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COMPLEX ACOUSTICAL ANALYSIS OF BELL SOUNDS FROM TEMPLES IN MAHARASHTRA

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Abstract

Analysis of bell sounds from four prominent temples were carried out and compared with the help of Wavanal program. A study of partials was done through recordings of the bell sounds and its influence on amplitude and intensity of sound was also studied. Significant differences were observed in the main partials. The sound spectrum of the bells is also examined in this study to reveal the parameters responsible for differences in the perception of sound from these bells. The present paper shows the results of a thorough acoustical analysis of the sounds emitted by the temple bells.

***Keywords**: acoustical analysis, spectrum, partials*

I. Introduction

For any temple, its ringing bells are representative both from the architectonic and aesthetic point of view, along with their sound perception [1]. Details about the proper material, wall thickness, shape, size and number of bells have to be studied prior to the acquisition of a bell. As known, bells belong to the percussion musical instrument class. A note or a set of notes on a musical scale are assigned to each bell, thus identifying and differentiating between them. This particular assigned note is also used to judge whether a bell is 'in tune' with others if there is a set of bells (*i.e.* a *chime* [2]). The sound impression of a bell is called *pitch*. More precisely, the pitch represents a subjective sensation in which a listener assigns perceived tones to relative positions on a musical scale based primarily on the vibration frequency [3, 4]. In order to differentiate objectively between sounds, one needs to perform complex sound analysis both in the time domain and in the frequency domain using physical methods[5-7]. In this paper, the performances and the usefulness of the acoustics was analysed by computer program named Wavanal [8].

II. Theoretical notions

The sound emitted from a bell is composed by the sum of its specific partials and from residual noise. A partial is a certain frequency from the sound spectrum, given by a certain mode of bell vibration. Except from the percussion class, all the other musical instruments have partials at integer multiples of the fundamental frequency emitted from each instrument. In the case of bells, which belong to the percussion class of instruments, the partials represent fractional multiples of the fundamental frequency [3]. The sound spectrum of a bell, i.e. the amplitude or intensity of sound versus frequency, is composed of peaks corresponding to the partials, with background given by the bell's noise.

The partials with frequencies bigger than that of the fundamental component of a certain complex sound are known as overtones or upper partials and they have specific names, in increasing order of their frequencies: *hum*, *prime*, *tierce*, *quint*, *nominal* and *superquint* [2-4, 9-13].

The acoustic intensity (I) is defined as the sound power per unit area, expressed in W/m^2. The sound intensity level is defined as [2]

$$\text{Sound intensity level} = 20\log\frac{I}{I'} \quad (1)$$

where, I' is the reference intensity.

The sound intensity level is expressed in dB. Concerning the reference intensity, its value is taken as 10^{-12} W/m^2 in most of the cases. However, in case of bells, the reference intensity is that of the partial from the sound spectrum with frequency closest to the note of 440 Hz, whose intensity level thereby comes out to be zero [1][2][3].

III. Experimental

Sound file recording of bell from four prominent temples viz. Kapaleshwar Temple (Nashik district), Kashivishweshwar Temple, Pataleshwar Temple and Meneshwar Temple (Pune district) were analysed. Wavanal software was used for the analysis of sound in .wav format. All the bells selected were of similar structure and dimensions, approximately 30 cm in diameter at the 'lip' of the bell. However, all the recordings were carried out by placing the recorder at identical positions, i.e. 1 foot below the centre of bell. All the bells were hung at approximately 8 feet high from the ground level. All the temples under consideration were of similar structure with stone as the major material used for construction. The comparative study aims at identifying the structural dissimilarities in terms of acoustical parameters. The

Wavanal program allows for precise analysis of the bells' sounds in terms of frequency identification of each partial, of the exact amplitude and intensity of each partial, as they are contributing to sound perception. This analysis was performed for the recorded sound files. The corresponding sound spectra allowed comparison and identification of differences between the sounds [2]. In the present paper, the term 'amplitude' is used for intensity of sound and the term 'intensity' refers to the intensity level in decibels.

