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# ANALYSIS OF ACOUSTIC PARAMETERS TO DETERMINE THE APPROPRIATENESS OF TEMPLE ENCLOSURES FOR SPEECH AND MUSIC, REFERENCE TO TEMPLES IN PUNE

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**Abstract:** Worship spaces are amongst the most challenging projects an acoustician can undertake. They are challenging not only because they ought to fulfill expectations of devotees concerning peace of mind, but also because they must appropriately be designed for congregational activities. The analysis of sound emitted by bells from five heritage temples in Pune district of India was performed by means of complex acoustic analysis programs Wavanal and VizIR. The acoustical parameters assessed were reverberation time, early decay time and clarity. Rather than focusing on absolute values, emphasis has been placed on looking at deviations between reverberation time and early decay time. The ratio between the two has been found for all worship spaces. Temples with values of this ratio close to unity refers to a more diffused space, since decay curves in this case are more linear. The values also suggest the distribution and dissipation of sound energy within the worship spaces. The values of clarity of sound obtained indicates appropriateness of worship spaces for speech and/or music. This gives a brief idea about the subjective impression of acoustic quality of these places and further help architects in designing suitable worship places.
**Keywords:** acoustic parameters, reverberation time, early decay time, clarity, diffused spaces

## 1. INTRODUCTION

Acoustic study of spaces deals with the assessment of the distribution and dissipation of sound energy within a certain space. This is accomplished by assessing a set of acoustic parameters defined with respect to their objective and subjective characters. The former correspond to measureable physical parameters which strongly relate to enclosure's architectural characteristics, while the latter correspond to acoustic aspects subjectively acknowledged by a listener. The objective characteristics of a space are in a way interrelated to their subjective ones. The impulse response of spaces may be obtained by computational techniques, which are eventually used to retrieve the most relevant acoustic parameters in order to characterize conveniently the acoustical quality of the space. For temples, there are no pre-defined values of the parameters since architecture of each temple is different. Also, apart from music and speech, temples are meant for mass prayers and worship purposes, for which acoustic characteristics are entirely different, though significant.

Temples are usually meant for individual prayer, mass prayer, meditation, religious speech (like the *Keertana / Pravachana*) and musical performances. The acoustical characteristics for all such activities would have divergent standards keeping in mind the varied expected end effects of acoustical response which should benefit the priests/artists and the devotees alike. The quality of sounds as perceived by a listener essentially depends on four factors:

(1) physical characteristic of sound source (the source here may be a human being, a group of priests and/or devotees, a temple bell, a conch shell or a gong, or all of these sounded simultaneously);
(2) the relative position of the sound source and listener;
(3) architecture of the space (temple);
(4) impact / sensation by the sound stimuli perceived by devotees.

It is possible to quantify the first three parameters objectively, while the fourth factor remains on the boundary of measurements between Physics and Psychology. This is because every individual would have his or her own opinion about the acoustical quality of the space. This depends, to a very high extent, on the sensation of quality of perceived sounds and also on the kind of training an individual has been exposed to in understanding the nature of sound. However, psychologically, it is imperative to measure this factor in order to understand how contented devotees are following a temple visit. Psychoacoustics may prove to be a helping hand here which deals with various characteristics of sound that are related to subjective characteristics of spaces [1][2]. These characteristics may further be related to measureable physical quantities which are considered as objective indicators of acoustic quality of spaces [3][4].

The work done here is aimed at measuring values of reverberation time (RT), Early Decay Time (EDT) and Clarity of sound ($C_{80}$ and $C_{50}$) for bell sounds at few temples namely (abbreviations mentioned alongside names) Siddheswar (SD), Kashivishweshwar (KV), Belbag (BB), Omkareshwar (OK) and Pataleshwar (PE) in Pune district, Maharashtra State in India (Figure 1(a) to 1(e) shows four of these temples with bell photos incorporated). All these temples are heritage temples dedicated to Lord Shiva and material used for construction was mainly stone cut-outs. All the temples have different architectural styles [11][12][13].

