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Information model of acoustic string musical instrument and method of automated professional tuning of instruments

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ABSTRACT

The article discusses the issue of automating the tuning of acoustic string musical instruments. The goal of the work is to formalize the characteristics of acoustic signals that must be taken into account during automated professional tuning of instruments and to develop a corresponding information model and method based on it. The importance of automating the process of tuning musical instruments is substantiated. A review of the historical development of hardware and software tuning tools and available literature sources is carried out. The analysis showed that although the existing solutions are quite effective in terms of time spent, their use does not lead to the best results of tuning. In particular, this is due to the use of approximation methods, which as a result has a bad effect on the accuracy of the latter and contradicts the main tuning goal and the entire study. A review of available mobile tools for automated tuning of various acoustic instruments showed that none of them take into account the important tuning characteristics of the instruments. In the case of keyboard instruments, each tone has up to several strings, each of which produces a specific sound that can be resolved into a spectrum of harmonics (partials). In turn, each harmonic has its own characteristic frequency, intensity and duration of sound. Typically, in the considered analogues, instruments are tuned by determining the frequencies of the first harmonics according to equal temperament. As a result, a general model of an acoustic stringed musical instrument is proposed, represented by a six-tuple: a tonal composition of the instrument, a number of keys or open strings of the instrument, a tuple of first tone indices in chorus ranges with the same number of strings, a concert pitch and indices of temperament and temperament key. In the case of keyboard instruments, each tone has up to several strings, each of which produces a specific sound that can be resolved into a spectrum of harmonics (partials). In turn, each harmonic has its own characteristic frequency, intensity and duration of sound. This makes it possible to take into account additional characteristics and parameters that are important for application, such as the ratio of the frequencies of the partial tones of the signal, the frequencies of their interference beats, the instability and inharmonicity of string vibrations, and a method that describes the iterative process of automated tuning of instruments at a professional level based on overtone beats.

Keywords: Automated tuning; professional tuning; acoustic instrument; string instrument; electronic tuner; acoustic signal; sound characteristic; inharmonious vibration; overtone beats; information model; model parameters; tuning method

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1. INTRODUCTION

Acoustic musical instruments, such as piano, guitar, cello, etc., are an important part of both classical and modern musical art. They act as living organs capable of transforming thoughts and feelings, emotions, images of inner imagination and the surrounding world into a certain sound order [1, 2]. At the same time, they positively influence the spiritual development of individual, their cognitive (hard) and non-cognitive (soft) skills [3, 4].

However, they have a significant disadvantage: they get out of musical tune, which occurs due to various factors such as changes in humidity, temperature, deformation, intensity of use, etc. [5, 6].

Therefore, an important step in ensuring maximum expressiveness and harmony of such instruments is their regular tuning. On the one hand, it ensures better sound, durability and cost of instruments, on the other hand, it has a positive effect on musical hearing [7, 8]. In general, the tuning process, which is traditionally performed by ear, is complex and requires not only a high professional level but also certain time expenditure, especially for keyboard instruments [9, 10].

In today's fast-paced, technology-driven world, musicians are eager to innovate to make their creative work easier. In this context, the automation of the tuning process of acoustic instruments is particularly important. Information technologies allow not only to simplify this process, but also to increase its accuracy, providing the highest degree of control over the sound of the instrument, and its result will not be inferior to the aural tuning [11, 12].

Nowadays there is a wide range of musical instruments, each of which has its own peculiarities of sound and requires an individual approach to tuning. Taking these features into account in the development of the information model and method is a key aspect of creating a universal and highly efficient mobile software tool for automating the tuning of various acoustic instruments on a professional level.

The goal of the article is to formalise the characteristics of acoustic signals coming from instruments, to determine the optimal parameters, to develop an information model of an acoustic stringed musical instrument that covers these parameters, and to develop a method for automated professional tuning of these instruments. In order to achieve the set goal, it is necessary at the beginning to carry out a comprehensive analysis of available research and development in the field of automated tuning of acoustic stringed musical instruments.

2. REVIEW OF LITERATURE AND EXISTING SOLUTIONS

Musical acoustics is a field of scientific research devoted to the study of the formation, propagation and perception of music sounds, in particular the study of the sound characteristics and vibratory behaviour of acoustic musical instruments [13]. The attention of scientists, musicians and artists has focused on the sound and vibration of these instruments since the first knowledge of physics appeared more than two thousand years ago. However, little research has focused on the physical properties of the instruments; much less on the characteristics of the acoustic signal they emit [14].

Particularly important is the tuning of acoustic string instruments (keyboard, bowed, plucked), where the process consists in adjusting the tension of the strings so that they sound in a given musical scale, that is, a certain mathematical ratio of the sound system degrees in pitch [15]. The history of automated instrument tuning dates back to the 1930s years [11, 12]. Then the Conn company invented the first electronic tuning device (hereinafter referred to as ETD), which made it possible to very accurately tuning the frequencies of the fundamental tones of sounds due to the principle of indication based on the stroboscopic effect – hence its name “Conn Strobotuner” [16]. However, such ETDs were bulky, expensive and inaccessible devices on electronic tubes, which were practically unknown to tuners.