IV. Results and Discussion

Figures 2 to 5 exhibit the plots of the Fourier transform of the recorded sounds from the four temples as resulting from the Wavanal program. Tables 1 to 4 present the acoustical characteristics of all the identified peaks in the spectra from Figures 2 to 5, respectively, done through Wavanal calculations. The frequency and the amplitude of each peak are given in columns 2 and 3. The sound intensity level is calculated in dB for each partial in column 4. The main upper partials are identified in column 5. The numbers given in column 6 represents the deviation in cents from the note with 440 Hz frequency, as obtained from Wavanal [3,8].

Note that, the *cent* is a logarithmic unit of measure used for musical intervals, being given by the interval of pitch between two frequencies ν_1 and ν_2 given by [1]:

$$1 \text{ cent} = 3986.31 \ \log \frac{\nu 2}{\nu 1} \tag{2}$$

Thus, one semitone has 100 cents (i.e. a cent represents one hundredth of a semitone) and one octave (with a frequency ratio of 2:1 from one end to the other) is equal to 1200 cents. The interval of one cent is much too small to be heard between successive notes, but its multiples are useful when one wants to measure extremely small musical intervals.

Fig 1(a) : Kapaleshwar Temple, Nashik

Fig 1(b) : Pataleshwar Temple, Pune

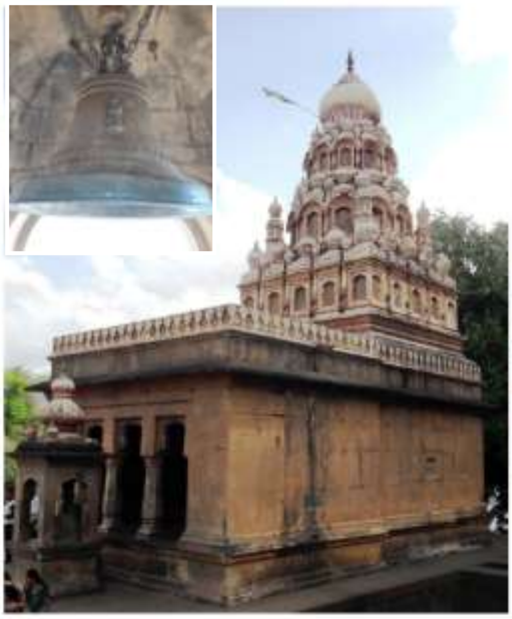

Fig 1(c) Meneshwar Temple, Pune

Fig 1(d) Kashivishweshwar Temple, Pune

Figure 1(a-d): Temples undertaken for the acoustical study (with photos of bells inscribed)

Columns 7 and 8 present the results of the computation of the ratios ν / ν_0 and ν / ν_{nom}, respectively, of each peak's frequency to that of the lowest frequency (ν_0) and to that of the nominal (ν_{nom}). The last four rows gives the minimum and maximum values of each parameter, the average values of parameters and their standard deviation, denoted as STDEV and defined as:

$$STDEV = \sqrt{\frac{\sum_{k=1}^{N}(x_k - \bar{x})^2}{N}} \qquad (2)$$

This magnitude expresses the degree of spread of a set $\{x_k\}$ of N data around their average value $\bar{x}$.

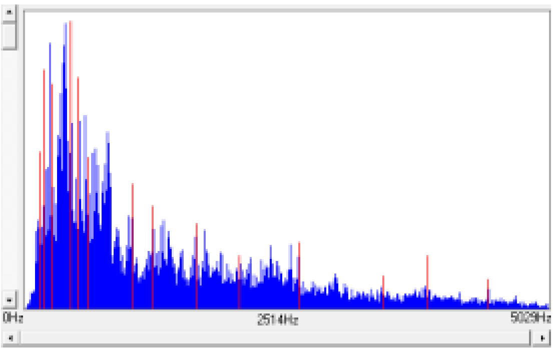

Figure 2: Fourier transform of recorded bell sound from Kapaleshwar Temple, Nasik, as resulting from Wavanal Program (amplitude of sound versus frequency)

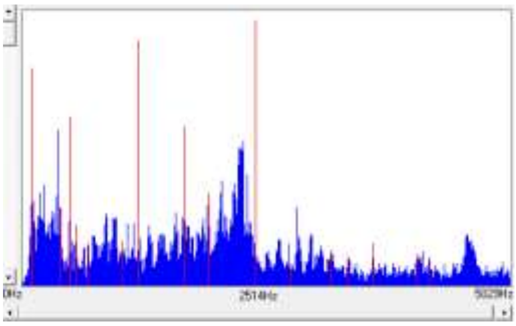

Figure 3: Fourier transform of recorded bell sound from Kashivishweshwar Temple, Pune, as resulting from Wavanal Program (amplitude of sound versus frequency)

