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Research Article

A harmonic-based musical scaling method with natural number frequencies

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Abstract

General acceptance arises from the most convincing method among the available options. Similarly, while the Western chromatic scale is the most widely used system today, it has limitations in representing harmonious intervals, microtonal performances, and the weak resonant effects of fractional frequencies This study introduces the Safir method, a novel approach to redefining musical note frequencies within an octave interval. Unlike traditional scales, Safir employs natural number-based values, ensuring more harmonious intervals and enhanced tuning consistency. A key strength of Safir lies in its ability to overcome the limitations of conventional tuning systems. The Safir method enhances spectral coherence by aligning note frequencies with the harmonic distribution of the Fourier series and strengthening the resonance effect through natural frequencies. This method has significant potential for various applications including music, speech and signal processing, spectral leakage reduction, and healthcare. Four key advantages of the Safir scale system are its its alignment with the harmonic series, , the strong resonant effect of note frequencies derived from natural numbers, the suppression of dissonant intervals in higher frequencies across the octave band, and its linear spacing within the octave, which ensures minimal deviation from compatible intervals even in microtonal divisions. This novel method represents a major advancement in tuning and musical scales. By providing a more precise, harmonious, and resonant frequency system, Safir addresses key shortcomings of traditional musical scales and opens new possibilities in both theoretical and practical domains.

Keywords

harmonic frequency analysis, harmonic scale intervals, healthcare, musical scale, Pythagorean tuning, temperament systems

Introduction

Sound is a wave motion generated by a vibrating object propagating through a material medium. The vibration of sound is described in terms of frequency, whereas its loudness is characterized by its amplitude. Music, on the other hand, is the art of shaping sound, dividing its formal properties into specific frequency regions called “notes,” and presenting them in a harmonious sequence that evokes emotional responses in listeners (Konar, 2019a; Moore et al., 2008).

In musical systems, the tuning system defines the note frequencies within a frequency range in which frequencies are double between octaves (the octave frequency range). This scaling system was applied uniformly across all octave layers. The selection of note frequencies that best reflect the harmony between sounds is critical to musical composition. The foundations of musical scales date back to the 600 BCE when the Greek philosopher Pythagoras discovered that a vibrating string of fixed length produces distinct sounds based on its tension and length (Konar, 2019b, 2019a). Pythagoras established the “pentatonic scale,” demonstrating the importance of ratios involving whole numbers such as 2:1, 3:2, 4:3, and 5:4 for harmonious intervals. While Pythagorean tuning is not widely used in modern Western music, the influence of its proportional relationships remains evident in the frequency ratios of notes like do, re, mi, fa, sol, la, and si. However, challenges such as the “wolf interval,” which occurs as the octave progresses or moves toward microtonal notes, highlight the limitations of certain tuning methods (Crismani, 2022).

Modern chromatic scales, particularly the 12-tone (12-TET) equal temperament, dominate Western music due to their versatility and consistent intonation across keys. The 12-TET system divides the octave into 12 equal logarithmic intervals, facilitating easy transposition and harmonic exploration (Brown, 2016; Hinrichsen, 2016). However, it sacrifices pure harmonic relationships, as natural frequency ratios like the 3:2 perfect fifth and 4:3 perfect fourth are only approximated, leading to a slight loss in harmonic clarity. Despite the widespread adoption of the 12-TET chromatic system, there is growing interest in exploring alternative tuning systems that achieve harmonic compatibility and reduced dissonance across octaves and microtonal regions. Musical tuning systems have evolved significantly over centuries, shaped by diverse cultural, mathematical, and auditory considerations (Isaacson, 2023).

The other scaling system, 53-tone equal temperament (53-TET), central to traditional Turkish music, divides the octave into 53 microtonal intervals of 22.64 cents each, allowing for a detailed representation of modal systems like the Turkish Makam. This finer division better approximates natural harmonic ratios, capturing the nuances of modal systems of Turkish Makam (Uyar et al., 2014). While 53-TET provides greater resolution for microtonal accuracy, it also introduces complexity in performance and notation, requiring specialized skills and familiarity with microtonal frameworks. Despite these challenges, 53-TET remains a valuable alternative for representing the subtleties of non-Western music, offering a closer alignment with natural harmonics than 12-TET. Recent psychoacoustic research suggests that human ears can detect pitch differences as small as 5-20 cents, indicating that 12-TET may struggle with microtonal accuracy (Smit et al., 2019; Yost, 2009). Additionally, cross-linguistic studies on speech and music suggest that microtonal scales, such as those in 53-TET, might better align with human auditory perception (Altun & Egermann, 2021; Bozkurt et al., 2014). However, the complexity of 53-TET presents challenges; its numerous intervals make tuning and performance more demanding, especially in live settings, and specialized training is often necessary for performers and composers. Despite offering greater microtonal flexibility, some intervals only approximate natural harmonic ratios, impacting harmonic purity. In practice, a 24-tone subset is frequently used, following the Arel-Ezgi-Uzdilek pitch system, but this system falls short of fully expressing the intricacies of Turkish music (Aktas et al., 2019; Bozkurt et al., 2014).

The coexistence of these systems raises critical questions about the intersection of tradition and innovation in music. For example, in Turkish Makam music, scales such as Rast and Segah rely on specific intervals that are not adequately captured by 12-TET. While the standardization of A4 as 440 Hz in both systems serves as a point of convergence, the methodologies for deriving other pitches diverge significantly. In 12-TET, pitch frequencies are determined by a constant ratio ($2^{(1/12)}$), whereas 53-TET employs a finer subdivision with ratios like $2^{(1/53)}$, which, despite its precision, may also present difficulties in terms of accessibility and ease of use.

The Just Intonation (JI) method refines the 12-TET scaling system by using whole number frequency ratios derived from the harmonic series, allowing for pure intervals such as the 5:4 major third and 6:5 minor third, which are more consonant than their counterparts in 12-TET. JI uses rational numbers, setting a prime number limit such as a 5-limit (primes 2, 3, and 5) or a 7-limit (primes 2, 3, 5, and 7) to define harmonic ratios. This results in harmonically pure chords that align with the natural overtone series, but the precision of JI limits its flexibility across different keys, posing challenges for compositions that require frequent modulation (Lindley, 2001).

While there are several alternative tuning systems like Pythagorean tuning, Just

Intonation, and even modern experiments with 432 Hz, they do not specifically employ natural numbers like the Safir method for harmonics and scale construction. Some systems, such as the 432 Hz tuning, draw inspiration from natural harmonic ratios and have been associated with claims of providing a more harmonious listening experience. However, these systems are still based on traditional temperaments or specific frequency values rather than an innovative use of natural numbers as a primary design principle for musical frequency scaling. Similarly, the octatonic scale, though systematic, remains confined within 12-TET's structure. This study introduces a novel scaling method where musical note frequencies are defined as natural numbers. After a detailed literature review, the proposed method of using natural numbers for frequency scaling (from now on referred to as 'Safir' to distinguish it from other methods) appears unique. The Safir method creates a more balanced frequency system that reduces the prominence of higher frequencies and offers new insights into harmonic tuning, especially in terms of auditory health. This also suggests a potential avenue for further research and development in music theory and sound therapy. This approach aims to enhance harmony and consistency while addressing the limitations of existing systems, offering potential benefits for both theoretical exploration and practical application in music composition and performance. By leveraging mathematical models and psychoacoustic principles, the proposed framework aims to redefine scale construction, enhance its adaptability to traditional and contemporary musical contexts, and offer new perspectives on integrating microtonal and equal-temperament systems.