Only half a century later, with the development of microelectronics, compact inexpensive ETDs appeared, which a tuner could already put in their work briefcase. However, LED analogues were not as accurate as strobe devices because of the limited number of indication elements on the display. As a consequence, they had a rather large tolerance for ‘good’ tuning, i.e., only approximates accuracy, which actually resulted in distorted intonation [17].

The above devices can be considered first generation ETDs. Despite the described advantages and disadvantages of each, they are not suitable at all for professional tuning. These devices do not take into account the frequencies of partial tones and their ratio, allowing tuning only by fundamental tones.

A major breakthrough in the world of electronic tuners was the invention of Harvard Professor of Physics and Electronics, Dr Albert E. Sanderson III’s “Sanderson Accu-Tuner” device, which already provided much more accurate readings and also calculated the stretch of strings to compensate for their inharmonicity [18, 19].

With the development of modern information technologies, specialised software for tuning musical instruments began to be developed. Mobile devices proved to be particularly convenient for this task. They can be easily converted into the same ETDs, as they already have the necessary audio input/output devices and are equivalent to them in size. Fig. 1 shows a scheme of development of hardware and mobile software tools for automated tuning of instruments.

To date, a number of works have been published, revealing the topic of automated tuning. Thus, in [20] the basic mathematical foundations of tuning theory are described and an experimental set of “Matematica” tools for listening to scales and chords for a better understanding of the material is presented.

An algorithm for estimating the tuning of musical instrument samples (samplings) is presented in [21]. It obtains the desired pitch of the sample and compares it with the actually measured pitch to determine the tuning error in cents (a logarithmic unit of the ratio of two frequencies: $a / b = 2^{1/1200}$ Hz, 1/100 semitone). It works by filtering the sample to isolate the tone under test using a fast Fourier transform bandpass filter and an additional time domain filter. A zero-crossing detector then estimates the actual frequency of the isolated tone. Through an iterative process, the filters are adjusted and the accuracy is improved. Tests show that the algorithm can achieve accuracy within five cents for samples longer than two seconds in the full range of musical tones, even with noisy signals. The algorithm has been successfully used to fine-tune samples for a computer hearing programme. Its potential applications include building

