DOI HTTPS://DOI.ORG/10.2298/MUZ1824095N
UDC 789.983
534
534.4:530.145

Synthesis and Analysis of Sounds Developed from the Bose-Einstein Condensate: Theory and Experimental Results*

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Received: 20 April 2018
Accepted: 7 May 2018
Original scientific paper

Abstract

Two seemingly incompatible worlds of quantum physics and acoustics have their meeting point in experiments with the Bose-Einstein Condensate. From the very beginning, the *Quantum Music* project was based on the idea of converting the acoustic phenomena of quantum physics that appear in experiments into the sound domain accessible to the human ear. The first part of this paper describes the experimental conditions in which these acoustic phenomena occur. The second part of the paper describes the process of sound synthesis which was used to generate final sounds. Sound synthesis was based on the use of two types of basic data: theoretical formulas and the results of experiments with the Bose-Einstein condensate. The process of sound synthesis based on theoretical equations was conducted following the principles of additive synthesis, realized using the Java Script and Max MSP software. The synthesis of sounds based on the results of experiments was done using the MatLab software. The third part or the article deals with the acoustic analysis of the generated sounds, indicating some of the acoustic phenomena that have emerged. Also, we discuss the possible ways of using such sounds in the process of composing and performing contemporary music.

Keywords: Bose-Einstein Condensate, Quantum Music, synthesis of sound, acoustics

* This article was written for the project *Quantum Music*, co-financed by the EACEA within the programme *Creative Europe* (559695-CREA-1-2015-1-RS-CULT-COOP1).

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At first glance, music, as an aesthetized form of sound, and quantum physics, as part of physics dealing with the elemental structure of the material reality, with which we have no sensory or experiential contact, have nothing in common. A sound cannot exist without the matter through which it would spread, while quantum particles exist at a level that is completely independent of what we perceive as the material structure of the world that surrounds us. Music is a phenomenon perceived by the sense of hearing, while this sense in no way has any contact with the quantum world. Acoustic as the branch of physics that deals with the theory and practice of the origination, distribution and reception of sound waves, on the one hand, and quantum physics on the other seemingly narrate completely different stories.

A good illustration of the complete disconnection of these two worlds can be the fact that several hundred quantum particles pass through the human body at every second of its existence, but we are entirely unaware of this. The dimensions of the atoms that constitute the structure of our material reality are appoximately 10^{-10} m are disproportionately larger than the dimensions of the quantum particles, which are approximately 10^{-35} m. This difference of 25 orders of magnitude is so huge that quantum particles in their propagation through material reality do not "see" anything else but an endless vastness of emptiness, the absence of any material structure, which modern science describes using the term *quantum vacuum*. How, then, can we attempt to establish a meaningful, realistic and scientifically grounded connection between sound and quantum physics, which is the basic premise of the Quantum Music project?

If we accept a scientifically proven fact that the fundamental structure of the whole existence is based on the vibration of energy and the matter derived from it, these two worlds suddenly obtain conceptual outlines that can be connected. Because sound is really nothing more than the spread of mechanical vibrations — waves, through the elastic environment, while each quantum particle in itself is a phenomenon that can be described in terms of vibration and wave. By taking the next step and recognizing the undeniable existence of the fundamental principle of nature that is manifested through repetition of the same patterns in its various forms of manifestation, a large philosophical field opens up to establish analogies between acoustic and quantum systems. Physical concepts such as waves, frequencies, harmonics, oscillators, standing waves, wave equations – these are all concepts used both in acoustics and in quantum physics. These connections between acoustics and quantum physics extend very deeply, reflecting even in the fact that too much complexity of both phenomena has led both acoustics and quantum physics to attempt to quantify the phenomena that they deal with in a a definite and uselful way, thus turning into statistical theory, abandoning the complete and always precisely defined quantification of the phenomena that they deal with.