Literature Review

An interdisciplinary approach to how everyday Western music works and why tones, melodies, and chords come together is presented in (Parncutt, 2024), whose theory on major-minor tonality is supported by evidence from psychoacoustic research, experiments, and mathematical models. He explores concepts like interval, consonance, chord root, leading tone, harmonic progression, and modulation, discussing the influence of biology and culture on music perception. Bailes and colleagues found that microtonal intervals are perceived differently from 12-TET intervals, noting that musical expertise enhances the ability to categorize microtonal intervals and shape their perception (Bailes et al., 2015). Additionally, Clader explores the mathematical construction of scales using Pythagorean tuning, suggesting that alternative tuning systems based on powers of prime numbers may offer new insights into music theory (Clader, 2018). A new method was introduced to model the geometry of 12-TET, simplifying its mathematical principles for better comprehension (Ashton-Bell, 2019). The limitations of 12-TET in representing microtonal music have led to the exploration of alternative systems, such as Just Intonation, which uses rational ratios to maintain pure harmonic intervals but limits flexibility due to its dependence on specific fundamental tones (Schwartz et al., 2003). Table 1 represents tonal frequencies [F(i)=440*(2^(i/12))] of the 12-TET chromatic scale system, in which indexes are between (i=-57 → 50).

Table 1. Note frequencies of the 12-TET chromatic scale system of Western music between [0-8] octaves

Octaves	Do	Do#	Re	Re#	Mi	Fa	Fa#	Sol	Sol#	La	La#	Si
m:octave index	Cm	C#m	Dm	D#m	Em	Fm	F#m	Gm	G#m	Am	A#m	Bm
index	-57	-56	-55	-54	-53	-52	-51	-50	-49	-48	-47	-46
Octave-0	16,35	17,32	18,35	19,45	20,60	21,83	23,12	24,50	25,96	27,50	29,14	30,87
index	-45	-44	-43	-42	-41	-40	-39	-38	-37	-36	-35	-34
Octave-1	32,70	34,65	36,71	38,89	41,20	43,65	46,25	49,00	51,91	55,00	58,27	61,74
index	-33	-32	-31	-30	-29	-28	-27	-26	-25	-24	-23	-22
Octave-2	65,41	69,30	73,42	77,78	82,41	87,31	92,50	98,00	103,83	110,00	116,54	123,47
index	-21	-20	-19	-18	-17	-16	-15	-14	-13	-12	-11	-10
Octave-3	130,81	138,59	146,83	155,56	164,81	174,61	185,00	196,00	207,65	220,00	233,08	246,94
index	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2
Octave-4	261,63	277,18	293,66	311,13	329,63	349,23	369,99	392,00	415,30	440,00	466,16	493,88
index	3	4	5	6	7	8	9	10	11	12	13	14
Octave-5	523,25	554,37	587,33	622,25	659,26	698,46	739,99	783,99	830,61	880,00	932,33	987,77
index	15	16	17	18	19	20	21	22	23	24	25	26
Octave-6	1046,50	1108,73	1174,66	1244,51	1318,51	1396,91	1479,98	1567,98	1661,22	1760,00	1864,66	1975,53
index	27	28	29	30	31	32	33	34	35	36	37	38
Octave-7	2093,00	2217,46	2349,32	2489,02	2637,02	2793,83	2959,96	3135,96	3322,44	3520,00	3729,31	3951,07
index	39	40	41	42	43	44	45	46	47	48	49	50
Octave-8	4186,01	4434,92	4698,64	4978,03	5274,04	5587,65	5919,91	6271,93	6644,88	7040,00	7458,62	7902,13

Cross-disciplinary research, including psychoacoustic studies, has shown that natural frequency ratios resonate more effectively with human perception than equal-tempered systems. Just Intonation is discussed, with its strengths in harmonic purity highlighted, but its limitations in modulation between distant keys are acknowledged (Lindley, 2001). Moreover, understanding harmonic tonality at microtonal scales reveals the impact of musical signs and interpretations on cultures (Thoegersen, 2024).

In their study, Schwartz and colleagues used voice recordings from over 600 individuals in the TIMIT acoustic-phonetic speech database, containing English sentences, to obtain the probability distribution function of average frequency-amplitude behavior in speech signals (Schwartz et al., 2003). They also tested different spoken languages and found that while the resonance amplitudes of various languages varied, the resonance frequency ranges showed similar scaling patterns. The graphs revealed that the resonance frequency ranges within a two-octave interval in speech signals and the note frequency ranges specified in music signals for harmonics were parallel. The frequency resonance points in the statistical average amplitude-frequency distribution of the human voice demonstrate the ability of the human ear to perceive harmonic tone scales in music successfully. As listed in the article (1, 1.2, 1.33, 1.25, 1.4, 1.5, 1.6, 1.67, 1.75, 1.8, 2), these scales correspond to frequency ratios in the frequencies identified in Table 3.

Advancements in computational musicology, particularly through digital signal processing, have facilitated more nuanced analyses of traditional scales. Studies have shown the adaptability of microtonal systems like 53-TET in representing diverse musical traditions, although challenges remain in practical usage and musical interpretation due to the large number of intervals. The intervals of the 53-TET system, as applied in the current Arel-Ezgi-Uzdilek system, can be seen in Table 3 (Aktas et al., 2019; Bozkurt et al., 2014).

Despite advancements, significant gaps remain in integrating tuning systems across cultural and mathematical frameworks, leaving room for innovative approaches that balance harmonic accuracy and modular convenience.

Methodology

The Safir method introduces a new scale for musical note frequencies based on natural numbers, addressing the limitations in existing tuning systems. These systems often rely on fractional frequency values, resulting in inaccuracies and inconsistent harmonic intervals. The method aims to provide a more harmonious frequency scale for tonal intervals between octaves by transitioning from the intervals used in contemporary systems to a more harmonically consistent structure, with all frequency values expressed as natural numbers instead of fractional values. The primary objective is to construct a note frequency scale that defines tonal frequencies between two octaves, ensuring that the intervals between notes are harmonically aligned. By expressing the frequencies as integer-based ratios, the method eliminates the use of fractional values and ensures a precise and natural harmonic structure. Additionally, this scale serves as a reference template in digital signal processing for obtaining resonance frequencies, natural harmonics, and spectral amplitudes in signal spectrum analysis. This approach not only enhances musical coherence but also facilitates its application in signal processing, particularly spectral analysis, where resonance frequencies, natural harmonics, and spectrum amplitudes can be analyzed more accurately. The method involves the following key steps, for algorithmic steps for musical scale definition (Figure 1a):

Octave Layer Definition: The process begins by defining the tonal frequencies of octave layers (Kf). Here the Kf value is defined as a power of 2. Each octave layer is indexed by i, and the number of frequency segments within each octave (Sf) is also a power of 2. Together, these layers and segments form the structure of the musical scale. A frequency ratio (FR) is initialized as empty.