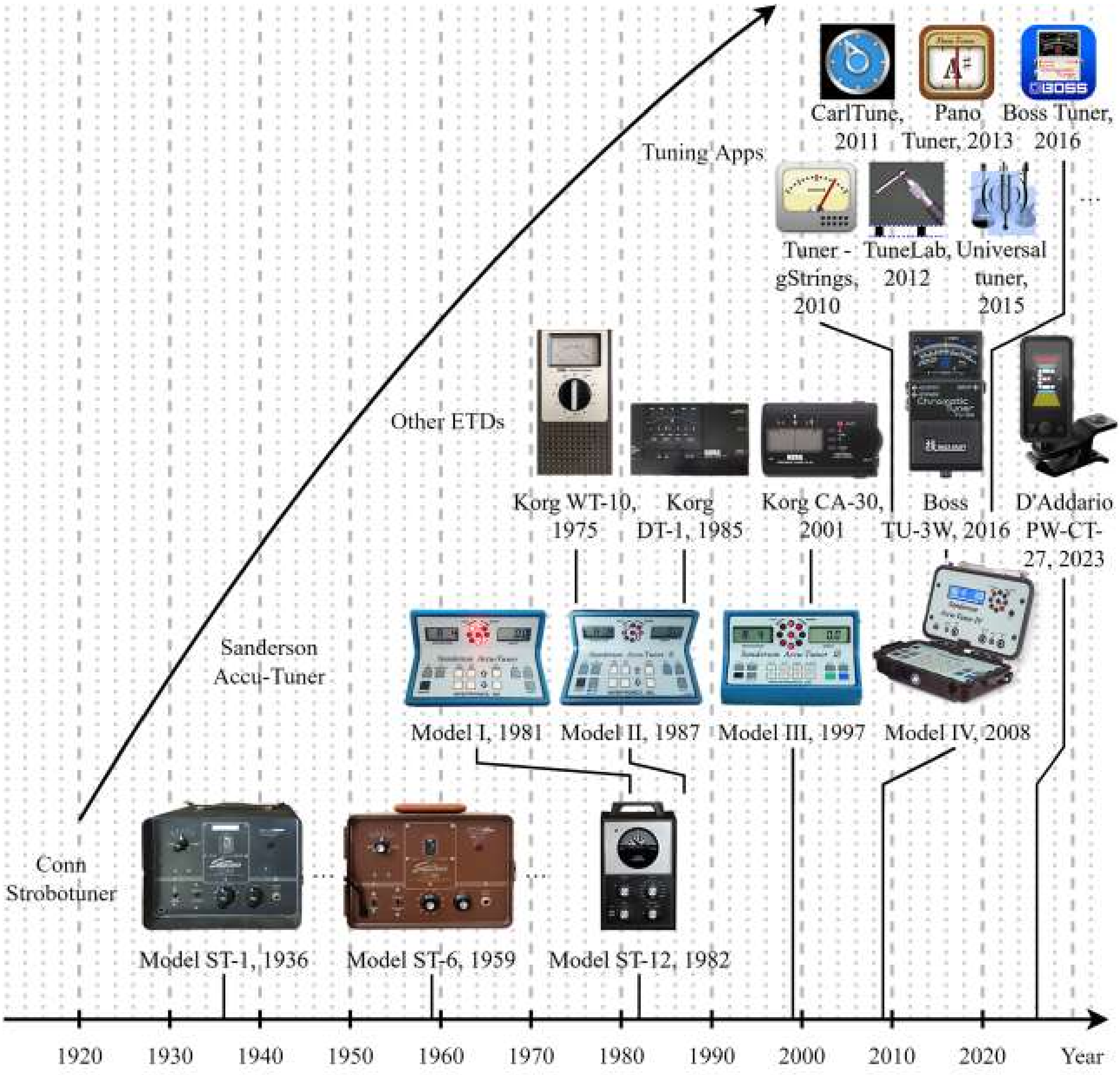

Fig. 1. **Development of tuning tools for acoustic string musical instruments**

Source: **compiled by the authors**

a sample library, correcting poorly tuned samples, and objective tuning evaluation.

The authors of [9] propose an automated piano tuning system called "PitchImpact", which uses reinforcement learning to control a special adjustable tuning hammer. The system uses software to analyse the acoustic spectrum to determine the pitch error and the appropriate strike force and direction required to tune each string of an instrument. The agent then determines the appropriate strike setting on the hammer to adjust the tuning pins and tune the string. Experiments with the system on a test 'hexachord' show that it can tune strings compared to a trained amateur tuner in a small number of strikes. The system has the potential to allow piano owners to tune their own instruments with minimal equipment, making the process much more convenient and accessible.

The paper [22] describes a method for tuning musical instruments such as pianos based on entropy minimisation. It notes that modern musical scales are based on equal temperament, but tuning exactly to it can cause instruments to sound bad due to inharmonious overtone spectra. Professional tuners compensate for this by stretching out certain intervals based on the perception of harmonics that match between tones as being more consonant. Initial tests reproducing the tuning curves of real pianos suggest that the method captures irregular pitch fluctuations similar to high-quality aural tuning. Although simple to implement, it has limitations and open questions that require further research.

In [23], a parametric model is proposed to jointly characterise the inharmonicity and tuning of the piano over the entire note range (tessitura). The inharmonicity coefficient is modelled using two asymptotes corresponding to the bass and discant bridges. The tuning model includes octave stretching caused by inharmonicity as well as the tuner's choice of octave type. Algorithms are presented for estimating the parameters of the model from individual notes or chords, provided that the notes are known. The model successfully captures the main trends of inharmonicity and deviations from equal temperament for different types of pianos. Potential applications of the model include assessing the condition of pianos, providing information for selecting tuning curves and parameterising the tuning of piano synthesizers. Overall, the work demonstrates the possibility of global parameterisation of inharmonicity and tuning using a small number of physically meaningful parameters.

The paper [10] presents research on the development of an automatic method for tuning the high tones of a piano. The authors tested four simple octave interval tuning rules by matching different partial frequencies of the lower and upper registers. They conducted a listening test to determine which rule provided the best tuning, as judged by listeners. The test showed that matching the first superimposed harmonics was rated the best. The authors also proposed a new method of assessing tuning quality by analysing the beat frequencies between overtones. In general, the research aims to develop a complete automatic piano tuning system, and this study focused on finding an optimal high-tone tuning rule based on human perception.

In addition to the review of available studies, an analysis of mobile tuning tools was conducted. It showed that there is no solution that allows tuning any instrument at a professional level, taking into account all the necessary characteristics of its sound. For example, tuning software so common among tuners, such as [24], does not take into account harmonic beat frequencies, does not measure the stability of the latter, and does not provide smooth changes in these frequencies. Analogues with a Google Play Store user rating of 4.5/5 or higher and a number of their reviews 10K+ also have shortcomings. In addition to the above, the app [25] does not take into account the inharmonicity of string vibrations and does not have a stroboscopic detector for ultra-precise tuning of instruments. Tuner [26] also offers a very limited choice of tuning error magnitude, while [27] does not allow setting its own tolerance limits at all. Applications [28] and [29] also have fixed margin of error.

As it can be seen, there are quite a few approaches to automating piano tuning. They are mostly designed to facilitate the process, and there is also a solution to automate it completely. Many of them are aimed at significant acceleration of tuning, but they sacrifice accuracy, which is the main criterion for achieving a high quality of sound of an instrument and provides harmonious reproduction of musical works. This contradiction determines the relevance of the study.

3. INFORMATION MODEL OF ACOUSTIC STRING MUSICAL INSTRUMENT

To formalise the general sound properties of an acoustic stringed musical instrument and build an appropriate model, it is first necessary to define its tonal composition represented by an ordered set (tuple) T_A:

$$T_A = \langle T_1^A, T_2^A, \ldots, T_i^A, \ldots, T_m^A \rangle, \qquad (1)$$

where T_i^A is a tone, produced by the instrument A, of the i-th key or open string; $i = \overline{1, m}$.

A single key of an instrument can affect the sound of either one or several strings, which must be tuned to the same pitch, i.e., in unison (such a group of strings is called a choir):

$$T_i^A = \langle S_{i,1}^A, \ldots, S_{i,j}^A, \ldots, S_{i,n}^A \rangle, \qquad (2)$$

where $S_{i,j}^A$ is the j-th string of the i-th tone T_i on the musical instrument A; $j = \overline{1, n}$.