A definitive theoretical-philosophical basis for the establishment of deeper analogies between acoustics and quantum physics was established by French physicist Louis de Broglie in the mid-1920s by providing insight into the possibility of treating an electron moving in its orbit around the atomic nucleus as a standing wave (De Broglie 1929). After Russian physicist Igor Tamm introduced the notion of phonon into the theory of quantum mechanics (Tamm 1932), a quantum of mechanical vibration, which can indeed be treated as a quantum – the smallest energetic unit of sound (analogous to a photon representing a quantum of light), the possibility of establishing theoretical-philosophical analogies and the connection between acoustics and quantum physics became numerous and quite interesting. There have been further attempts to establish such analogies, and the Austrian scientists Volkmar Putz and Karl Svozil have probably pushed the farthest (Putz and Svozil 2015). However, all these connections continued to be without a basis in the reality embodied in the experiment. Although the theoretical foundations of such an experiment were set up in the mid-1920s, its realization had to wait until the end of the twentieth century.

Bose-Einstein Condensate

In 1925 Albert Einstein and Satyendra Nath Bose predicted that the matter cooled to an extremely low temperature would begin to exhibit completely non-specific characteristics, so unique that they declared this state of matter a new one, and gave it a special name — a condensate. This state of matter is now called the Bose-Einstein Condensate, after these two scientists (hereinafter referred to as BEC). It was experimentally achieved in 1996 by physicists Eric A. Cornell, Wolfgang Ketterle and Carl E. Wieman who received the Nobel Prize in Physics in 2001 for it (Andrews et al. 1997). In addition to the three states of matter that we are familiar with – solid, liquid and gaseous – and after plasma as the fourth state of matter that is established at extremely high temperatures, condensate is the fifth and final (so far) state of matter known to man, formed at unimaginably low temperatures.

Figure 1: *Satyendra Nath Bose and Albert Einstein, creators of the theoretical assumption about the possibility of the existence of the fifth aggregate state of matter – condensate*

After the first successful experiment, this state of matter is now achieved in laboratories around the world, with the level of sophistication of the equipment by which this experiment is performed such that it enables extremely precise analyzes of such a newly formed condition in which the substance is located.

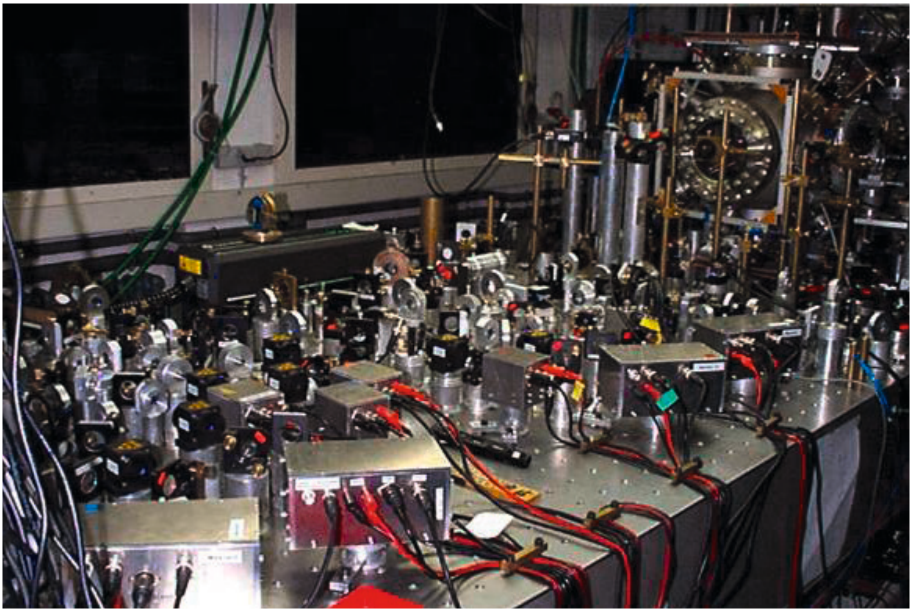

Figure 2: *The experimental equipment needed to create and analyze BEC*

Each gas at the temperatures close to us implies a very chaotic and disordered movement of atoms (the so-called Brownian motion). In such a system, each atom acts as a system for itself, with a defined energy state and a vibration mode, on the basis of which it interacts with other atoms in the environment. In the process of cooling the atoms, the level of disorder of the system begins to decrease, atoms vibrate at lower frequencies, until at one point, defined by the so-called critical temperature, a phase transition happens, after which all the atoms in the system begin to occupy the lowest possible energy state (Pitaevskii and Stringari 2003). Since modern science assigns to each particle simultaneously both corpuscular and wavelike properties, it is easy to conclude that, by decreasing the temperature, the oscillation velocity (frequency) of the atoms decreases, i.e. the wavelength of the atom as a wave increases. The phase transition is carried out at temperatures measured in nanoKelvins (nK) – a billionth part of one degree near the absolute zero. The temperature of zero Kelvin or absolute zero is the temperature at which all movement of matter ceases and which, according to today's science, cannot be reached. The intergalactic space, as the coldest area outside the laboratory known to man, is at temperatures of 3-4 K, which means that the temperature that the substance enters in these experiments is the lowest known temperature, or, as it is often said, the condensate is located at the lowest temperature in the Universe known to men.