Frequency Calculation: A loop calculates the tonal frequencies of all layers (Kf) for each octave layer. Here, k=i-5 is used to match the octave band index numbers between 12-TET and Safir. Starting from a base frequency of 1 Hz, the frequencies for each segment within the octave are calculated. Fi=2^(i-1) represents the starting frequency of (i-1)-th layer and Fi2=2^(i) represents the first frequency of (i)-th layer. The frequency at the jth segment of the kth layer is given by the formula: FR(i,j) = Fi1 + (j−1) * DIV, where DIV is the division factor calculated as, DIV=(Fi2−Fi1)/Sf.

Frequency Adjustment and Repetition for Other Octave Layers: The process continues for each octave layer until the algorithm ensures that all frequencies between octaves and divisions are processed. Once all octaves are processed, the frequency generation process is completed. The content of the FR matrix represents the designed octave band frequencies.

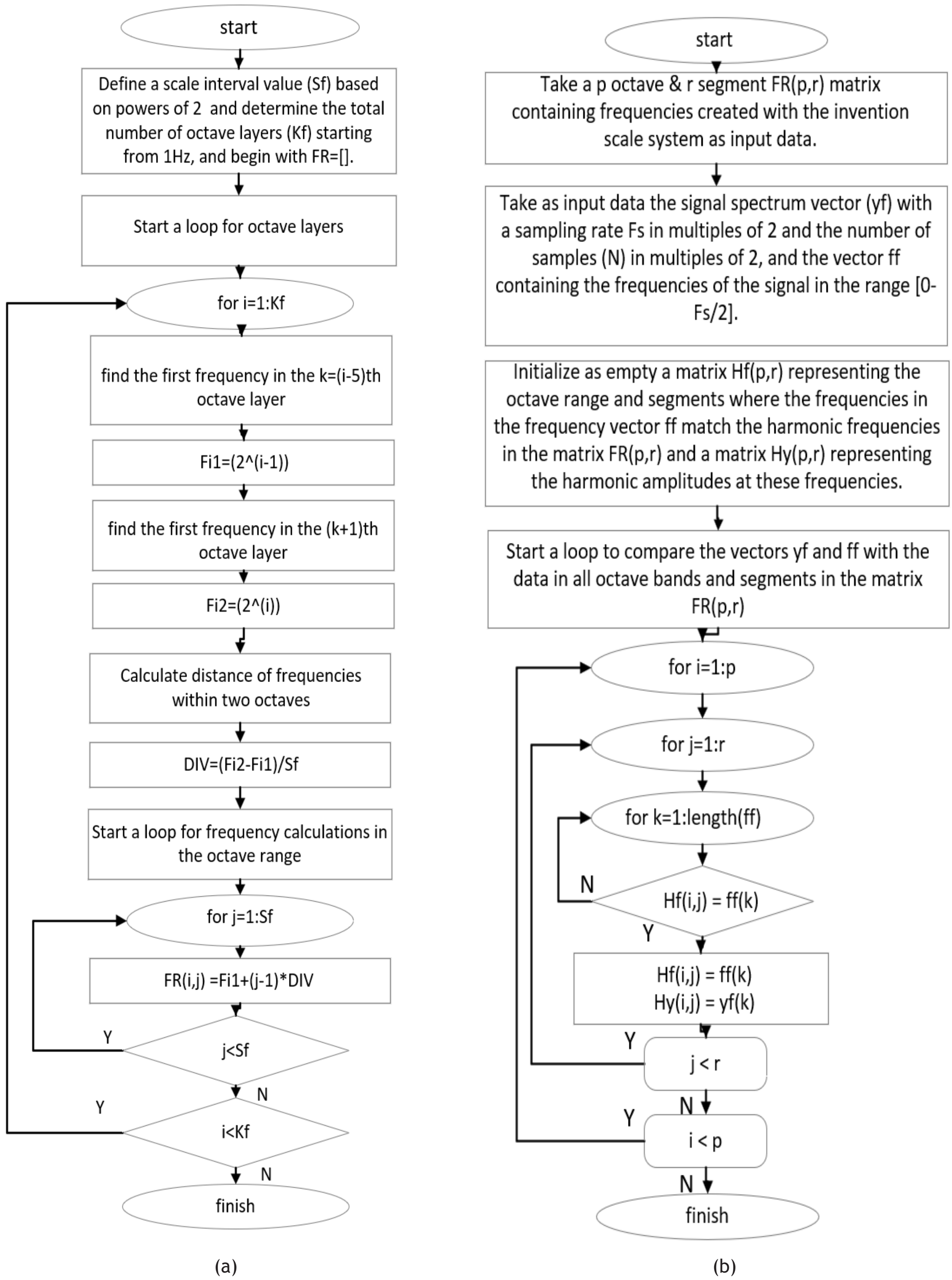

Figure 1. a). A representation of the Safir scale method workflow, in which musical note frequencies consist of natural numbers. b) Representation of the workflow of determining the spectrum amplitudes and harmonics of the signals appropriate to the scale system, by taking an FR matrix as a reference scale system which is produced by using the method in Figure 1a.

Table 2. Note frequencies of the 16-note scale system of the Safir method between [0-8] octaves

Note frequencies	f1	f1#	f2	f2#	f3	f3#	f4	f4#	f5	f5#	f6	f6#	f7	f7#	f8	f8#
Note Symbols	C (Do)	C#	D (Re)	D#	E (Mi)	E#	F (Fa)	F#	G (Sol)	G#	A (La)	A#	H (Ve)	H#	B(Si)	B#
octave-0	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
octave-1	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60	62
octave-2	64	68	72	76	80	84	88	92	96	100	104	108	112	116	120	124
octave-3	128	136	144	152	160	168	176	184	192	200	208	216	224	232	240	248
octave-4	256	272	288	304	320	336	352	368	384	400	416	432	448	464	480	496
octave-5	512	544	576	608	640	672	704	736	768	800	832	864	896	928	960	992
octave-6	1024	1088	1152	1216	1280	1344	1408	1472	1536	1600	1664	1728	1792	1856	1920	1984
octave-7	2048	2176	2304	2432	2560	2688	2816	2944	3072	3200	3328	3456	3584	3712	3840	3968
octave-8	4096	4352	4608	4864	5120	5376	5632	5888	6144	6400	6656	6912	7168	7424	7680	7936

Table 2 shows the note frequency table of the Safir method for the 16 notes in the octave ranges [0-8]. To create a 16-note musical scale system between the octave range [0-8] with the Safir method, Kf=13, and Sf=16 can be selected in the algorithm in Figure 1a, and the results in Table 2 can be obtained. It includes 7 whole-tone used today, accepts the number of notes containing multiples of the nearest 2 as a note sequence, and contains 8 whole-tone frequencies in an octave range (C, D, E, F, G, A, H, B) using

Table 3. Representation of frequency ratios of 16-tone spanning two octaves as both rational numbers and fractional values

