dict&dict_id=22

[68] Strutt, John William, and Baron Rayleigh. *The Theory of Sound*. Doves Publication, 1945.

acoustician Hermann Helmholtz (1821-1894) On the Sensations of Tone as a Physiological Basis for the Theory of Music (1863) 'provides this work the role of the starting point of all reasoning that relate to sound sensations for a long time"[69].

Acoustician, Professor Irina Aldoshina (n.d.) writes that Helmholtz asserted: 'the difference in the musical quality of a tone (timbre) depends only on the presence and intensity of partial tones (overtones), and does not depend on the phase difference with which these partial tones enter into the composition.' And she notes that 'this definition has determined the direction of research for almost a hundred years, has changed greatly and was significantly refined only at the end of the last century'.

According to the authors, the main scientific results on the theory of sound are set out in Chapter XXIII of Theory of Sound by Lord Rayleigh. In particular, he indicates some facts about the influence of phase relationships on sound and its timbre. He writes that, according to Helmholtz's observations, phase changes did not have a noticeable effect on the timbre of a complex sound. However, the question of the effect on the ear of a change in the phase relationships of different components of sound can be studied by the method of "slightly mistuned consonances", that is, by adjusting the intensity and phase of the components by a slight change in the pitch (eigentone), as suggested by Helmholtz himself[70].

Acoustician and musicologist Harbuzov (1880-1955) notes that there are several theories of consonance and dissonance, the most famous of which is the theory of Helmholtz, who explained the phenomenon of consonance and dissonance by the degree of audibility of the beats of the pitch and overtones[71]. German psychologist, music theorist Karl Stumpf (1848-1936) determined the phenomenon of consonance and dissonance by psychological factors, depending on whether the audible two-tone in consciousness merges into one sound or not.

The development of musical theory in line with the theory of acoustics and mathematics in the 19th—20th centuries

Based on the data of modern musical acoustics, the issue of the consonance and dissonance of intervals has a more complex explanation[72]. Indeed, the feeling of consonance and dissonance of intervals always

[69] Strutt, John William, and Baron Rayleigh. *The Theory of Sound*. Doves Publication, 1945.
[70] Idem.
[71] Harbuzov, Nikolaiy. *Musical acoustics*. Muzgiz, 1954.
[72] Idem.

occurs when two sounds sound simultaneously. And with “slightly mistuned perfect consonances” the “beat” effect arises, and there is a pronounced influence of the phase relations of the two sounds on the nature of the sound in this case.

American physicist Feynman (1918-1988) gave an instructive explanation of the phenomenon of beats. According to Feynman (1965), for two sound sources of the same frequency, when the phase of one of the sources changes, we will see several weak and strong “pulsations” at some point in space. But the statement that one source with a constant speed change its phase in relation to another is equivalent to the fact that oscillations with a slowly pulsating intensity, that is, beats, are obtained in the case of addition of oscillations of sources the frequencies of which are somewhat different[73].

As Ananiev noted, ‘the phenomenon of beats is extremely significant in the perception of musical sounds. He writes that the beats reveal the complex nature of the sensation of sound as a whole, they play a role in the study of the phenomenon of masking sounds, binaural beats, and also manifest themselves when tuning musical instruments[74].

According to the authors, this phenomenon is the so-called “slightly mistuned consonance”, demonstrating the effect of phase changes between signals, which is expressed in a change in the timbre of the signal, on the “ear”. Some uncertainty of the opinion of Helmholtz in this matter is explained by the absence in his time of the theory of signals, which are close in terms of structure to harmonic, but with modulated parameters.

Let us give some reasoning about the formation and development of such a concept as the phase properties of the spectral representation of musical sound in the 20th century. In the first half of the 20th century, the theory of frequency and phase modulation was developed. The concept of instantaneous amplitude, frequency and phase of the signal was also introduced, and a conclusion was made about the equivalence of frequency and phase modulation. The definition of frequency as a time derivative of the current phase of the signal was introduced. It became clear why a change in the signal phase, not associated with a change in the signal frequency, but caused by a change in the additional part of the phase, which has a nonzero derivative, leads to a change in the signal frequency, that is, the timbre.

[73] Feynman, Richard, Leyton, Richard, et al. *Feynman Lectures in Physics*. Mir, 1965.
[74] Ananiev, Anatoliy. *Acoustics for sound engineers: a guide.* Feniks, 2012.

Professor Fink (1910-1988), who studied the theory of signal transmission, noted that for a long time specialists who studied signals made mistakes based on the inability to clearly distinguish between two similar, but by no means coinciding concepts — the instantaneous frequency of the signal and the frequency of its spectral component[75].

Thus, the instantaneous frequency of a signal is a function of time, while the frequency of its spectral component does not depend on time. The instantaneous frequency for a given signal at a given moment in time takes one single value, and there is a finite, countable or uncountable set of spectral components with different frequencies for a given signal at any moment in time. At the same time, the instantaneous frequency can change when the signal passes through a linear circuit with constant parameters. The spectral component does not change when the signal passes through a linear circuit with constant frequency parameters. Only their amplitudes and initial phases can change[76].