At temperatures close to absolute zero wavelengths of atoms become large enough to form overlapping waves of individual atoms that act as individual systems on higher temperatures. In other words, all atoms descend to an identical, lowest possible energy state, overlap their waves and become one quantum system. It is this state of matter, in which groups consisting of millions of atoms, which is a specific quantity of matter, begin to act as a single quantum system, opens the possibility of establishing direct bonds between acoustic and quantum mechanics systems (Lee, Huang and Yang 1957).

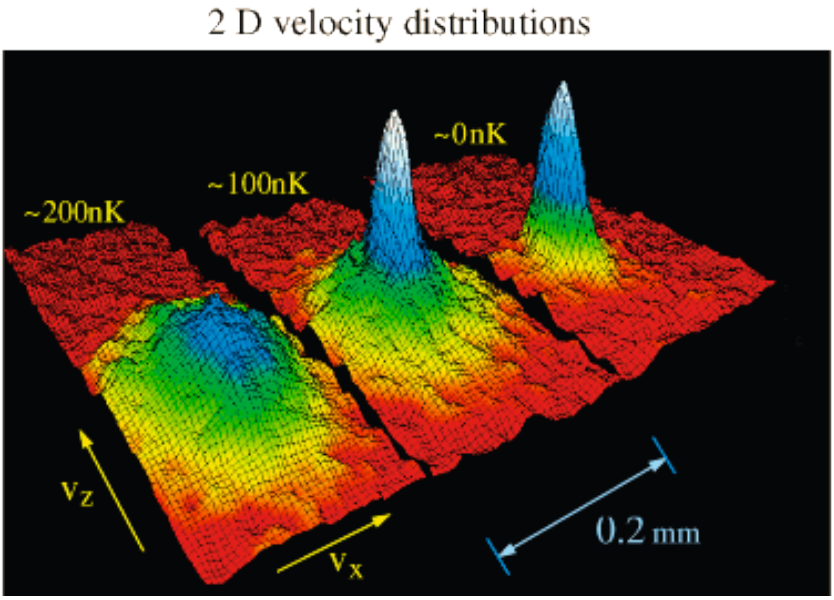

Figure 3: *Graphical representation of atomic velocity distribution (red – higher speed, blue – lower speed) dependent on temperature (lowering of temperature from left to right) — a display of the process of transition in reaching BEC*

Once the state of the condensate is reached in the experiment, it can be analyzed in different ways. One of the classic ways is its laser beam excitation. This energy impact to BEC leads to a change in density in parts of the condensate. This change in density is transmitted as a mechanical wave through a quantum system which in the case of condensate is a material environment with its elastic properties. Given the already mentioned definition of sound as a mechanical wave in an elastic environment, we can completely assuredly assume that in a condensate, which is described by its quantum properties and subject to the laws of quantum mechanics, sound waves occur. The quantum physics field that deals with a highly specialized study of this phenomenon is called Quantum Acoustics, while the described experiments with BEC represent the touch point of the two worlds that had seemed so incompatible at first glance. It is from this point of departure that the idea of Quantum Music, as a project that tries to answer the questions of mutual relations of sound and music on the one hand, and the quantum world on the other, began to develop.