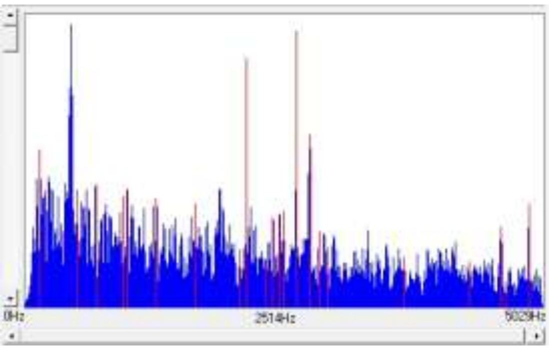

Figure 4: Fourier transform of recorded bell sound from Pataleshwar Temple, Pune, as resulting from Wavanal Program (amplitude of sound versus frequency)

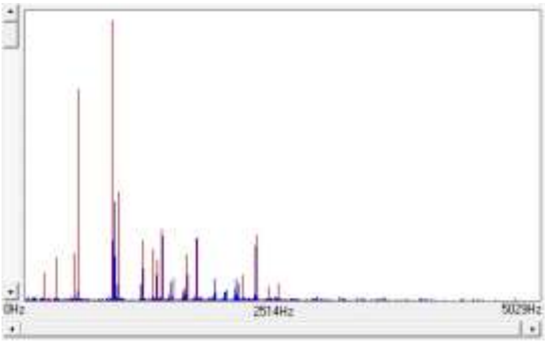

Figure 5: Fourier transform of recorded bell sound from Meneshwar Temple, Pune, as resulting from Wavanal Program (amplitude of sound versus frequency)

Table 1: Characteristics of Bell Sound from Kapaleshwar Temple

No.	Frequency (Hz)	Ampli. (a.u.)	Sound Intensity level (dB)	Partial	Cents	Ratio to lowest freq.	Ratio to nominal
1	158.5	1.2288	-5.1944		-3258.4	1.0000	0.1523
2	204	1.8641	-1.5746		-2821.5	1.2871	0.1960
3	280.5	1.7528	-2.1093	hum	-2270.2	1.7697	0.2695

4	453.5	2.2346	0.0000	prime	-1438.5	2.8612	0.4356
5	534.5	1.7991	-1.8829		-1154	3.3722	0.5134
6	627	1.1894	-5.4774	tierce	-877.7	3.9558	0.6023
7	1041	0.9817	-7.1444	nominal	0	6.5678	1.0000
8	1235.5	0.8121	-8.7918		296.5	7.7950	1.1868
9	1648.5	0.6726	-10.4289		795.8	10.4006	1.5836
10	2066.5	0.4246	-14.4244	oct. nom.	1187	13.0379	1.9851
11	2625.5	0.5286	-12.5215		1601.5	16.5647	2.5221
12	3425	0.2734	-18.2480		2061.7	21.6088	3.2901
13	3862	0.4209	-14.5004		2269.6	24.3659	3.7099
14	4427.5	0.2474	-19.1160		2506.2	27.9338	4.2531
Min.	158.50	0.25	-19.12		-3258.40	1.00	0.15
Max.	4427.50	2.23	0.00		2506.20	27.93	4.25
Average	1613.54	1.03	-8.67		-78.71	10.18	1.55
STDEV	1449.69	0.66	6.36		1925.42	9.15	1.39