These acoustical parameters are basically based on how sound energy is propagated through space in time. These parameters are calculated by using computer software Wavanal and VizIR. The purpose of the bell waveform analysis program (Wavanal.exe) is the analysis of bell sounds using a personal computer. It provides facilities for graphical display of recorded bell sounds, identification of partial frequencies, and synthesis of bell sounds from a list of partials. It allows complete determination of the harmonic character of a bell using the facilities available on any multi-media home PC. It also allows exploration of the way that changing the tuning of a bell changes its resulting sound [5]. VizIR does automatic calculation of acoustics criteria from a .wav impulse response without manual selection of the response time frame [6].

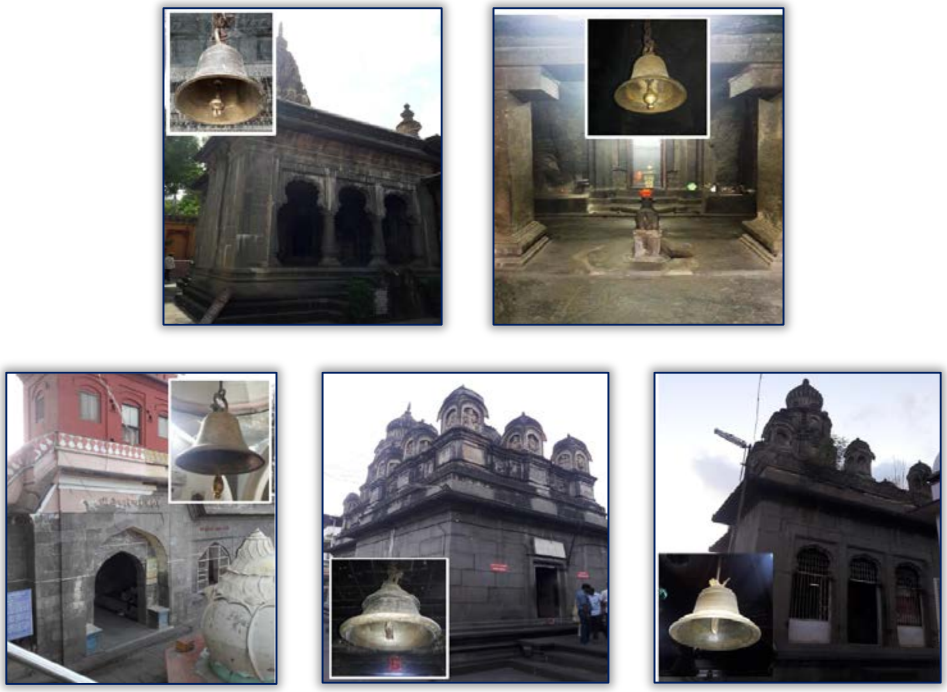

Figure 1: Temples undertaken for the acoustical study (with photos of bells): (a) Siddheshwar Dhom, Pune; (b) Pataleshwar Temple; Pune (c) Omkareshwar Temple, Pune; (d) Kashivishweshwar Temple, Pune ; (e) Belbaug Temple, Pune

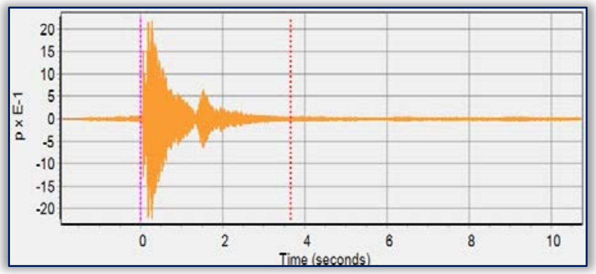


Figure 2 : Impulse Response of bell Sound from Omkareshwar Temple (for 1000 Hz)

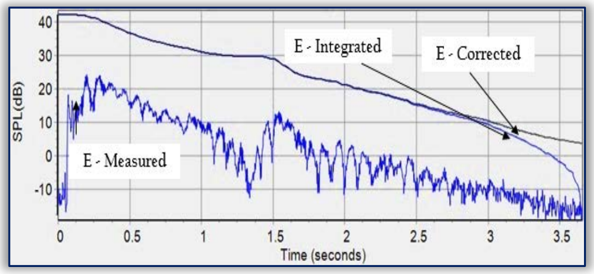


Figure 3 : Decay Curve of bell Sound from Omkareshwar Temple (for 1000 Hz)