An acoustic signal, including the one generated by a string of an instrument during playing, is complex and characterised by a spectrum – a set of harmonic vibrations of a certain frequency (pitch), intensity (volume, strength) and duration (time):

$$S_{i,j}^A = \langle h_{i,j,1}^A, \ldots, h_{i,j,2}^A, \ldots, h_{i,j,k}^A, \ldots, h_{i,j,p}^A \rangle, \qquad (3)$$
$$h_{i,j,k}^A = \langle f_{i,j,k}^A(t), s_{i,j,k}^A(t) \rangle,$$

where $h_{i,j,k}^A$ is the k-th harmonic (h) of the j-th string of the i-th tone T_i^A on the instrument A; $k = \overline{1, p}$; it is characterised by frequency $f_{i,j,k}^A > 0$ (Hz) and intensity $s_{i,j,k}^A \geq 0$ (dB) ($s_{\max(i,j,k)}^A = a_{i,j,k}^A$ – amplitude), which in turn depend on time t (μs). If $k = 1$, then we speak about the frequency of the fundamental tone of the signal, which is used to determine the pitch of a string.

Tuning an instrument involves equalising the pitch ratio of the degrees of the sound system, i.e., maintaining a certain *tmp* temperament. The most common is 12-equal (equal-tempered musical scale, or 12-ET):

$$f_{i_1,j_1,1}^{A\,(\alpha+\beta)} = 2^{\frac{\beta}{12}}\, f_{i_1,j_1,1}^{A\,(\alpha)}, \tag{4}$$

where α is the index of the current frequency; β is the difference number of semitones; $\alpha+\beta$ is the index of the new frequency of the fundamental tone in the chromatic range of the instrument. It is not difficult to notice that at $\beta = 12$ the harmonic frequencies will differ by a factor of 2, since they are located on the octave interval (12 semitones).

The general information model of an acoustic string musical instrument can be represented as a tuple A:

$$A = \langle T_A, m_A, I_n^A, f_A, i_{tmp}^A, i_T^A \rangle, \tag{5}$$

where T_A is a tonal composition of the instrument; m number of tones (keys or open strings of the instrument); I_n^A is a tuple of indices of the first tones in ranges of choirs with the same number of strings, at the same time the projection number of this tuple corresponds to the number of strings in the choir; f_A is a concert pitch (frequency of the tuning fork); i_{tmp}^A is a temperament index ($i_{tmp}^A = 0$ for 12-ET); i_T^A is an index of the temperament reference tone (temperament key).

The value of the parameter m differs depending on the particular instrument being tuned. For example, for violin $m_v = 4$, for classical guitar $m_g = 6$, for modern piano $m_p = 88$. Also, for bowed and plucked instruments one tone always corresponds to one string, i.e., $n_v = n_g = \ldots = 1 = \text{const}$. At the same time for pianos $n_p = 1 \ldots 3 \neq \text{const}$ – depending on the register. Usually in the lowest one there is one string per tone ($\text{pr}_1 I_n^A = 0$), in the highest – three (the index of the first tone corresponds to $\text{pr}_3 I_n^A$).

The following two parameters are important for tuning of any instrument:

– a concert pitch f_A, which is actually a reference (calibration) point for the entire musical scale of an instrument. It is usually the A note (la) of the one-line octave, or A4. To this day, various reference frequencies are used in orchestral music to reproduce the playing conditions of a particular old music [30, 31]. However, according to the modern ISO 16 standard, the optimal value of this frequency is $f^{69} = 440$ Hz ($\alpha = 69$ is the A4 index according to the MIDI standard), then the theoretical frequency of any other 12-ET tone can be determined using formula (4);

– the reference (initial) tone of the selected temperament, or temperament key, represented by index $i_T^A \in \{0, 1, \ldots, 11\}$ (12 possible tones within one octave). This is the reference point (note) against which the instrument's temperament is further built.

The scheme in Fig. 2 shows the described model on examples of some common acoustic musical instruments (A_1–A_3).

In fact, tuning keyboard string instruments such as the piano is not limited to determining the frequencies of the fundamental tones, concert pitch, or even application of different temperaments. Generally, with the invention of the first ETDs, it seemed that the problem of temperament and tuning in general had already been solved. However, it was soon realised that this was not the case at all: the temperaments built by such devices are not of high quality. The reason for this is that they only considered the frequencies of $h_{i,j,1}^A$. While tuning many instruments by the frequencies of the first harmonics may be sufficient, for example, the tuning of a piano (both 12-ET and any other temperament) is determined mainly by the ratio of frequencies not of the basic tones of its sounds, but precisely of the overtones.

Fig. 3 shows a refined scheme that takes into account additional properties of the sound on the example of the piano. See formula (3): if $k > 1$, then we speak of partial tones (overtones), or subharmonics: $h_{i,j,2}^A, \ldots, h_{i,j,p}^A$ (Fig. 3a and Fig. 3b) – that is, the second and subsequent vibrations of the strings (solid curves) relative to their resting states (dashed median straight lines). Usually, the value considered in the tuning process is $p \neq \text{const}$ for different i. For example, the lowest piano tones are the most harmonically saturated ($p_{lp}^{\max} = 8..10$, mostly $p_{lp} = 2..5$, for $i \to 1$), whereas for the highest ones $p_{hp} \ll p_{lp}$, sometimes down to $p_{hp} = 1$ for $i \to m_p$.