Table 2: Characteristics of Bell Sound from Kashivishweshwar Temple

No.	**Frequency (Hz)**	**Ampli. (a.u.)**	**Sound Intensity level (dB)**	**Partial**	**Cents**	**Ratio to lowest freq.**	**Ratio to nominal**
1	107	1.4715	8.7849		-4992.1	1.0000	0.0559
2	397.5	0.5352	0.0000		-2720.1	3.7150	0.2078
3	496.5	1.1436	6.5952	hum	-2335.1	4.6402	0.2595
4	560.5	0.4217	-2.0703		-2125.2	5.2383	0.2930
5	681.5	0.2986	-5.0685		-1786.8	6.3692	0.3562
6	1032.5	0.3099	-4.7459	prime	-1067.6	9.6495	0.5397
7	1201.5	1.6594	9.8287	tierce	-805.2	11.2290	0.6281
8	1675	1.0799	6.0973	quint	-230	15.6542	0.8756
9	1913	0.6379	1.5247	nominal	0	17.8785	1.0000
10	2400.5	1.7907	10.4901		392.9	22.4346	1.2548
11	2769	0.1595	-10.5151	superquint	640.2	25.8785	1.4475
12	3169.5	0.247	-6.7164		873.8	29.6215	1.6568
13	3346	0.21	-8.1259		967.9	31.2710	1.7491
14	3603.5	0.2981	-5.0831		1096.2	33.6776	1.8837
15	4052	0.225	-7.5267		1299.3	37.8692	2.1181
16	4174	0.2025	-8.4418		1350.7	39.0093	2.1819
Min.	107.00	0.16	-10.52		-4992.10	1.00	0.06
Max.	4174.00	1.79	10.49		1350.70	39.01	2.18
Average	1973.72	0.67	-0.94		-590.07	18.45	1.03
STDEV	1398.52	0.57	7.21		1802.42	13.07	0.73

Table 3: Characteristics of Bell Sound from Pataleshwar Temple

No.	Frequency (Hz)	Ampli. (a.u.)	Sound Intensity level (dB)	Partial	Cents	Ratio to lowest freq.	Ratio to nominal
1	150.5	0.9308	2.5587		-4603.3	1.0000	0.0700
2	510	0.6933	0.0000	hum	-2490.5	3.3887	0.2373
3	693	0.7284	0.4290		-1959.6	4.6047	0.3224
4	961.5	0.6587	-0.4447		-1392.7	6.3887	0.4473
5	997	0.6989	0.0699	prime	-1330	6.6246	0.4638
6	1279	0.645	-0.6272	tierce	-898.7	8.4983	0.5950
7	1653.5	0.6139	-1.0565	quint	-454.1	10.9867	0.7692
8	2085	0.3485	-5.9744		-52.7	13.8538	0.9700
9	2149.5	1.4628	6.4853	nominal	0	14.2824	1.0000
10	2331	0.2883	-7.6215		140.3	15.4884	1.0844
11	2403.5	0.5377	-2.2076		193.3	15.9701	1.1182
12	2467	0.5533	-1.9592		238.5	16.3920	1.1477
13	2506.5	0.5701	-1.6994		266	16.6545	1.1661
14	2629.5	1.6258	7.4029		348.9	17.4718	1.2233
15	2754	1.0186	3.3416		429	18.2990	1.2812
16	2848	0.4521	-3.7137		487.1	18.9236	1.3250
17	2934.5	0.3573	-5.7578		538.9	19.4983	1.3652
18	3671.5	0.3046	-7.1438		926.8	24.3953	1.7081
19	4301	0.2762	-7.9940	oct. nom.	1200.8	28.5781	2.0009
20	4606	0.4803	-3.1882		1319.4	30.6047	2.1428
21	4643	0.1635	-12.5481		1333.2	30.8505	2.1600
22	4872.5	0.6138	-1.0579		1416.7	32.3754	2.2668
Min.	150.50	0.16	-7.62		-4603.30	1.00	0.07
Max.	4872.50	1.63	7.40		1416.70	17.47	1.22
Average	2429.41	0.64	-0.33		-197.40	10.83	0.76
STDEV	1370.90	0.36	4.01		1446.59	5.63	0.39