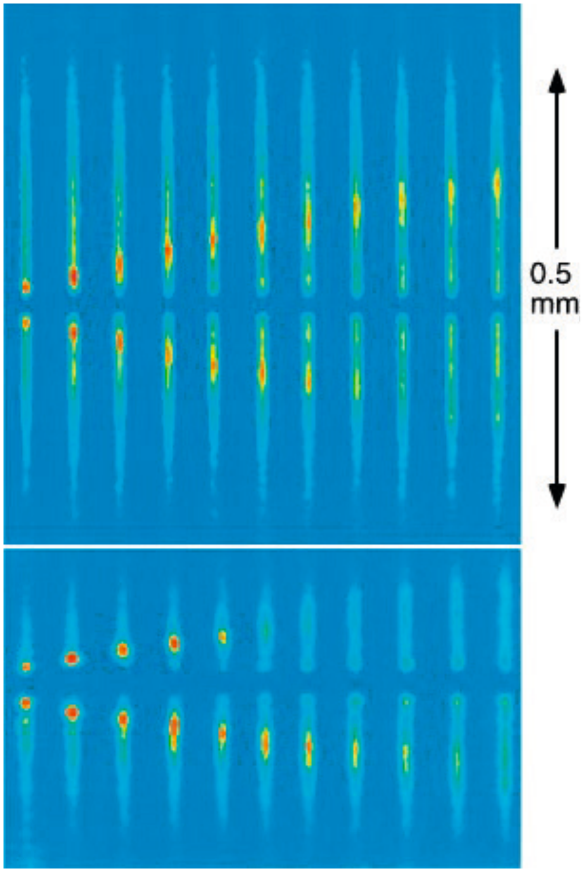

Figure 4: *Photographic distribution of the acoustic pressure in time (x axis) in BEC. The pulsation of the condensate, which is completely analogous to the pulsation of the classical sound source, can be clearly observed (Putz and Svozil 2015)*

Theory and Experiment Behind Quantum Sounds Synthesis

In quantum physics there is an experiment in which the quantum system (BEC) manifests some acoustic phenomena. The basic question that the Quantum Music project has set out is: how does the sound wave formed in this way actually sound? In order to answer the question, it was necessary to collect all the available theoretical and experimental data, on the basis of which it was possible to begin the process of synthesis of sound in the hearing range of the human hearing sense.

For the purpose of this project, two basic ways of generating sounds have been used, which have their foundation in the BEC theory and experiment. In the laboratory of the University of Aarhus (Denmark), this type of experiment has been successfully carried out for years. As one of the leading quantum physicists of today and an associate on the Quantum Music project, Dr. Klaus Mølmer is affiliated with this university, we had the opportunity to directly access labs and the results of experiments of Quantum Acoustics. These results, which are presented in the form of graphic and table displays of the change in the acoustic pressure in the condensate in time, are directly translated into sounds using the MATLAB software. In this process, we came across the first completely unexpected result of this research. Namely, what we expected was that the phenomena of the sound waves generated in this experiment far outweigh the boundaries of the audible range of the human hearing sense. It turned out that it was not so. The movement of atoms and the speed of their oscillations at such extremely low temperatures led to the generation of extremely "slow" waves, which are in the frequency range of several tens to several thousand Hz, which is precisely the range of human hearing. This surprising situation gave us the right to conduct direct translations, comparisons and interpretations of quantitative and qualitative properties of quantum-acoustic and acoustic waves in the research process, without the need for additional scaling.

Time [s]	Oscillation amplitude [μm]
0.000402	0.260083953279704
0.000804	-0.377531081606413
0.001206	-0.493760351117199
0.001608	-0.047198762130531
0.00201	0.496089615143493
0.002412	0.801934592795067
0.002814	1.08721664595616
0.003216	0.898500343585876
0.003618	1.00907843748546
0.00402	0.448001220075295
0.004422	-0.0193749707718567
0.004824	-0.136392070383462
...	...

Table 1: A small part of the tabular display of experimental results in Quantum acoustics used for the synthesis of real sounds

The second group of generated sounds was derived from the application of mathematical formulas that model the energy-vibration condition of the condensate. These formulas have a form from which it is easy to generate the theoretically boundless number of harmonic series, by simply changing the variable parameter n (Fig. 5, 1st formula), and the parameters m and n (Fig. 5, 2nd formula), which take arbitrary values from a set of real numbers. By changing the parameters m and n, a spectral sequence is formed, where the number of possible combinations is infinite. The first formula refers to vibrations of the condensate in one dimension, and the second formula to vibrations of the condensate in two dimensions.

$$f(n)=\sqrt{(n*(n+1))}*fo$$
$$f(n,m)=\sqrt{(2n^2+2nm+3n+m)}*fo$$

Figure 5: Mathematical formulas describing the vibration of condensate in one and two dimensions, which were used to generate series of harmonics