Frequency rates (fi/fj)		C# f2	D f3	D# f4	E f5	E# f6	F f7	F# f8	G f9	G# f10	A f11	A# f12	H f13	H# f14	B f15	B# f16
C	f1	1,0625	1,1250	1,1875	1,2500	1,3125	1,3750	1,4375	1,5000	1,5625	1,6250	1,6875	1,7500	1,8125	1,8750	1,9375
	rate	17/16	18/16	19/16	20/16	21/16	22/16	23/16	24/16	25/16	26/16	27/16	28/16	29/16	30/16	31/16
C#	f2		1,0588	1,1176	1,1765	1,2353	1,2941	1,3529	1,4118	1,4706	1,5294	1,5882	1,6471	1,7059	1,7647	1,8235
	rate		18/17	19/17	20/17	21/17	22/17	23/17	24/17	25/17	26/17	27/17	28/17	29/17	30/17	31/17
D	f3			1,0556	1,1111	1,1667	1,2222	1,2778	1,3333	1,3889	1,4444	1,5000	1,5556	1,6111	1,6667	1,7222
	rate			19/18	20/18	21/18	22/18	23/18	24/18	25/18	26/18	27/18	28/18	29/18	30/18	31/18
D#	f4				1,0526	1,1053	1,1579	1,2105	1,2632	1,3158	1,3684	1,4211	1,4737	1,5263	1,5789	1,6316
	rate				20/19	21/19	22/19	23/19	24/19	25/19	26/19	27/19	28/19	29/19	30/19	31/19
E	f5					1,0500	1,1000	1,1500	1,2000	1,2500	1,3000	1,3500	1,4000	1,4500	1,5000	1,5500
	rate					21/20	22/20	23/20	24/20	25/20	26/20	27/20	28/20	29/20	30/20	31/20
E#	f6						1,0476	1,0952	1,1429	1,1905	1,2381	1,2857	1,3333	1,3810	1,4286	1,4762
	rate						22/21	23/21	24/21	25/21	26/21	27/21	28/21	29/21	30/21	31/21
F	f7							1,0455	1,0909	1,1364	1,1818	1,2273	1,2727	1,3182	1,3636	1,4091
	rate							23/22	24/22	25/22	26/22	27/22	28/22	29/22	30/22	31/22
F#	f8								1,0435	1,0870	1,1304	1,1739	1,2174	1,2609	1,3043	1,3478
	rate								24/23	25/23	26/23	27/23	28/23	29/23	30/23	31/23
G	f9									1,0417	1,0833	1,1250	1,1667	1,2083	1,2500	1,2917
	rate									25/24	26/24	27/24	28/24	29/24	30/24	31/24
G#	f10										1,0400	1,0800	1,1200	1,1600	1,2000	1,2400
	rate										26/25	27/25	28/25	29/25	30/25	31/25
A	f11											1,0385	1,0769	1,1154	1,1538	1,1923
	rate											27/26	28/26	29/26	30/26	31/26
A#	f12												1,0370	1,0741	1,1111	1,1481
	rate												28/27	29/27	30/27	31/27
H	f13													1,0357	1,0714	1,1071
	rate													29/28	30/28	31/28
H#	f14														1,0345	1,0690
	rate														30/29	31/29
B	f15															1,0333
																31/30

the new system. In the new scale method, the intervals between any two octaves are adjusted to cover all tones in the current 12-TET system, when the number of notes (tones) between two octaves is selected as 16, as seen in Table 2, 8 of which are main-tones. 16 note frequencies are created. Here, the missing note in the current notation systems is named as the letter 'H' and the name 'Ve' note.

To increase or decrease the note intervals, it is necessary to change the Sf value. Table 3 shows the frequency rates as both rational numbers and fractional values in the 16-tone scale spanning two octaves. In Table 2, the value of the frequencies in the upper octaves progresses as twice the frequencies in the previous octave (harmonics). In this method, although the ratio of adjacent frequencies is not equal, note frequencies in two octaves are equal distances. (Table 2 and Table 3). It is considered that the chromatic note frequency table presented in the method will be of significant benefit to both the music and the signal processing applications, as it contains strong sinusoidal signal examples representing resonance frequencies consisting of natural numbers. As seen in Table 3, whole-4th intervals and whole-5th intervals in music are formed with the invention. Another important advantage of the invention is that whole-5th intervals are formed between two different notes in the same octave range. (f9/f1 and f15/f5 frequency ratios). Table 4 represents a comparative representation of the tone scale ratios of different common musical scales in the 2-octave range with Safir.

In addition to the definition of musical scale with Safir, it can also be used as a reference scaling system for spectrum evaluation of the different signals. The method involves the following key steps for algorithmic steps for spectrum scale definition (Figure 1b). Algorithmic Steps for Frequency Calculation and Analysis as a spectrum scaling system steps are primarily based on the FR matrix calculated by using the steps in Figure 1a for selected octave bands and segment values. Below is a high-level breakdown of the algorithm.

Table 4. Illustration of tone scales-ratios in the 2-octave range for the Pythagorean scale, 12-TET equal temperament scale, 53-TET Turkish music, JI, and Safir scale with 16-Note.

Musical scale names	Octave 1	Minor2	Major2	Minor3	Major3		Perfect 4	Tritone	Perfect 5	Minor6	Major6	Minor7	Major7	Minor8	Major8		Octave 2
fi/f1 rates	f1	f2	f3	f4	f5	f6	f7	f8	f9	f10	f11	f12	f13	f14	f15	f16	f17
Notes	C1	C#	D	D#	E	E#	F	F#	G	G#	A	A#	H	H#	B	B#	C2
Pythagorean scale rates	1,0000	(3^7)/(2^9)	(3^2)/(2^3)	3^9)/(2^14	(3^4)/(2^6)		(2^2)/(3^1)	(2^10)/(3^6)	(3^1/(2^1)	(3^8)/(2^12)	(3^3)/(2^4)	(3^10)/(2^15)			(3^5)/(2^7)		2,0000
Pythagorean scale rates	1,0000	2187/2048	9/8	9683/1638	81/64		4/3	1024/729	3/2	6561/4096	27/16	59049/32768			243/128		2,0000
Pythagorean scale(fractional	1,0000	1,0679	1,1250	1,2014	1,2656		1,3333	1,4047	1,5000	1,6018	1,6875	1,8020			1,8984		2,0000
12-TETscale rates	1,0000	2^(1/12)	2^(2/12)	2^(3/12)	2^(4/12)		2^(5/12)	2^(6/12)	2^(7/12)	2^(8/12)	2^(9/12)	2^(10/12)			2^(11/12)		2,0000
12-TETscale (fractional)	1,0000	1,0595	1,1225	1,1892	1,2599		1,3348	1,4142	1,4983	1,5874	1,6818	1,7818			1,8877		2,0000
53-TET Turkish Makaam	1,0000	2^(4/53) 2^(5/53)	2^(9/53)	2^(13/53) 2^(14/53)	2^(18/53)		2^(22/53)	2^(26/53) 2^(27/53)	2^(31/23)	2^(35/23) 2^(36/23)	2^(40/53)	2^(44/53) 2^(45/53)			2^(49/53)		2,0000
53-TET Turkish Makaam	1,0000	1,0537 1,0675	1,1249	1,1853 1,2009	1,2654		1,3333	1,4049 1,4235	1,4999	2,8714 1,6013	1,6873	1,7779 1,8013			1,8981		2,0000
Just intonation	1,0000	16/15	9/8	6/5	5/4		4/3	45/32	3/2	8/5	5/3	7/5			15/8		2,0000
Just intonation fractional	1,0000	1,0667	1,1250	1,2000	1,2500		1,3333	1,4063	1,5000	1,6000	1,6667	1,7500			1,8750		2,0000
Proposed Method Scale	1,0000	17/16	18/16	19/16	20/16	21/16	22/16	23/16	24/16	25/16	26/16	27/16	28/16	29/16	30/16	31/16	2,0000
Proposed Method Scale	1,0000	1,0625	1,1250	1,1875	1,2500	1,3125	1,3750	1,4375	1,5000	1,5625	1,6250	1,6875	1,7500	1,813	1,8750	1,9375	2,0000