Two frequencies f_{i_1,j_1,k_1}^A and f_{i_2,j_2,k_2}^A can be compared in tuning when the following requirements for the indices of these frequencies are satisfied:

$$\forall (i_1, i_2, j_1, j_2, k_1, k_2)\ i_1, i_2 = \overline{1,m} \wedge j_1, j_2 = \overline{1,n} \wedge \\ \wedge\, i_1 \neq i_2 \wedge (k_1 \neq 1 \vee k_2 \neq 1). \tag{6}$$

These constraints apply to any index values. Here $i_1 \neq i_2$ means that the requirement is relevant to different tones; $k_1 \neq 1 \vee k_2 \neq 1$ – tones can be basic but not simultaneously, although according to [10] the exception can be upper register tones where $p_{hp} = 1..3$.

This principle of tuning acoustic instruments is based on the consideration of:

– inharmonicity of string vibrations. Let there be a string $S_{i,j}^A$ with a fundamental tone of frequency $f_{i,j,1}^A$ on the instrument A, then each subsequent overtone will have a frequency multiple of the fundamental one:

$$f_{i,j,\gamma}^A = \gamma\, f_{i,j,1}^A,\ \gamma > 1 \wedge \gamma \in \mathbb{N}. \tag{7}$$

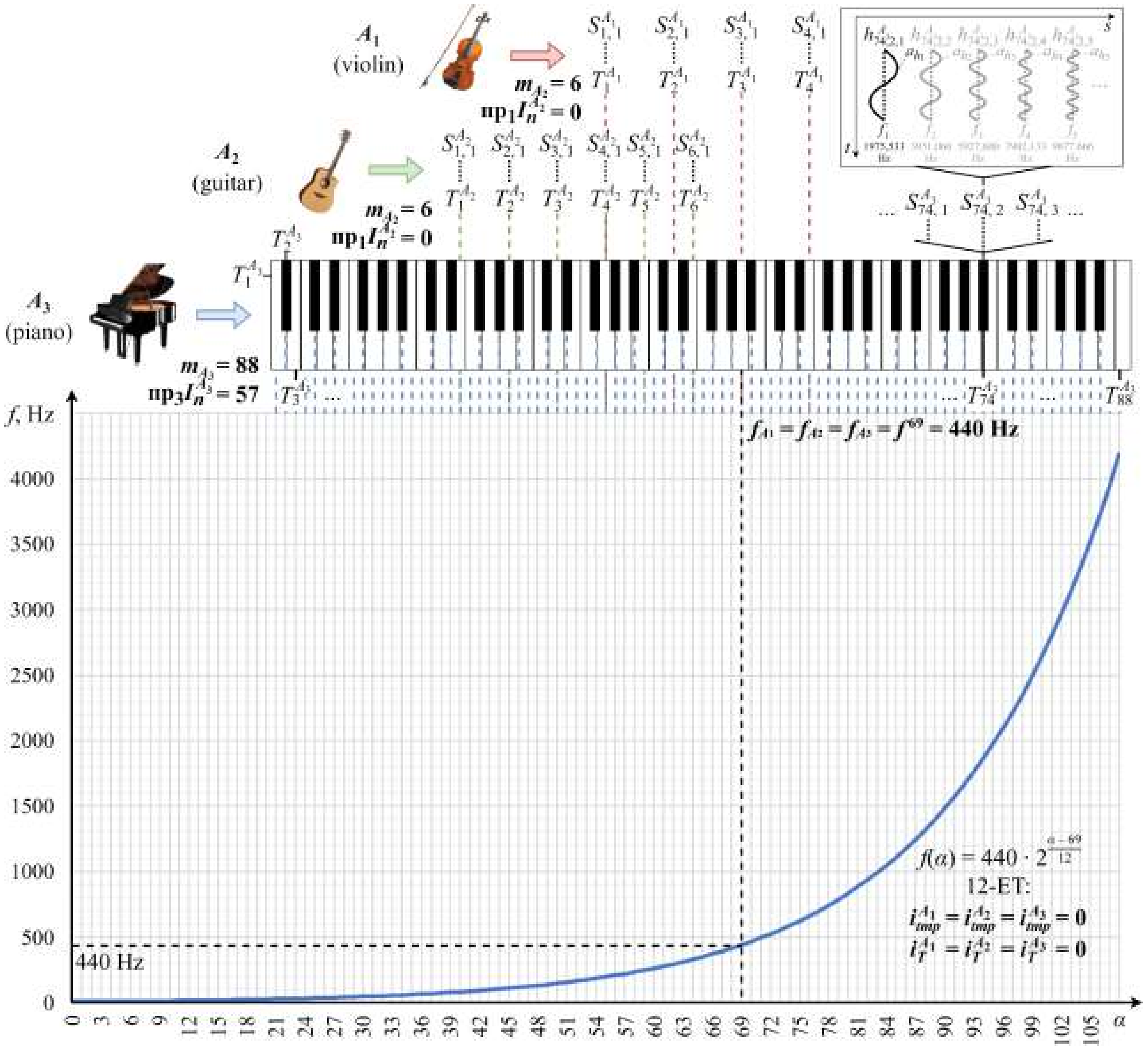

Fig. 2. **General acoustic characteristics of musical instruments:**
α – MIDI index; f – frequency
***Source:* compiled by the authors**