The Copenhagen interpretation of quantum physics, which is predominantly used today, allows for the existence of virtually any quantum state, with the definition of the likelihood of such a state occurring. This principle, applied to the analyzed situation, practically means that all the combinations of mutual relations of the levels of individual harmonics in the spectrum are possible, with a lower or higher probability, all depending on the initial conditions in the realization of the experiment. Since mutual relations of harmonics define the timbre of the sound, it turns out that the used formulas contain virtually infinite number of different types and colours of sounds. This theoretical situation allowed us to treat the newly-formed sounds with a high degree of freedom, adapting them to the aesthetic demands of the performance, arrangement and composition, while preserving a strong foothold in the theory of quantum physics. Synthesis of spectral arrays was performed in the Max MSP combined with Java Script software, according to the principle of classical additive synthesis, which is based on the superposition of individual harmonics in a harmonic array that defines the final tone.

Synthesis of Sounds

Additive synthesis is, historically speaking, the first type of synthesis of sound. It is based on the principle of generating sound by adding harmonics and forming the final spectral envelope. The principle of additive synthesis is very simple: each wave can be presented as a series of free tones, pure sine waves, distributed at different positions in the spectrum, which add a specific tone to the collection. In additive synthesizers, therefore, there must be a number of basic signal oscillators, whose outputs are connected to the corresponding amplifiers by which the spectral signal envelope is formed. The output of each amplifier is connected to a mixer that collects all spectral components generated in this way, producing the final signal at its output (Novković 2013).

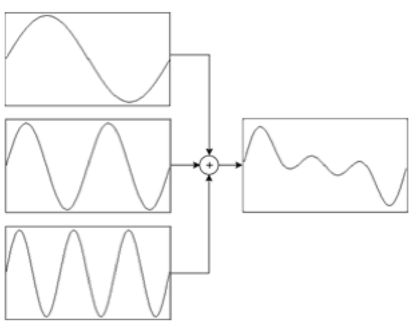

Figure 6: *An example of the basic principle of the additive synthesis process – 3 simple tones combined into the more complex, three-harmonic tone*

Behind this simple principle of synthesis is the mathematical analysis developed at the beginning of the nineteenth century by French mathematician Jean Baptist Joseph Fourier (1768–1830), which is the basis of analysis and signal synthesis in a much wider domain. Probably the single most important conclusion of Fourier's analysis is that any analyzed signal can be decomposed into a series of simple, sinusoidal signals, which make the individual, simple harmonics of the analyzed complex signal. On the basis of this, it is easy to arrive to the aforementioned principle that underlies the additive method of sound signal synthesis: by adding a number of simple tones, it is possible to reconstruct or synthesize any complex sound.

Modern multi-core processors are powerful enough to be able to count on a large number of harmonics in real time, so virtual instruments that use additive synthesis are much more common than their hardware counterparts.

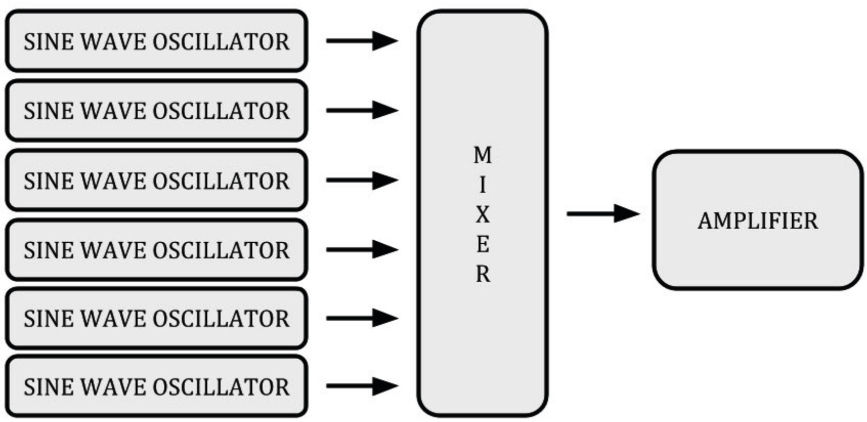

Figure 7: *Principal block scheme of the additive synthesizer*

Given the specific requirements of the synthesis of quantum sounds, the software part of the Quantum Synthesizer was created in the Max MSP program. This software is a key link in the research process carried out during the work on this project, where the options for its creative use are such that there are practically no limits.