Initialization: At first, produce an FR(p,r) matrix, containing harmonic frequencies, by using the steps in Figure 1a. The segment value r is defined as a power of 2, along with the total number of octave layers p.

Input Data for Harmonic Frequency Matching: Take input data consisting of a signal spectrum vector (yf), sampled at a specific rate, and a frequency vector (ff) within the range [0, Fs/2]. Matrices Hf(p, r) and Hy(p, r) are initialized to store matched harmonic frequencies and their corresponding amplitudes.

Matching Harmonic Frequencies: The algorithm compares each frequency in the ff frequency vector with those in the FR matrix. If a match is found, the frequency is stored in Hf(i, j), and the corresponding amplitude is recorded in Hy(i, j).

Repetition and Finalization: The matching process is repeated for all octaves and segments, ensuring that all frequencies are matched and stored. Once all frequencies are processed, the algorithm concludes and finalizes the frequency and amplitude data for all octave bands.

If the sampling frequency (Fs) and FFT sample length (N) of a signal are selected as multiples of 2 and the FFT is taken, the frequency resolution (Δf=Fs/N) and frequency distributions occur in terms of natural numbers. For this reason, for example, to obtain the spectrum distributions of musical signals composed and recorded with frequencies appropriate to the Safir scale system in Table 2 in integer values, the Fs and N values must be multiples of 2.

Test and Evaluation

Several tests were conducted to observe the distribution of spectrum amplitudes for note frequencies in the Safir method and the 12-TET chromatic scale system. Initially, the parameters were set to N=32 and Δ=32 for the tests. A sinusoidal signal, X(t), was created to represent 8 tonal frequencies (f_1 to f_8) over a two-octave range.

$$X(t) = \sin(2\pi f_1 t) + \sin(2\pi f_2 t) + \sin(2\pi f_3 t) + \sin(2\pi f_4 t) + \sin(2\pi f_5 t) + \sin(2\pi f_6 t) + \sin(2\pi f_7 t) + \sin(2\pi f_8 t) \quad (1)$$

The sinusoidal signal X(t), two different sets of frequency values were tested:

i) Proposed Method: The 8-tone frequencies in the proposed method, representing notes within the range of 8 Hz to 16 Hz (C, D, E, F, G, A, H, B), were assigned the values [8, 9, 10, 11, 12, 13, 14, 15] Hz. These values were substituted for the variables [f_1, f_2, f_3, f_4, f_5, f_6, f_7, f_8] in the X(t) function as defined in Eq.1. The FFT of the X(t) signal was then performed.

ii) 12-TET Chromatic System: In the 12-TET chromatic system, 7-tone frequencies within the range of 8 Hz to 16 Hz (C, D, E, F, G, A, B) were represented by the values [8.176, 9.177, 10.30, 10.913, 12.250, 13.750, 15.434] Hz. These were substituted for the variables [f_1, f_2, f_3, f_4, f_5, f_6, f_7] in the X(t) function as defined in Eq.1. The FFT of the X(t) signal was then performed. Since the 12-TET system does not have an 8th note within this range, f_8 was set to 0.

During the test, an FFT transformation was applied to the signal for a duration of t = 1s, resulting in the signal X(f) = fft(X(t), N). When plotted as a single-sided linear spectrum over the frequency range of [0-16 Hz], the results shown in Figure 2a were obtained. As seen in Figure 2a, in the first plot representing the proposed method with integer frequencies ranging from 8 to 15 Hz, each line in the frequency spectrum retained its amplitude without any spectral leakage to the sidebands. In contrast, the sinusoidal signal composed of 12-TET frequency samples exhibited spectral leakage across different signal frequencies, leading to changes in the linear spectrum amplitudes and visible leakage into the sidebands (Figure 2b). Therefore, the note frequency values in the 12-TET system appear to be far from being considered true resonance frequencies.

A simple test was conducted to observe the differences in spectrum distribution between integer and fractional frequency values of a sinusoidal signal. In this context, the FFT was applied to the function x1(t) = sin(2πft) with two different frequency values: f_1=16Hz (Figure 3a) and f_2=16.35Hz (Figure 3b). Sampling Frequency (Fs) for the signal in Figure 3 was chosen as Fs=64Hz to cover the signal nyquist frequency. The FFT amplitudes and frequency distribution for both sinusoidal signals are shown.

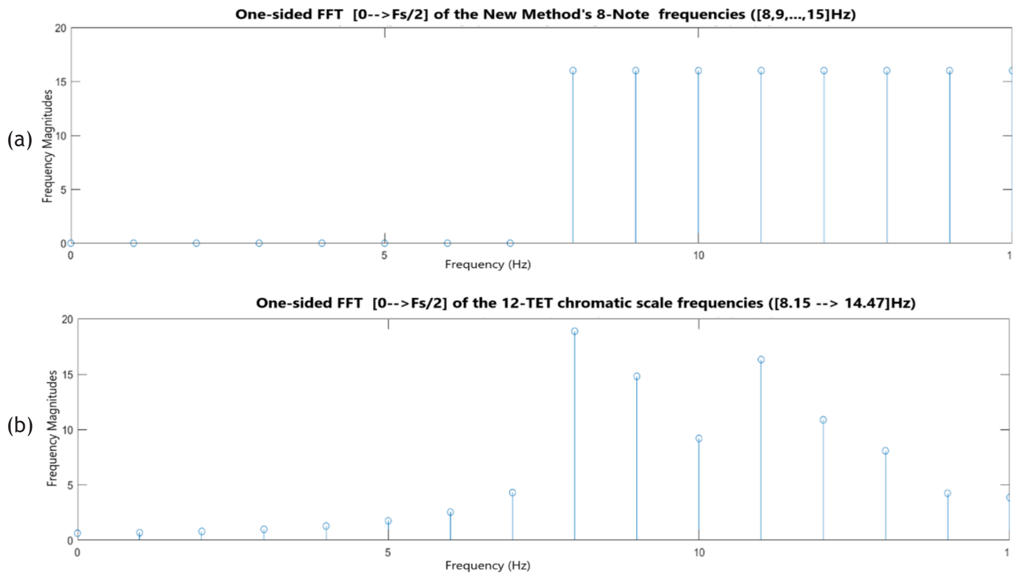

Figure 2. a) Representation of the single-sided FFT spectrum amplitudes for the x(t) signal, which was created by summing the 8-note frequencies of the proposed method (8 to 15 Hz) within the 8–16 Hz frequency range. b) Representation of the single-sided FFT spectrum amplitudes for the x(t) signal, created by summing the 7-note frequencies within the 8–15 Hz range in the 12-TET equal temperament system