That is, the frequencies of these tones are correlated in such a way that they form a series of natural numbers (harmonic, or overtone, series):

$$f_{i,j,1}^A : f_{i,j,2}^A : f_{i,j,3}^A : \ldots : f_{i,j,\gamma}^A = 1 : 2 : 3 : \ldots : \gamma. \quad (8)$$

However, in real conditions each string is characterised by inharmonicity coefficient δ:

$$f_{i,j,\gamma}^A = \begin{cases} \gamma f_{i,j,1}^A, \text{ if } \delta = 0, \\ \gamma f_{i,j,1}^A \sqrt{1 + \delta\gamma^2}, \text{ if } \delta \neq 0 \end{cases}. \quad (9)$$

The inharmonicity of string vibrations is caused by the complex influence of the factors of its thickness, stiffness, tension, etc., which must necessarily be taken into account when tuning, especially low tones [32, 33];

– interference beats of interval overtones. The main task here is to avoid these beats or, if this is impossible, to minimise or smooth their frequencies in a certain way (for example, by smoothly changing the latter in chromatic sequences of eponymous consonances), especially when the overtone frequencies are unstable.

The two phenomena are closely related. For example, let us take the two tones T_{49}^A and T_{61}^A, corresponding to the A notes of the one-line and two-line octaves. In Fig. 3 they are highlighted by the parallel green and crossed blue shading respectively on the keyboard. In this register we have three strings per tone (respectively $S_{49,1}^A$, $S_{49,2}^A$, $S_{49,3}^A$ and $S_{61,1}^A$, $S_{61,2}^A$, $S_{61,3}^A$), of which we next consider the first strings (j = 1): $S_{49,1}^A$ (Fig. 3a) and $S_{61,1}^A$ (Fig. 3b).

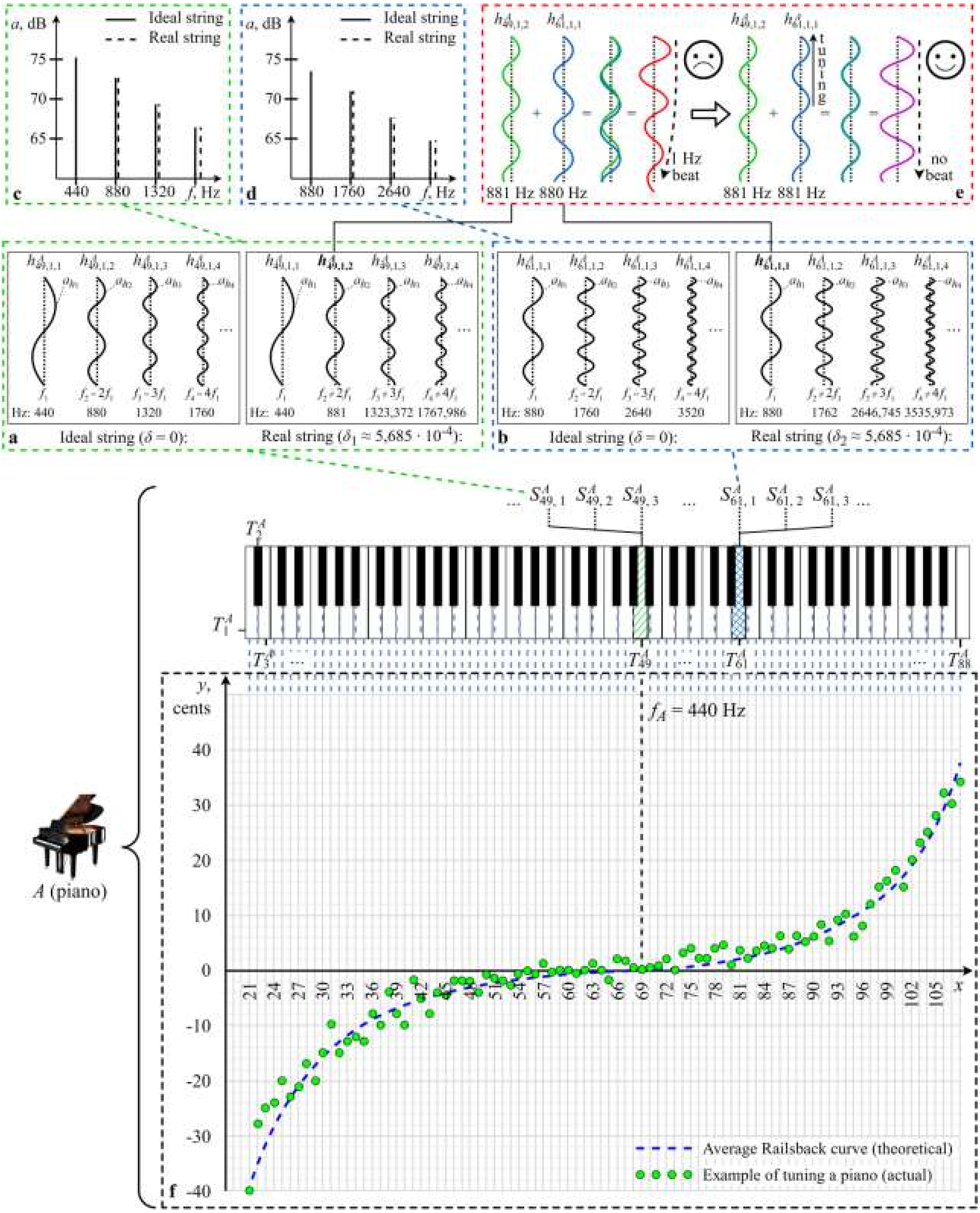

Fig. 3. **Additional tuning parameters of string keyboard instruments**: *x* **– MIDI index;** *y* **– pitch deviation**