Table 4: Characteristics of Bell Sound from Meneshwar Temple

No.	Frequency (Hz)	Ampli. (a.u.)	Sound Intensity level (dB)	Partial	Cents	Ratio to lowest freq.	Ratio to nominal
1	48	0.4075	-19.1170		-5104.1	1.0000	0.0986
2	194.5	2.2643	-4.2209		-2681.7	4.0521	0.3994
3	244	0.4061	-19.1469	hum	-2289.2	5.0833	0.5010
4	323	3.3735	-0.7579		-1803.6	6.7292	0.6632
5	487	3.6811	0.0000	prime	-1092.7	10.1458	1.0000
6	528.5	16.0294	12.7788	tierce	-951.1	11.0104	1.0852
7	859.5	21.2219	15.2161		-109.2	17.9063	1.7649
8	915.5	8.3236	7.0867	nominal	0	19.0729	1.8799
9	1145.5	4.6363	2.0039		388	23.8646	2.3522
10	1255	4.0133	0.7505		546	26.1458	2.5770
11	1292	3.2296	-1.1366		596.3	26.9167	2.6530
12	1337.5	5.4509	3.4098	superquint	656.2	27.8646	2.7464
13	1452	1.7987	-6.2204		798.4	30.2500	2.9815
14	1584.5	3.6085	-0.1730		949.6	33.0104	3.2536
15	1674.5	4.8624	2.4175		1045.3	34.8854	3.4384
16	1795.5	0.3515	-20.4010		1166.1	37.4063	3.6869
17	2129.5	2.0931	-4.9038		1461.4	44.3646	4.3727

18	2257.5	5.087	2.8097	1562.5	47.0313	4.6355
19	2382	1.2051	-9.6991	1655.4	49.6250	4.8912
20	2471.5	1.4476	-8.1066	1719.3	51.4896	5.0749
21	3069	0.4096	-19.0724	2094.4	63.9375	6.3018
22	3242.5	0.3469	-20.5155	2189.3	67.5521	6.6581
Min.	48.00	0.35	-19.15	-5104.10	1.00	0.10
Max.	3242.50	21.22	15.22	2189.30	33.01	3.25
Average	1394.93	4.28	-0.68	127.12	17.36	1.71
STDEV	921.36	5.14	9.79	1801.73	10.87	1.07

The graphs in Figures 6 to 9 present the dependencies amplitude versus for the recorded bell sounds.

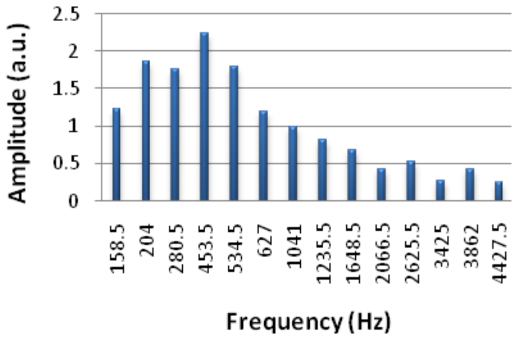

Figure 6: Amplitude dependence on frequency for the recorded bell sound from Kapaleshwar Temple

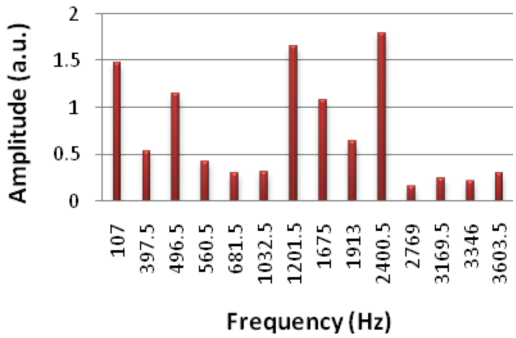

Figure 7: Amplitude dependence on frequency for the recorded bell sound from Kashivishweshwar Temple

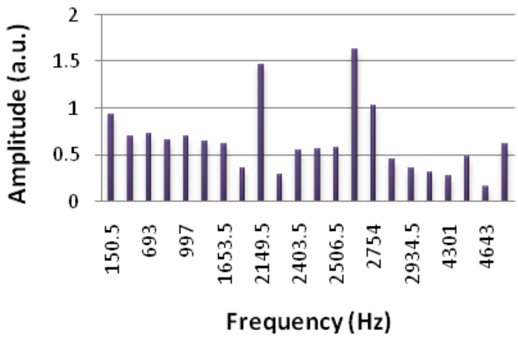

Figure 8: Amplitude dependence on frequency for the recorded bell sound from Pataleshwar Temple