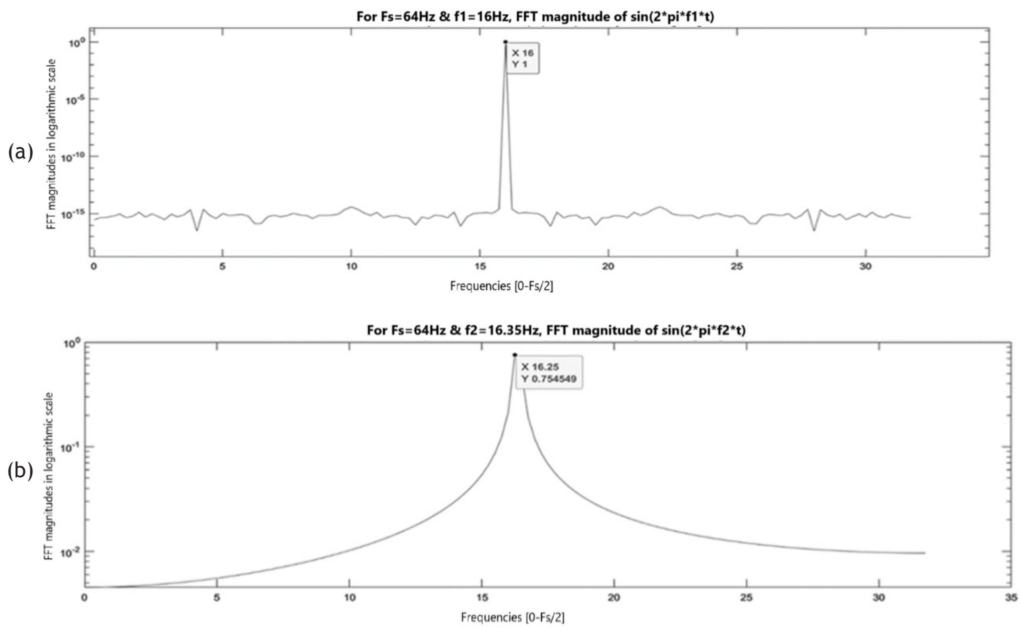

Figure 3. a) Representation of the FFT spectrum amplitudes for the signal x1(t) = Sin(2*π*16*t) sampled at Fs=64Hz. b) representation of the FFT spectrum amplitudes for the signal x2(t) = Sin(2*π*16.35*t) sampled at Fs=64Hz

As observed, the FFT behavior of the sinusoidal signal with f_1=16Hz closely aligns with the expected 'Delta' (δ) function behavior from Fourier transforms of sinusoids, maintaining its resonance even at logarithmic amplitude levels of $10^{(-15)}$. In contrast, the sinusoidal signal with f_2=16.35Hz exhibits both a reduction in harmonic amplitude and a dispersion of energy into side frequency bands. This demonstrates that sinusoidal signals with fractional frequency values lose the characteristics of being true resonance frequencies.

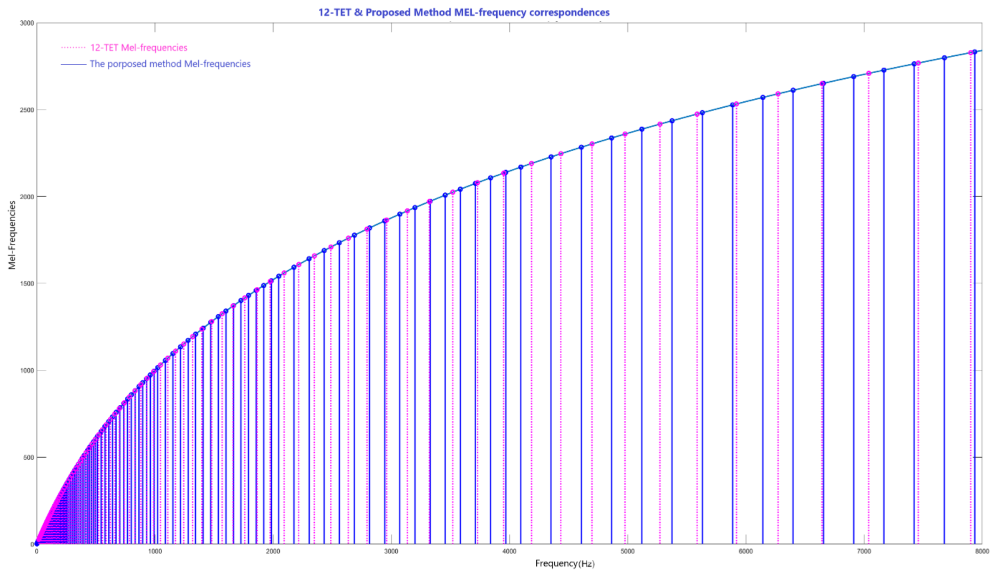

Figure 4. Graph of the Mel-frequency equivalents of frequencies between [1–8000 Hz] for both the 12-TET chromatic scale and the proposed 16-TET scale

In the current state of the art, the most common method for determining the relative frequency perception of a sound emitted from a source is the Mel-frequency calculation method (Alvarez et al., 2007). According to this method, the Mel-frequency equivalent of a sound at frequency f is calculated using the formula provided in Eq.2.

$$f = 2595.\log_{10}\left(1 + \frac{f}{700}\right) \qquad (2)$$

Figure 4 illustrates the Mel-frequency equivalents for frequencies in both the 12-TET scale system and Safir frequencies, calculated using the Mel-frequency formula. In the Safir system, frequencies are evenly spaced within each octave band. This linear scaling of the octave band reduces the impact of higher-pitched frequencies towards the end of the band. In contrast, the 12-TET equal temperament scale, due to its logarithmic scaling, results in wider frequency intervals towards the end of each octave band. Consequently, the differences in Mel-scale frequency equivalents between adjacent frequencies increase at the end of the octave band, making the selectivity of higher-pitched notes more distinct than Safir. When examining the regions in Figure 4 where the frequencies on the horizontal axis increase in multiples of 2 (indicating octave intervals), the Mel-scale frequency differences between adjacent frequencies in Safir octave bands favor the lower notes at the beginning of the octave. However, in the 12-TET system, the Mel frequency difference increases for adjacent notes at the end of the octave band, favoring the higher-pitched notes. In the Safir system, the balanced distribution of frequencies within each octave band results in a closer alignment of high-pitched frequencies in the Mel scale towards the end of the octave, reducing their auditory prominence. This leads to a decreased selectivity of high-pitched frequencies in the ear, thus diminishing their dominant effect.