Spectral components are represented as $A \sin(\omega t+\psi)$, where: A – amplitude; ω — frequency; t — the current time; ψ — the initial phase. Using the well-known trigonometric transformation, we have:

$$A \sin(\omega t+\psi) = A \sin(\omega t) \cos \psi + A \cos(\omega t) \sin \psi = AS \sin(\omega t)+AC \cos(\omega t).$$

In this expression, the spectral component is represented through "elementary, or simple" harmonic components (tones) $\sin(\omega t)$ and $\cos(\omega t)$ with amplitudes AS and AC, respectively. In other words, each overtone with frequency ω is the sum of two simple harmonic components. It is in this form that the representation of the Fourier series is used to calculate the amplitudes AS and AC of each harmonic using the Euler-Fourier formulas.

The physical meaning of the initial phase ψ of the spectral component can be interpreted as a value that determines the "weights" of the elementary overtones $\sin(\omega t)$ and $\cos(\omega t)$, with which these partial frequencies (overtones) enter, according to Helmholtz, 'into the composition'. According to the authors, the clarifications of the notion of "phase" given by the authors in relation to the spectral structure of an audio signal are rather nontrivial. As Ukrainian acoustician, Associate Professor Ananiev (1944-2017) noted, the widespread use of synthesis of sounds and their studio processing requires clarification of the terminology used by specialists in the field of creating musical products. So, for example, the

[75] Fink, Lev. *Signals, interference, errors ... (Notes on some surprises, paradoxes, and delusions in communication theory)*. Sviaz, 1978.

[76] Idem.

word “timbre” is often used incorrectly, without any explanation’, although this term has no clear explanation so far[77]. The above also applies to the word “phase” to a certain extent.

The second half of the 20th century was the start of the active use of computer technology in scientific research, in particular, the study and development of spectral-temporal representations of sound vibrations. As Aldoshina (n.d.) noted, this contributed to the ‘accumulation of experimental data that the hearing aid is sensitive to phase changes between different signal components. This stage of studying the main characteristics of sound allowed moving on to new developments in the field of “timbre morphing”[78].

Discussion

The development of sound musical technologies requires a significantly higher scientific level of their study, strengthening of the “mathematization” of their presentation, the creation of a coherent conceptual system based on modern musical science. The application of an interdisciplinary approach to the consideration of the musical-theoretical concepts of “consonance and dissonance” based on modern physical and mathematical sciences to explain some sound phenomena allowed us to expand the boundaries of the ideas about some acoustic parameters. The consideration of the above musical aesthetic and scientific technical categories in their historical development is currently of interest to specialists in the field of theoretical and practical application of sound technologies, their connection with musical, acoustic, objective, and subjective characteristics of sound.

A retrospective review of the development of the concepts of “consonance and dissonance” in the physical and mathematical interpretation is carried out as a comprehensive description and review of the formation of concepts in the temporal sequence of their creation. Turning back to the past through a review of significant discoveries and achievements in music and natural science allowed tracing the formation of the doctrines of “consonance and dissonance” from the standpoint of the interdisciplinarity of modern humanitarian knowledge. Table 1 contains the main points. “Stages of the formation of the theory of consonance and dissonance.”

[77] Ananiev, Anatoliy. *Acoustics for sound engineers: a guide*. Feniks, 2012.
[78] Oskolkov, Sergey. *Modern sound engineering: creativity, technology, education*. SPbGUP, 2013.

Table 1

Period (era)	Thinkers, researchers, scientists, representatives of the era	Stages of formation of the theory (key points)	Formation of the concepts of “consonance and dissonance” in the physical and mathematical interpretation
Antiquity	Plato (approx. 427-348 B.C.) Archytas (approx. 435/410-360/350 B.C.);	The origins of the theory of consonance and dissonance.	The formation of an understanding of dissonance and consonance was associated with physical acoustics. Ancient Greek thinkers understood consonance as the ratio of whole numbers (Archytas).
Middle Ages	Basil of Caesarea (330-379); Ambrose of Milan (approx. 340-397); Augustine Aurelius (354-430); Anicius Manlius Severinus Boetius (approx. 480-525); Flavius Cassiodorus (490-593); Isidore of Seville (560-636); Bede the Venerable (approx. 672-735); Aurelian of Rheome (IX century); Hucbald (840-930); Johann Scott Eriugena (810-877).	The problems of harmonized sounding of voices and the creation of a “theory of consonance” were developed.	Music begins to be thought of in relation to mathematics. In the understanding of medieval thinkers, music should be understood as one of the four branches of mathematics. Music can be expressed in numbers.
Renaissance	Johannes Cotto (11^{th}—early 12^{th} century), Johannes de Grocheo (approx. 1255—approx. 1320); Joahannes Tinctoris (1435-1511); Joseffo Zarlino (1517-1590)	Attempts were made to define the concepts of “consonance” and “dissonance”	Attempts were made to differentiate the intervals: consonances and dissonances. The concept of counterpoint is introduced in the context of the problem of consistency of intervals, consonances and dissonances The mathematical calculation of the major and minor fret scales is introduced. The concept of “consonantis” is introduced — namely, euphoniousness and discordance, consonance and inconsistency of consonances and dissonances.