## 2. AN ILLUSTRATION OF THE IMPULSE RESPONSE AND DECAY CURVE FOR BELL SOUND IN TEMPLES

Decay curves are obtained by the impulse response method as given by Schroeder [7] which demonstrated that the spectrum of sound energy associated with the average of the infinite decay curves is identical to the energy spectrum associated with the impulse response obtained with a single measurement. In general, a linear fit is performed over the points of the decay curve obtained and the reverberation time, defined as the time necessary for the sound level to decrease by 60 dB. It is given graphically by

$$T = \frac{60}{m}$$

where, m is the rate of sound energy decay given by the slope of the line in dB/s. According to the standard document [8], the linear fit should be performed by using 30 dB decay (in the range of 5 to 35 dB below the stationary state level). That slope is used in the computation of reverberation time, $T_{30}$.

## 3. OBJECTIVE MEASUREMENTS

### — Reverberation, Reverberation time (RT) and Early Decay Time (EDT)

Reverberation refers to persistence of sound in an enclosure after the sound source has been disconnected. The human perception to this phenomenon is quantified by the objective parameter reverberation time (RT). The sensation of 'liveliness' is associated with the reverberation time at mid-frequencies (average of octaves 500 Hz, 1000 Hz and 2000 Hz), although in some enclosures it may be related to the parameter early decay time (EDT). The EDT is an expression of reverberation time but based on the decay from 0 to -10 dB. A 60-dB or even 30-dB decay is rarely encountered in temples if bells are struck continuously or devotees and priests enchant prayers uninterrupted. This is because new notes emerge before the previous notes are decayed. Thus, here EDT is considered to be a good descriptor of reverberance which is the term used to describe the subjective experience of reverberation. The EDT, theoretically, is calculated from the initial slope of the decay trace curve and the decay trace is derived by integration in reverse time of the squared impulse response [9].

— Clarity of Sound

Clarity is a subjective parameter to evaluate the degree of separation of successive sounds and the ability to distinguish between overlapping tones [4]. The usual physical measurement of clarity is the ratio of the energy in the early sound to that in reverberant sound, designated by $C_{80}$ for music and $C_{50}$ for speech. Clarity is a parameter to measure how correctly and definitely the sounds are perceived in an enclosure. It is defined as the ratio between the initial sound energy (early sound) received between the instants 0 and t seconds, and the received reverberated energy after t. It is given by

$$C_t = 10\log\frac{\int_0^t p^2(t)dt}{\int_t^\infty p^2\,(t)dt}$$

where, t is the initial time of sound arrival (early sound) and function p(t) corresponds to the measured impulse response. The clarity parameter influences the intelligibility of the perceived sounds inside enclosures. In the case of speech enclosure, the early sound must be higher than the reverberated energy and $C_{50}$ will be positive. A higher value of $C_{50}$ indicates better intelligibility of speech. In an enclosure meant for music, negative values of $C_{80}$ are acceptable. The value of t is greater for music than that for speech, which means that the part of initial energy, received later (between 50 ms and 80 ms) is still useful for the definition mixture of musical sounds.

Clarity, to a large extent, demands a low reverberation time while sustained loudness calls for a higher reverberation time. According to Barron, the ear's response to low tones in the 125 Hz and 250 Hz octave bands is slow, therefore the objective clarity is usually calculated as an average of values corresponding to 500 Hz, 1 kHz and 2 kHz bands. Clarity is inversely proportional to reverberation.

— Early Decay Time (EDT) compared with Reverberation Time (RT)

To design an enclosure meant for speech and/or music, like a temple, the reverberation time is usually specified based upon the intended sense of reverberation in the enclosure. Using Sabine's formula, then, the appropriate volume of the enclosure may be predicted. However, in case of temples, it is not clear if acoustical characteristics were taken into consideration prior, during or after designing of the temple structure. Also, from a subjective point of view it is necessary to specify the early decay times within a specified range. In temples, therefore, the differences between EDTs and RTs may be quite large, and this paper aims at those temples where these two values are significantly different. In the present time, for design purposes we need to know the causes of significant differences between them.