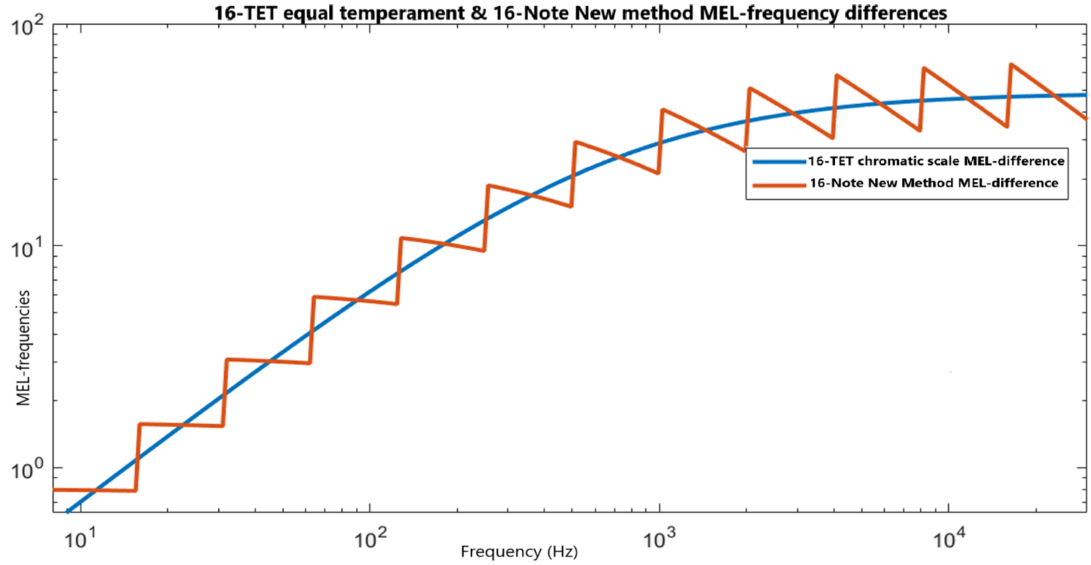

Figure 5. Representation of the 16-TET equal temperament scale system and the frequency differences of the 16-note invention adjacent frequencies in the Mel scale

Figure 5 presents the differences in Mel-frequency equivalents between adjacent frequencies for the 16-note scales in both the 16-TET equal temperament (using a multiplication factor of 2^(1/16) and Safir scale with 16-octave segments (Sf=16). As shown in Figure 5, the Mel-frequency intervals in the 16-TET scale progressively increase, enhancing the selectivity of high-pitched notes within the octave band. In contrast, in Safir, the Mel-frequency differences at octave transitions are higher compared to 16-TET, but decrease throughout the octave band as the notes become higher in pitch. This results in greater clarity at octave transitions in Safir, while selectivity within the band decreases as the pitch rises. This characteristic is considered beneficial for hearing health, particularly in high-frequency music signals.

Figure 5 illustrates that in the 16-TET equal temperament scale, the ratio of adjacent frequencies remains constant across the entire frequency range, while the Mel-frequency differences consistently increase across the octave bands. This implies that as one moves towards higher frequencies in the equal temperament chromatic system, particularly at high frequencies, the selectivity of higher-pitched notes within the band becomes more pronounced compared to lower-pitched notes. For instance, in a music signal composed using the equal temperament scale and sampled at 48 kHz, high-pitched notes are more distinctly perceived than lower-pitched tones in each octave band when compared to the Safir scale.

Based on the results in Figure 5, it can be said that the equal temperament scale is a system that enhances the auditory selectivity of higher-pitched notes over lower-pitched notes within an octave band. This phenomenon appears to apply to all musical scale methods that use a multiplicative factor to scale intervals within an octave band based on frequency ratios. In the Safir scale, however, the selectivity of lower-pitched notes is enhanced within the same octave band, while the Mel-frequency difference decreases as one moves towards higher-pitched notes. Since the Mel scale represents the human ear's synthetic perception of frequencies, it is suggested that music signals composed with the Safir scale will emphasize the selectivity of lower-pitched frequencies in high-frequency regions of the octave band while suppressing the selectivity of higher-pitched frequencies.

Table 4 presents a comparative analysis of the tone ratios within a 2-octave range for the Pythagorean scale, 12-TET equal temperament scale, and the 16-note scale of Safir. As shown, both the 12-TET scale and the Pythagorean scale generate intervals based on a multiplication factor, resulting in similar interval values. In the 12-TET scale, the intervals between notes are scaled according to a base-2 logarithmic system, and as shown in Figure 4, the differences between note intervals continuously increase towards higher frequencies. In contrast, in the Safir system, the frequency intervals within the same octave are equal, but the frequency ratios decrease as the end of the octave band is approached. Table 4 illustrates the tone scales-ratios in the 2-octave range for the Pythagorean scale, 12-TET equal temperament scale, 53-TET Turkish music, JI, and Safir scale with 16-Note. As observed in Table 4, in the Safir method, adjacent frequency ratios narrow continuously toward the end of the octave band. Consequently, the Mel-scale frequency values of the notes near the end of the octave band become more distinct and are more readily perceptible by the ear. Towards the end of the octave band, the Mel frequency intervals shrink, as seen in Figure 4. In the Safir method, the scales marked in Table 4 overlap with those of other systems, while the unmarked frequency tones are either present at different frequency ratios within the octave band, as seen in Table 3, or can be divided into finer scaling intervals within 32-note or 64-note Safir scales. This can be seen in the frequency ratios for 16, 32, and 64 notes in Table 5. Comparing Table 3 and Table 4, it is evident that many of the consonant ratios in the JI (Just Intonation) system in Table 4 appear at different frequency ratios in Table 3. (Note: For the 'comma' intervals in the 53-TET system and the intervals in other scales that do not exactly match, two scale values are provided in the 53-TET system in Table 4.)

Innovative Effects of the Safir Method on Digital Signal Processing Applications

This method offers a variety of innovative ways to improve spectrum analyzers, from minimizing spectral leakage to improving harmonic resolution and supporting multi-octave analysis. These advances could have important applications in fields as diverse as audio engineering, speech processing, animal communication analysis, and signal processing in noisy environments. Providing more accurate, natural-sounding frequency analysis, this approach could pave the way for next-generation spectrum analyzers and provide a clearer, more precise understanding of complex signals.

This method could also provide breakthroughs in many areas of speech processing by providing more accurate pitch and harmonic analysis. Whether improving speech recognition, emotional analysis, synthesis, or improving voice clarity in noisy environments, this approach addresses limitations in existing systems that rely on less accurate or artificially constrained frequency representations. Each of these application areas offers significant potential to push the boundaries of current speech-processing technology by aligning more closely with natural speech and human auditory perception. The Safir method, which uses natural number-based frequencies and harmonic analysis, can potentially be used to study animal vocalizations and communication as it allows precise measurement of resonant frequencies and harmonics. By capturing these frequencies, we can analyze the sounds of different species with high accuracy and understand their unique frequency responses and harmonics. This method could be particularly useful in bioacoustics, where understanding the frequency properties of animal sounds (such as sounds from whales, birds, or bats) is essential for studying animals' behavior, communication, and even environmental adaptations.