The MAX interface used for the realization of the Quantum Synthesizer is shown in Figure 8.

Figure 8*: Work environment of the Max MSP software used for the synthesis of quantum sounds; this is a display of a patch that generates 10 harmonics*

The first thing that this synthesizer had to enable was to calculate the value of the positions of individual harmonics in the spectrum. The focus was on creating a link between Max and JavaScript, which is how a network of objects that perform these computational operations was built. An object that is designed in JavaScript sends values to all oscillators, which generate the spectral components specified by the previously introduced variable. Each oscillator, a set value that changes, depends on the variable, and it is connected to a gain control that determines its intensity, which is then added to the outputs from all other oscillators via the Master object.

The idea was to create an automated system where, by introducing three basic variables, a harmonic series would be generated on the basis of the results of the mathematical formulas shown in Figure 5. For the example of the second formula of Figure 5, the three basic variables are:

The value of the parameter n (or m)
The initial frequency value f_0
The total number of harmonics generated in the process of synthesis.

The value of the parameter *n* is fixed, after which the formula generates all the values of the frequencies of the spectral components by changing the non-fixed parameter *m*. The same procedure is performed in the case of fixing the parameter *m*, whereby then the values of the parameter *n* are sequentially generated. In these procedures, natural numbers are used for parameter values *m* and *n*. This process generates a series of real numbers, which define the mutual relations between the position of individual harmonics in the final spectrum.

The parameter f_0 can have an arbitrary value, and the absolute values of the positions of the individual harmonics in the spectrum are dependent on it. Changing this parameter changes the position of the fundamental harmonic in the final sequence, and therefore the pitch of the generated sound. By selecting low values of this parameter, spectra with rich content within the lowest frequencies range are formed, while this frequency range is suppressed by selecting higher values.

The third parameter, the total number of harmonics, is also arbitrary and can be chosen. Given the existence of a square root in the formula used, the positions of the generated harmonics in the spectrum are very close (very often the difference between the previous harmonic and the next one in the spectrum is not greater than 20–30 Hz). That is why the total number of sound harmonics generated in the audio range is very large, often several hundred. By selecting a smaller number of harmonics, the synthesized sounds have a poorer harmonic content in the high frequency range, while by selecting a large number of harmonics this part of the spectrum is filled up.

Since an amplifier that determines the level of each individual harmonic at the output of the oscillator can be set to an arbitrary value, in the process of synthesis the issue of treating the levels of gain controls was raised. A decision was made to make the synthesis so that all harmonics in the spectrum have the same level, and that the end-user of the sounds synthetized in this way is given the option to use the filter to suppress or emphasize certain parts of the spectrum, thus enabling the subjective, aesthetic moment. As already mentioned, from the standpoint of quantum physics, such manipulation of the levels of individual components in the spectrum is justified by the fact that all level combinations have a certain probability of occurrence, depending on the initial conditions of the experiment that is performed. In this way, the interaction between the computational mathematical values of the used formulas on which the process of the synthesis itself is based, and the aesthetic upgrade that the end-user can enter without violating the initial scientific principles of quantum physics, leaves an enormous space in the process of further theoretical work, processing, composing and playing using the sounds obtained in this way.

Acoustic Analysis of Synthesized sounds

Depending on the selection of the initial parameters, the synthesized sounds have different tonal characteristics, whereby two basic groups of received tones could be defined: harmonic and disharmonic. Both groups have their aesthetic value, and depending on the type of purpose and composition they can be used in the composing process. Given the theoretical and experimental basis of all the sounds produced, it is precisely at this place that an interesting possibility of further analysis of the concepts of harmony and disharmony is opened, with the search for possibilities of their more fundamental objective rooting in the framework of quantum physics. This topic goes beyond the scope of this paper, but it is an example of one of the directions in which further research in this project will move.