Table 1 : EDT – RT values for bell sound at Siddheshwar temple

| Criteria | Octave (Hz) | | | | | Mean | Standard deviation | Coeff. of variation of EDT (Relative) |
|---|---|---|---|---|---|---|---|---|
| | 125 | 250 | 500 | 1000 | 2000 | | | |
| T30 | 1.19 | 1.53 | 6.34 | 6.33 | 13.85 | | | |
| T60 | 2.38 | 3.06 | 12.68 | 12.66 | 27.7 | | | |
| EDT | 0.83 | 0.79 | 10.51 | 10.53 | 3.55 | 5.242 | 4.9463 | 0.9435 |
| EDT : T60 | 0.3487 | 0.2581 | 0.8288 | 0.8317 | 0.1281 | 0.4791 | | |

Table 2 : EDT – RT values for bell sound at Pataleshwar temple

| Criteria | Octave (Hz) | | | | | Mean | Standard deviation | Coeff. of variation of EDT |
|---|---|---|---|---|---|---|---|---|
| | 125 | 250 | 500 | 1000 | 2000 | | | |
| T30 | 0.34 | 0.65 | 2.29 | 0.1 | 5.6 | | | |
| T60 | 0.68 | 1.3 | 4.58 | 0.2 | 11.2 | | | |
| EDT | 13.67 | 5.92 | 4.96 | 0.62 | 6.75 | 6.384 | 4.7086 | 0.7375 |
| EDT:T60 | 20.1029 | 4.5538 | 1.0829 | 3.1 | 0.6026 | 5.8884 | | |

Table 3 : EDT – RT values for bell sound at Omkareshwar temple

| Criteria | Octave (Hz) | | | | | Mean | Standard deviation | Coeff. of variation of EDT |
|---|---|---|---|---|---|---|---|---|
| | 125 | 250 | 500 | 1000 | 2000 | | | |
| T30 | 0.23 | 0.1 | 0.13 | 7.4 | 5.33 | | | |
| T60 | 0.46 | 0.2 | 0.26 | 14.8 | 10.66 | | | |
| EDT | 0.62 | 0.71 | 0.63 | 5.86 | 5.24 | 2.612 | 2.6911 | 1.0303 |
| EDT : T60 | 1.3478 | 3.55 | 2.4230 | 0.3959 | 0.4915 | 1.6416 | | |

Table 4 : EDT – RT values for bell sound at Kashivishweshwar temple

| Criteria | Octave (Hz) | | | | | Mean | Standard deviation | Coeff. of variation of EDT |
|---|---|---|---|---|---|---|---|---|
| | 125 | 250 | 500 | 1000 | 2000 | | | |
| T30 | 0.25 | 0.05 | 0.24 | 0.65 | 37.84 | | | |
| T60 | 0.5 | 0.1 | 0.48 | 1.3 | 75.68 | | | |
| EDT | 0.5 | 0.99 | 0.45 | 1.31 | 2.56 | 1.162 | 0.8589 | 0.7392 |
| EDT : T60 | 1 | 9.9 | 0.9375 | 1.0077 | 0.0338 | 2.5758 | | |

Table 5 : EDT – RT values for bell sound at Kashivishweshwar temple

| Criteria | Octave (Hz) | | | | | Mean | Standard deviation | Coeff. of variation of EDT |
|---|---|---|---|---|---|---|---|---|
| | 125 | 250 | 500 | 1000 | 2000 | | | |
| T30 | 0.47 | 0.61 | 0.86 | 0.19 | 1.06 | | | |
| T60 | 0.94 | 1.22 | 1.72 | 0.38 | 2.12 | | | |
| EDT | 1.21 | 1.17 | 2.09 | 0.58 | 6.27 | 2.264 | 2.3034 | 1.0174 |
| EDT : T60 | 1.2872 | 0.9590 | 1.2151 | 1.5263 | 2.9575 | 1.5890 | | |

There are two options to specify the difference between EDT and RT: either to find the difference between the two, or to find the ratio between them [9]. Here we consider the ratio between EDT and RT and name it as EDT-RT ratio, since this appears more appropriate from the point of view of comparison. The mean EDT's for temples divided by their respective reverberation times are plotted in Figure 4. The ratios in Figure 4 are the average for the octaves 500, 1000 and 2000 Hz. The enclosure mean EDT-RT ratios are seen to vary from 0.59 to 1.89; with two of the values below 1 and three values above 1 reaching as high as 1.89. If the full decay in an enclosure is perfectly linear, the EDT and RT are the same. EDT is dependent on enclosure position whereas RT is more stable.