Modern period and the era of the Enlightenment			
17th century	Newton (1643-1727); Gottfried Wilhelm Leibniz (1646-1716); Jean-Baptiste Fourier (1768-1830); Leonard Euler (1707-1783) Georg Ohm (1789-1864) Ercole Bottrigari (1531-1612); Claudio Monteverdi (1567-1643) and others. Pietro Della Valle (1686-1652); Mykola Deletskyi (1630-1690); Johannes Kepler (1571-1630); Anastasius Kircher (1601-1680); Rene Descartes (1596-1650); Marin Mersenn (1588-1648); Andreas Werckmeister (1645-1706).	The origin of modern science. Formation of natural science. The issues of harmonization of musical, physico-mathematical, and acoustic terminology became relevant with the advent of natural science research.	The foundations of “classical” physics and its section — mechanics — were laid. Physical and mathematical developments in the theory of sound were underway. The doctrine of the “euphony of music”, which is the result of a certain proportion of consonances. Explanation and mathematical calculation of the phenomenon of “temperament”.
18th century	Johann Mattheson (1681-1764); Friedrich Marpurg (1718-1795); Johann Scheibe (1708-1776); Jean-Jacques Rousseau (1712-1778) Jean Philippe Rameau (1683-1764); Jean D’Alembert (1717-1783); Giuseppe Tartini (Tartini, 1692-1770); Hugo Riemann (1849-1919).	The understanding was formed that music is a science that is based on the principles of mathematics.	Scientists approached virtually equal temperament, anharmonicity and ordering of the musical tuning. The doctrine of harmony was formed. Many acoustic phenomena were understood in terms of music and natural sciences. There were statements that mathematics had the property of bringing sound and its proportions to numerical order.

Modern period and the era of the Enlightenment			
19th — early 20th century	Hugo Riemann, 1849-1919; Gottfried Wilhelm Leibniz (1821-1894); Albrecht Durer (1471-1528); Hermann Helmholtz (1821-1894); John William Strutt (Lord Rayleigh, 1842-1919); N.A. Harbuzov (1880-1955); Karl Stumpf (1848-1936); R. Feynman (1918-1988); L.M. Fink (1910-1988) and others.	Development of musical theory in line with the theory of acoustics and mathematics. Explanation of the phenomena of consonance and dissonance from different positions of mathematics, psychology, physics, etc.	The musical tone was mathematically modelled using such a concept as "sinusoid function" with the parameters "amplitude", "frequency", "phase". Doctrines on auditory sensations and the physics of sound. The phenomenon of consonance and dissonance was determined by psychological factors. It was established that the "beat" effect arises with "slightly mistuned perfect consonances". The theory of frequency and phase modulation was developed. The concept of instantaneous amplitude, frequency and phase of a signal is introduced. A conclusion was made about the equivalence of frequency and phase modulation. The definition of frequency was introduced as a time derivative of the current phase of the signal. Experimental evidence was accumulated that hearing aids are sensitive to phase changes between different signal components.
Middle 20th —early 21st century	Goryukhina N.A., Herasymova-Persydska N.A., Moskalenko V.G., I.A. Kotlyarevsky, I.M. Kokhanik, S.V. Ship, A.B. Ananiev, Belyavina N.D., Belyavin V.F., Dyachenko V.V., A.I. Bondarenko, V.D. Shulgina, V.I. Grishchenko, I.A. Aldoshina, A.V. Hharuto and others.	Theoretical generalization of consonance in musicology. Consonance is viewed in the context of the history of the development of European music as an integral system.	Consonance is considered within the framework of the musical theoretical systems of European art history in their logical content and evolution. They represent the processes of auditory perception in various aspects based on a mathematical model of a physical process. The phase properties of the spectral representation of musical sound are specified. The theory of frequency and phase modulation was developed. Research related to audiovisual technologies for recording and processing sound, with the creation and use of acoustic engineering. Developments in the field of musical acoustics, including psychoacoustics, computer analysis of sound in musical science.

Stages of the formation of the theory of consonance and dissonance

Conclusion

Retrospective, as a look back, referring to the previous meaningful information regarding "consonance" and "dissonance", allowed not only to assess phenomena, processes in the same terms, but also to clarify certain concepts of physical and mathematical terminology used in modern audiovisual technologies.

According to the authors, the updates of the concept of "phase" in relation to the spectral structure of an audio signal, based on the representation of the Fourier series in the form of the sums of the products of the Euler-Fourier coefficients and the corresponding simple sine and cosine functions, are quite nontrivial and correct. The authors concept of clarifying the concept of "phase" in relation to the spectral structure of a sound signal was outlined based on the concept of "slightly mistuned consonance". The physical meaning of the initial phase of the spectral component is proposed to be interpreted as a quantity that determines the contribution of elementary sine and cosine overtones, with which these overtones (partial frequencies) enter "into the composition", as Helmholtz stated.

The further process of development of sound musical technologies requires a significantly higher scientific level of their study, strengthened "mathematization" of their presentation, and the creation of a coherent conceptual system based on modern musical science.

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