In the process of the synthesis of sounds in the manner described above, a very interesting phenomenon occurs, which requires additional analysis and interpretation. Namely, when one defines the values of the initial parameters, which determine the harmonic positions in the spectrum, they do not change either by frequency or by level in the process of synthesizing one sound. Therefore, the process of synthesis is such that there are no changes in the spectrum with the flow of time, from which one derives a logical conclusion that all the generated sounds are constant in time, i.e. that there is no change in the timbre or the level of sound that is being synthesized. However, in the process of applied synthesis, very frequently the final result was a sound that changes in time, being amplitudely modulated (AM) by itself, through the process of wave interference between simple waves genarated during the process of additive synthezis. This is the so-called *acoustic beating* phenomenon, which can be perceived in the form of a fluctuation of the tone around the basic frequency in the situation when the basic tone and the tone of the very close frequency are heard at the same time (Oster 1973). The beat frequency is equal to the difference between frequencies of the beating signals. Beat signal can sometimes be heard as a separate tone: the Tartini tone. Both are useful and important in practice for measuring frequencies and for tuning musical instruments.

If we consider two initial waves with the same amplitude (Figure 9), and frequencies f_1 (red wave) and f_2 (purple wave), they are not very different. Red and purple waves interfere in such a way that the resulting wave is one represented by the blue curve. Suppose that the waves start out in phase, so that they add up at the very beggining, resulting in maximum positive value of blue, resulting wave (i). Red wave has a slightly higher frequency, so it gradually changes its own phase relation to purple one, being one half cycle out of phase at one moment. At this extreme point, two initial waves cancel each other out almost completely, and the amplitude of the blue curve is near zero (*ii*). After an equal interval of time, following the newly formed cycle – beat cycle, they get back in step again. Being so, a completely new pulsation (marked with green line) is formed, that oscilates at so called beating frequency.

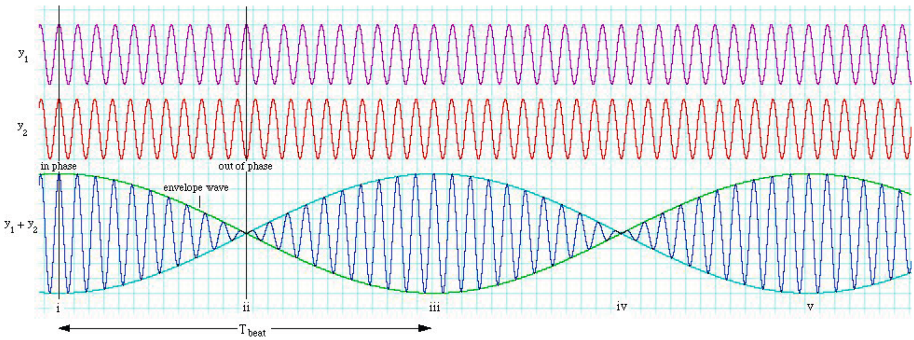

Figure 9: *Visual interpretation of beating phenomena*[2]

Provided that the difference in frequency is small enough, the resultant wave will sound loud when the two components are in phase and soft or absent when they are out of phase. The frequency of the blue wave is about halfway between that of the red and the purple waves, so we should hear a wave of intermediate frequency, getting regularly louder and softer. This is the acoustic example of the phenomenon of interfering beats.

If the beating frequency becomes higher than 20-30Hz, we can no longer hear beats in a way described above, but as separate tones of low frequencies. This is a specific kind of auditory illusion called Tartini tone. Tartini tone sounds like a low pitched simple note with a frequency equal to the difference between the frequencies of the two interfering waves. (Stewart 1917; Oster 1973; Schwarz and Taylor 2003).

The beating phenomenon, which usually appears very subtly in certain situations (for example, when tuning string instruments by a simultaneous plucking of two strings with a similar, but not exactly the same pitch), becomes very pronounced in the case of synthesized quantum sounds. The rich spectral content, in which some components are very close in frequency, leads to an intense occurrence of beating. This situation is diametrically opposed to the situation that comes with the synthesis of classical music tones, which are distinguished by the harmonic series in which the harmonics are positioned at frequencies that are whole-number multiplications of the frequencies of the fundamental harmonics. In such a system of synthesis, the beating is practically impossible. In the process of synthesis based on the use of mathematical formulas that model vibrations of the BEC, the beating practically becomes a prevalent acoustic phenomenon, which in many cases defines the final sound. Therefore, specific rhythmic/melodic structures emerge that can not be predicted before the

2 http://www.animations.physics.unsw.edu.au/jw/beats.htm

sound is generated, but which can be modified by adequate treatment of harmonic content in accordance with the requirements of the composition, its rhythmic or melodic structure. It turned out that quantum sounds *are* very musical. After completing the soundbank of quantum sounds, it will be offered to the widest public, with expectations to attract primarily musicians and composers.; we believe that further research and development of theoretically and practicaly endless possibilities of using quantum sounds for musical purposes can only be achieved through the process of playing and composing.