Source: **compiled by the authors**

Let $f^A_{49,1,1}$ = 440 Hz, $f^A_{49,1,2}$ = 881 Hz and $f^A_{61,1,1}$ = = 880 Hz. Obviously, the first two frequencies correspond to an inharmonic string since $f^A_{49,1,2} / f^A_{49,1,1} \neq 2$ and $\delta \approx 5{,}685 \cdot 10^{-4}$. Fig. 3c and Fig. 3d show the harmonic spectra of respectively taken strings, where solid straight lines correspond to the harmonics of ideal strings and dashed lines to those of real strings.

The beat frequency between the second harmonic of A of the one-line octave (A4) $h^A_{49,1,2}$ and the first harmonic of A of the two-line octave (A5) $h^A_{61,1,1}$ is:

$$|f^A_{61,1,1} - f^A_{49,1,2}| = |880 - 881| = 1 \text{ (Hz)}. \qquad (10)$$

In Fig. 3a and Fig. 3b their designations are in bold and the result of their superposition with each other (addition) is shown in Fig. 3e. To eliminate the resulting beat, the $f^A_{61,1,1}$ frequency must be readjusted to 881 Hz by tensioning the string slightly more. This is also effective for instruments other than the piano.

Such tuning, starting from the reference tone and moving towards the extreme tones, gradually leads to the stretching of intervals described at one time by the American scholar Ora Railsback [22], [23] (see Fig. 3f). The dashed blue line shows Railsback's theoretical average curve, and the round green dots show one of the string tuning options for a real piano.

4. METHOD OF AUTOMATED TUNING OF ACOUSTIC STRING MUSICAL INSTRUMENTS

The following method of automated professional tuning of instruments is proposed, consisting of six main steps:

1. Start. Selection of the musical instrument model, setting the model parameters (number of tones, numbers of the first strings in the chorus ranges, concert pitch, temperament and temperament key), as well as the acceptable value of the tuning error.

2. Alternate capturing of sound from all strings of the instrument. The captured acoustic signal represents the input data to the musical instrument model (its initial tonal composition).

3. Capturing the sound from a string (open or from choir) that corresponds to the temperament key.

4. Analysing the frequency of the fundamental tone (first harmonic) of the temperament key and identifying the current sound situation for the selected instrument by the sound processing module:

4.1. If the permissible error is exceeded, then generation of an instruction to tune this frequency by the recommendation module, otherwise, go to step 6.

4.2. If tuning is recommended, then perform a technical tuning of the instrument (manual intervention step, so the system is not automatic, but automated) and go to step 6.

5. Analysis of the harmonic beat frequency of two played tones and identification of the current sound situation:

5.1. If the permissible error is exceeded, then generation of an instruction to tune the second frequency, otherwise, go to step 6.

5.2. If tuning is recommended, then perform a technical tuning of the instrument.

6. If the currently tuned string is the last one, then stop, otherwise, capturing the sound from strings of the current and subsequent tone simultaneously and go to step 5.

The block diagram of this method is shown in Fig. 4. As it can be seen, in general a tuning process is iterative, so the efficiency is reflected both in the reduction of time for each step and in the reduction of the number of steps.

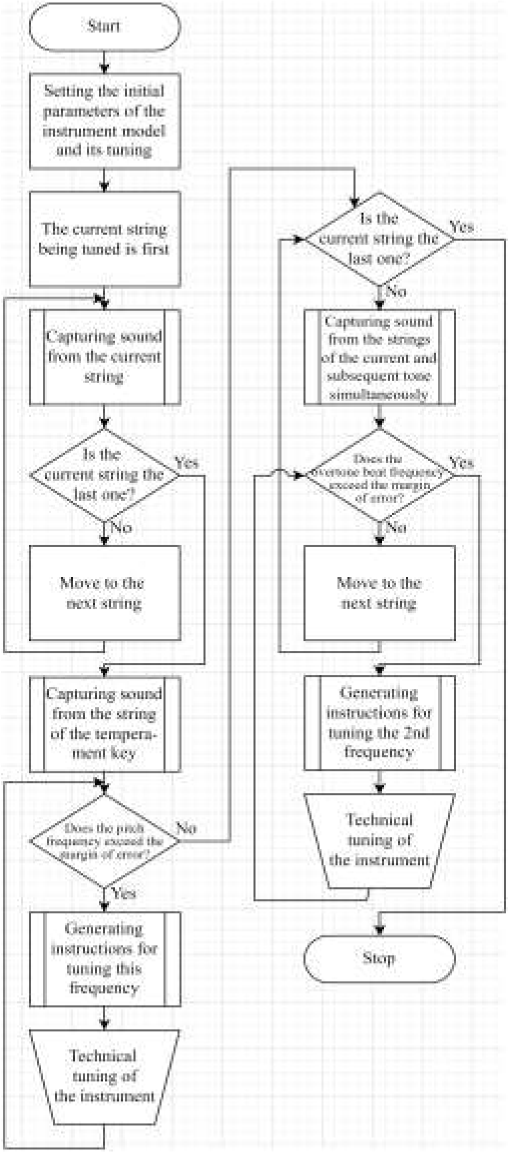

Fig. 4. **Block diagram of the proposed method of automated professional tuning of acoustic string musical instruments**