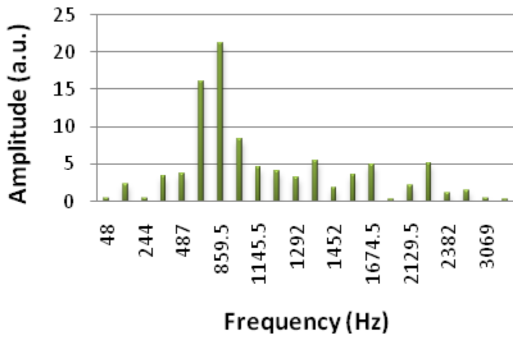

Figure 9: Amplitude dependence on frequency for the recorded bell sound from Meneshwar Temple

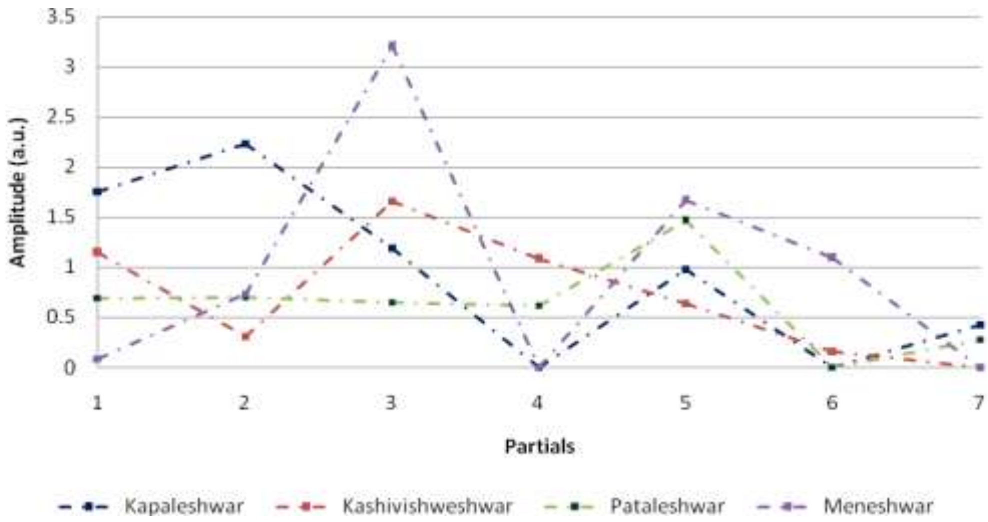

Figure 10 : Amplitude distribution with main partials for all temples

(1: hum, 2: prime, 3: tierce, 4: quint, 5: nominal, 6: superquint, 7: oct. nom.)

The analysis of main partials for the two bell sounds is done in Figure 10. In this, the superimposed plot of amplitude versus frequency is given only for the main partials of recorded sounds for all the temples. In Figure 10, one may notice that there are rather important differences between the amplitudes of the main partials of the analyzed sounds, especially at lower frequencies upto the partial quint beyond which the differences are not considerable. Figure 11 gives the relative standard deviation of amplitude variation with main partials, while Figure 12 presents the percentage deviation of amplitude from mean frequency for each temple. It can be seen that the relative standard deviation is minimum for the hum partial. This implies that the amplitude of sound for all temples is more clustered around the mean amplitude corresponding to hum partial, while the amplitude is more spread in case of superquint. As expected, the nominal stands somewhere in the centre of this deviation. From figure 12 it can be seen that the deviation is excessive in case of Kashivishweshwar and Pataleshwar temples, while deviations are lower for Kapaleshwar and least for Meneshwar. This shows that although the frequency of sound varies but the amplitude is more consistent in case of Meneshwar temple which suggests more hearing uniformity among the devotees present inside the temple.