In bioacoustics, animal vocalizations generally cover a wide range of frequencies; Some of these are frequencies that humans cannot directly perceive but are vital for animal communication. With good frequency resolution and the ability to map resonance harmonics, this method can provide insight into these vocalizations in a way that traditional methods cannot. It can also reveal patterns that are more difficult to capture using traditional tools such as 12-TET or linear frequency scales and do not account for the perceptual nuances of nonhuman hearing. One of the state of the art study animal communication through frequency analysis is the Fourier Transform (FFT) approach which identifies the frequency components of sounds but cannot effectively provide the resolution or perceptual fidelity that the natural numbers-based approach in this article can offer. Another method, Mel-Frequency Cepstral Coefficients (MFCCs), again cannot provide an effective solution as the filter structure is not specifically designed for the study of non-human species (Ijaz et al., 2024).

The new natural numbers-based scaling method can produce effective models in converting bioacoustic sounds into speech by producing and comparing models based on resonance frequencies and harmonics in animal communication. For example, species-specific vocalizations such as echolocation calls in bats, whistles in dolphins, and songs in birds often contain frequencies that vary significantly between species. Using the Safir method, researchers can directly relate these frequencies to a natural harmonic structure that reflects biological resonance patterns, leading to more meaningful insights into species' communication strategies. Additionally, differences in resonance frequencies can be analyzed about environmental factors such as habitat acoustics or predator-prey dynamics, further deepening our understanding of animal behavior and communication.

Another usage of Safir can be to detect Pitch Frequency Differences in Speech, after taking FFT to extract the fundamental frequency (F0), these frequencies can then be mapped onto a natural-number-based scale for harmonic clarity. Statistical analysis categorizes speakers by pitch patterns, revealing correlations with gender, age, and emotion. Applications include speech therapy, personalized voice analysis, and improvements in speech.

Recommended Practical Applications of Safir

The new scale represents tone frequencies using natural numbers and presents each tone as a pure sine wave without harmonic distortion. This offers clear spectral representation with undistorted peak signals. The linear scaling of tone intervals ensures that microtonal shifts remain harmonically close to related notes, providing a more harmonious interval structure compared to traditional systems. Adjustments supporting low frequencies in the MEL scale reduce the impact of high-frequency sounds, offering a healthier listening experience.

Signal Processing and Natural Speech Analysis: By linking tone frequencies to spectrum magnitudes, this method simplifies the analysis of resonance frequencies in various signals and aids in evaluating complex waveforms. It supports the analysis of both organic and inorganic sounds, allowing connections between sounds like vocalizations or environmental noises and their harmonic relationships. The use of natural number frequencies eliminates fractional values, creating more harmonious intervals and increasing efficiency and accuracy in the analysis and synthesis of musical frequencies (Kellermann et al., 2023).

Speech Recognition and Emotional Analysis: Traditional speech recognition systems struggle with nuances like tone variations, accents, and emotional tones when using 12-TET or standard frequency representations. Safir frequency scale captures subtle tone changes and harmonics better, enabling more accurate transcriptions under noisy or variable conditions. Since emotional tones are often conveyed through pitch, this method can provide more natural and precise outcomes in emotional and sentiment detection applications (Liu et al., 2023).

Flexible Scale Production and Consistent Frequency Analysis: The system offers flexible octave divisions, from traditional 7-note scales to more complex microtonal scales (e.g., 16 or 32 notes per octave). This flexibility opens up a wider range of musical expression and allows for more precise signal analysis. The Safir method overcomes perceptual issues in 12-TET and 53-TET systems, providing a harmonious frequency representation across octaves, and creating a more universal harmony for both composition and scientific analyses (Guers, 2023).

Wideband Spectral Analysis and Frequency Accuracy: By scaling octaves with higher multiples, the Safir method provides more accurate results in wideband spectral analysis. This facilitates analysis over broad frequency ranges, especially in structural health monitoring, environmental noise analysis, or detailed music signal processing. The natural number-based method allows spectrum analyzers to provide exact frequency values for resonance-like frequencies, contributing to more precise frequency determination and analysis (Wang et al., 2021).

Harmonic Resolution and Spectral Leakage Reduction: The natural number-based method improves the resolution of harmonic content, especially in the analysis of complex signals like speech, music, or animal sounds. While traditional methods like 12-TET can lead to spectral leakage issues, the new system reduces such leakages, making spectral peaks sharper and more distinct. This leads to clearer and more accurate results, particularly in noisy signal analysis (Puche-Panadero et al., 2021).

Sound Therapy, Health Monitoring, and Hearing Health: The new system offers a more balanced listening experience by reducing the emphasis on high-frequency sounds, minimizing discomfort associated with prolonged exposure to high-frequency audio. This is particularly relevant in music production, hearing technology, and signal processing fields, contributing to long-term hearing health. The system enhances the detectability of low frequencies while suppressing excessive emphasis on high frequencies, creating a balanced auditory experience (Sereda et al., 2018).

Conclusion

The 12-TET system approximates consonant intervals like the perfect fifth (3:2 ≈ 1.49832) and perfect fourth (4:3 ≈ 1.33482), compromising harmonic purity, particularly in higher frequencies, which tend to sound increasingly sharp, reducing clarity, especially in sustained high notes. Although 12-TET simplifies transposition and versatility in musical expression, it introduces perceptual distortions due to logarithmic frequency divisions. In contrast, the Safir method uses linear scaling, which eliminates the sharp rise in higher frequencies and results in a more harmonious frequency distribution across the entire scale. By using natural numbers in frequency calculations, the method ensures consistent intervals based on fundamental ratios rather than logarithmic approximations. Similarly, while the 53-TET system offers greater harmonic precision and aligns more closely with natural harmonic ratios, it faces practical challenges, including the need for 53 notes per octave and the generation of fractional frequencies, complicating its application in traditional settings. These issues, along with the complexity of maintaining accurate tuning across a wider tonal range, highlight the limitations of both 12-TET and 53-TET, with Safir offering a more accessible and harmonically coherent alternative.

The tests confirm that the natural number-based system of the study provides a more accurate and clearer frequency representation when subjected to FFT analysis, with well-defined harmonic content and no spectral leakage. This demonstrates that the system produces more natural-sounding tones with fewer artifacts compared to the 12-TET system.

The comparison between the 12-TET system and Safir scale using Mel-frequency calculations underscores the advantages of Safir scale in terms of natural frequency spacing and improved auditory perception, particularly for higher frequencies. The balanced frequency intervals within the octave band, along with the reduced emphasis on high-pitched sounds, suggest that the new system may offer a healthier listening experience, particularly in the context of long-term hearing health.

In summary, this novel method addresses the need for more balanced frequency scaling, enhancing the perceptibility of lower frequencies while suppressing the overemphasis on higher frequencies. This characteristic is especially beneficial for high-frequency sound analysis in fields such as music production, hearing technology, and signal processing. Compared to traditional systems like 12-TET, which can lead to imbalanced frequency distributions, the Safir scale system creates a more uniform auditory experience. Some systems, such as the 432 Hz tuning, draw inspiration from natural harmonic ratios and have been associated with claims of providing a more harmonious listening experience. The Safir method appears to be an original exploration into creating a more balanced frequency system that reduces the prominence of higher frequencies and could offer new insights into harmonic tuning, especially in terms of auditory health. This suggests a potential avenue for further research and development in music theory and sound therapy.

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