***Source:* compiled by the authors**

The implementation of the method also involves the development of two software modules – a sound processing module and a recommendation module:

– the first module is responsible for processing an acoustic signal received from a piano or other musical instrument to determine the parameters of spectral components and analysing the obtained data to determine tuning needs;

– based on the analysis, the second module recommends the necessary corrections to improve the quality of reproduction of the musical instrument, generating instructions for the tuner, i.e., the user, to perform tuning based on the identified problems.

Both modules work together to provide an efficient process of tuning musical instruments, allowing achieving a high quality of sound of the latter during playing.

So, the proposed model of acoustic string musical instrument with extended characteristics of acoustic signals, as well as the method of automated tuning of such instruments at the professional level on the basis of the model serves as a prerequisite for the creation of information technology of effective and accurate tuning process. In the future, it is planned to detail the above modules and to specify methods and algorithms for calculating the tuning of musical instruments depending on the selected parameters of their models, as well as various tuning techniques used by professional tuners in their practice.

6. CONCLUSIONS

Automation of tuning on a professional level, taking into account special sound qualities other than the generally accepted ones, is a complex and urgent task. Besides, it is applicable to various acoustic string instruments: plucked instruments (guitar, ukulele, banjo, harp, etc.), bowed instruments (violin, viola, cello, contrabass, etc.) and keyboard instruments (harpsichord, clavichord, upright piano, grand piano).

In this paper, a historical review of the development of tuning tools and an analysis of the available scientific developments has been carried out. As a result, the problem of tuning accuracy, both automatic and automated, although quite fast, has been identified. This leads to poor sound quality of instruments, in particular due to the use of approximation methods. This approach contradicts the main objective of professional tuning, hence the entire study. Also, a review of available mobile applications showed that they still do not solve the given problem.

A general model of an acoustic string musical instrument that takes into account the ratio of frequencies of partial tones of the signal, frequencies of their interference beats, instability and inharmonicity of string vibrations has been proposed, its parameters have been described and visualised, and the main characteristics of acoustic signals emitting from the strings of instruments that need to be taken into account during tuning have been described and visualised: basic tone, spectrum, frequency, intensity, duration, as well as tone composition, concert pitch, temperament and temperament key.

A method for automated professional instrument tuning based on overtone beat has also been created and proposed, containing six main steps, including setting initial parameters, capturing the sound from all the strings of the instrument, identifying the current sound situation and analysing the harmonic beat frequency of two played tones.

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Інформаційна модель акустичного струнного музичного інструмента та метод автоматизованого професійного настроювання інструментів

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АНОТАЦІЯ

У статті розглянуто питання автоматизації настроювання акустичних струнних музичних інструментів. Метою роботи є формалізація характеристик акустичних сигналів, які необхідно враховувати під час автоматизованого професійного настроювання інструментів, та розроблення відповідної інформаційної моделі та методу на її основі. Обґрунтовано важливість автоматизації процесу настроювання музичних інструментів. Проведено огляд історичного розвитку апаратних і програмних засобів настроювання та наявних літературних джерел. Аналіз показав, що хоча наявні рішення є досить ефективними з точки зору витрачуваного часу, проте їх використання призводить не до кращого результату настроювання. Зокрема це зумовлено застосуванням методів апроксимації, що в результаті погано позначається на точності останнього та суперечить головному завданню настроювання та загалом усього дослідження. Огляд наявних мобільних засобів автоматизованого настроювання різних акустичних інструментів показав, що жоден із них не враховує важливі для настроювання характеристики інструментів. Як результат запропоновано загальну модель акустичного струнного музичного інструмента, що представлена впорядкованою шісткою: тональний склад інструмента, кількість клавіш або відкритих струн інструмента, кортеж індексів перших тонів у діапазонах хорів з однаковою кількістю струн, частота коцертного тону та індекси температії й опорного тону температії. У разі клавішних інструментів для кожного тону передбачено до декількох струн, кожна з яких відтворює певний звук, який можна розкласти на спектр гармонік. Зі свого боку кожна гармоніка має свою характерну частоту, інтенсивність і тривалість звучання. Це дозволяє врахувати додаткові, важливі для застосування характеристики і параметри, як-от співвідношення частот часткових тонів сигналу, частот їхніх інтерференційних биттів, нестабільність та негармонічність коливання струн. Також запропоновано метод, що описує ітеративний процес автоматизованого настроювання інструментів на професійному рівні на основі биття обертонів.

Ключові слова: Автоматизоване настроювання; професійне настроювання; акустичний інструмент; струнний інструмент; електронний тюнер; акустичний сигнал; звукова характеристика; негармонічність коливання; биття обертонів; інформаційна модель; параметри моделі; метод настроювання

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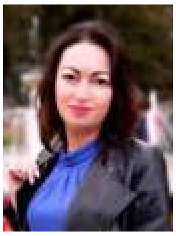

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