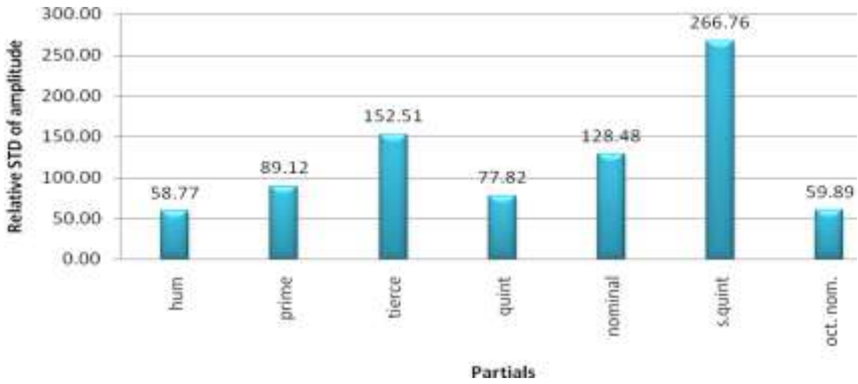

Figure 11 : Relative standard deviation variation for main partials

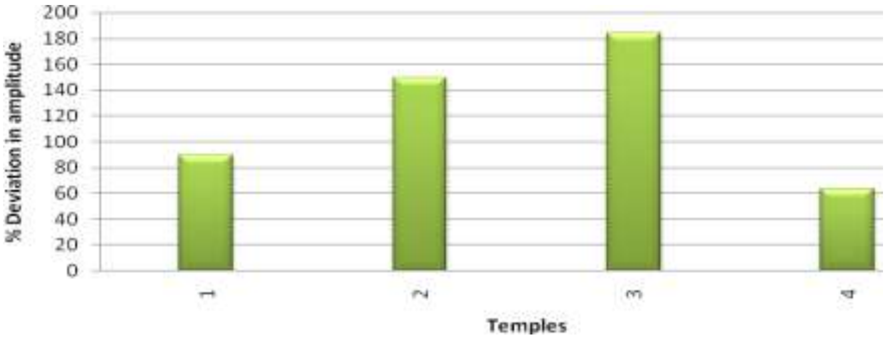

Figure 12 : Percentage Deviation from Mean Amplitude (Temple wise)

(1: Kapaleshwar, 2: Kashivishweshwar, 3: Pataleshwar, 4: Meneshwar)

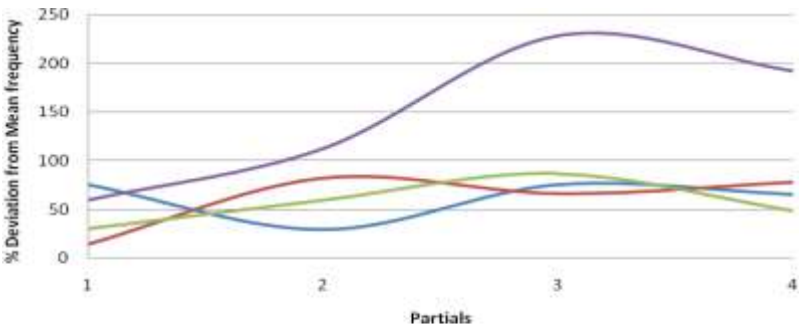

Figure 13 : Percentage Deviation from Mean Frequency (partial wise) for common partials

(1: hum, 2: prime, 3: tierce, 4: nominal)

Figure 13 gives the percentage deviation from mean frequency for the four common partials observed in all temples. It can be seen that the deviation here is maximum for nominal, while it is minimum for hum. It is also seen that partials are slightly separated in frequency, which is not in harmony, because of inevitable departures from perfect symmetry. It is thus evident that the temple bells are not known to have perfect harmonic natural frequencies [14].

V. Conclusion

The sound emitted from bells at Kapaleshwar Temple (Nashik district), Kashivishweshwar Temple, Pataleshwar Temple and Meneshwar Temple (Pune district) were recorded and analyzed by complex analysis program Wavanal. The comparative study ascertained the similarities and differences between the sounds coming from the bells which are similar in structure and dimensions both. The study showed that the main partials are obtained at different frequencies which make the bells sound different in all temples. It is therefore evident that the structure of temples must be playing an important role in overall perception of sound inside temples. An important point to note here is that the deviation in mean amplitude (temple wise) and deviation in frequency (partial wise) both are minimum in case of hum partial in all temples.

The amplitudes and intensities of bell's sounds were also studied and it was found that peaks appear at different frequency values. The complex analysis of sounds presented in this paper proves scientifically that each bell has its unique acoustical characteristics. While manufacturing a temple bell, changes in shape, dimensions, thickness, material used for constructing the bell, the process adopted to manufacture the bell, all of them play an important role to give the acoustical characteristics of the ringing bell. Scientific analysis using complex programs can help to identify such parameters and provide necessary calculations to manufactures to construct proper bells depending on the architecture of temples.

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