The described procedure for the synthesis of quantum sounds, as well as its results, provide an excellent basis for further acoustic-quantum-physics-musical analyses. One should also bear in mind that the complete process was based on the use of experimental results and theoretical formulas, without any real-time interaction of acoustic and quantum systems. One of the main goals for the further development of Quantum Music project will be to connect a hybrid piano with experimental equipment in real time (Lončar 2018; Lončar and Pavlović 2018).[3] This would mean that a direct connection with the laboratory equipment is established by means of mechanisms incorporated into the acoustic pianos, and that the audio signals generated in the piano directly modulate the laser beam by which the excitation of the BEC is performed. During this process, the condensate would enter the state of a constant "response" to the musical stimulation, which could be transferred back to the sound system in real time, and combined with the basic sound of the piano. In that case, we could speak about a direct music connection between the quantum world and our own, whereas the complete laboratory equipment could be treated as a unique musical instrument, with the condensate as a medium in which sound vibrations are generated – just like a string, an air column or a membrane in classical musical instruments. All technological preconditions for the realization of such a definite contact between music and the quantum world already exist, including the possibility that the laboratory equipment itself could be found on the stage, next to acoustic instruments. This type of complete, immediate and fully synchronized interaction of our world and the world of quantum physics through the medium of music is the ultimate goal of this project, toward which we strive, hoping that it will be achieved soon.

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3 The hybrid piano is a classic piano equipped with an interface that connects the instrument with electronic computer equipment; Cf. Lončar and Pavlović 2018.

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Драган Новковић, Марко Пељевић и Матеја Малиновић

Синтеза и анализа звукова развијених из Бозе-Ајнштајновог кондензата: теорија и експериментални резултати

(Сажетак)

Мало је позната чињеница да постоји област квантне физике која се означава термином *квантна акустика*. Два, наизглед неспојива света – свет звука који је неодвојиви део наше физичке реалности, и свет квантних честица – спајају се у серији експеримената које је могуће спровести над материјом која се хлади на незамисливо ниске температуре, реда величине милијардитог дела једног келвина. Ова температура, која се званично сматра најнижом у целом универзуму, доводи атоме у специјално стање битисања, које носи назив Бозе-Ајнштајнов кондензат. Након освајања технологије потребне за обављање овакви експеримената, дошло је до наглог развоја методологије за праћење најразличитијих својстава које материја у овако чудесном стању почиње да испољава, укључујући и могућност побуђивања механичких, тј. акустичких таласа.

Основно исходиште пројекта *Квантна музика* управо је овај експеримент, чији резултати и математички модели који га описују омогућавају синтезу звука. Ова синтеза обављена је директном применом експерименталних резултата у софтверу MatLab, као и употребом математичких формула које описују вибрације кондензата у наменски дизајнираном адитивном синтисајзеру реализованом у MaxMSP софтверском окружењу. Као резултат ове синтезе, формиране су банке звукова који су засновани на вибрацијама квантног система. Овако генерисани звуци испољавају веома интересантна акустичка својства, оличена пре свега у интензивној појави акустичког феномена избијања. Оваква ситуација доводи до појаве интересантних звучних ефеката који звуке, чији се спектрални садржај не мења у времену, преводе у временски променљиве звучне догађаје са изузетно занимљивим ритмичко-мелодијским структурама, које могу бити накнадно контролисане и употребљаване у процесу компоновања и извођења музике.

Први део овог рада описује експерименталне услове у којима се ови акустички феномени испољавају. Други део рада описује процес синтезе звука коришћен за генерисање аудио фајлова. Синтеза звука базирана је на употреби два основна типа података: теоријских формула и резултата експеримента са Бозе-Ајнштајновим кондензатом. Трећи део рада бави се акустичком анализом генерисаних звукова, уз указивање на неке акустичке феномене до чијег испољавања је дошло у процесу синтезе звука. Такође, дате су и основне смернице у вези са начинима употребе овако генерисаних звукова у процесу компоновања и извођења музике.

Кључне речи: Бозе-Ајнштајнов кондензат, квантна музика, синтеза звука, акустика