It should be noted here that EDT is a parameter similar to RT, but being only retrieved via the slope of a line fitted to 10 dB decay below the maximum sound level [10]. EDT, however, seems to be particularly sensitive to changes in the geometry of the enclosure.

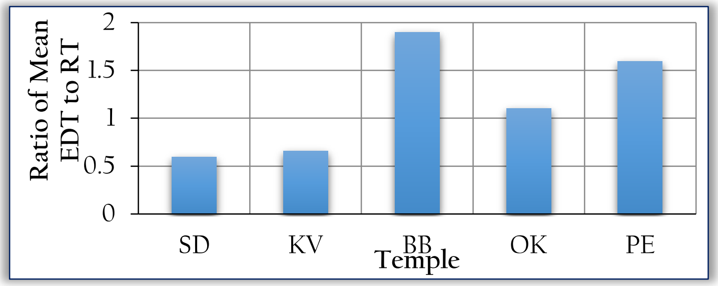


Figure 4: Ratio of mean EDT to RT for all temples taken over frequency octaves 500 Hz, 1kHz and 2kHz

### — Variation in EDT values within temples

For each temple, the standard deviation of EDT values measured has been calculated at each of the five octaves. One expects however a larger spread of EDT values when the mean EDT is larger. For this reason, results are presented here in terms of the standard deviation divided by the mean EDT for each temple. This dimensionless ratio of standard deviation to mean EDT is the coefficient of variation of the EDT is in a way the outcome of the process of normalization done in several other fields like communication; it will however be called here the 'relative standard deviation'. Values of the relative standard deviation at mid-frequencies (that is averaged between 500 and 2000 Hz) are plotted in Figure 5. Typical values for the relative standard deviation are between 0.49 and twice of this value in one of the temples. One would observe that although there is an excessive variation of EDT and standard deviation of EDT in all temples but the variation in relative standard deviation is small and all the values for relative standard deviation fall below 1.

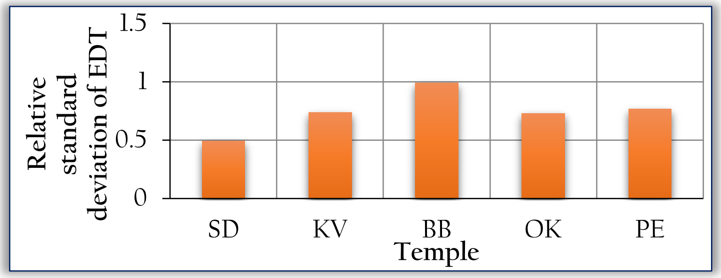


Figure 5: Relative Standard Deviation of EDT for all temples over frequency octaves 500 Hz, 1kHz and 2kHz.

### — Relative Standard Deviation of EDT as a function of frequency

The relative standard deviations of EDT for all temples as a function of frequency (500 Hz, 1 kHz and 2 kHz) are plotted in Figure 6.

Table 6 : Standard deviation and Relative standard deviation of EDT for frequencies 500 Hz, 1 kHz and 2 kHz

| Freq | EDT | | | | |
|---|---|---|---|---|---|
| | SD | KV | BB | OK | PE |
| 500 | 10.51 | 0.45 | 2.09 | 0.63 | 4.96 |
| 1000 | 10.53 | 1.31 | 0.58 | 5.86 | 0.62 |
| 2000 | 3.55 | 2.56 | 6.27 | 5.24 | 6.75 |

| Stdev of EDT | | | | |
|---|---|---|---|---|
| SD | KV | BB | OK | PE |
| 4.024 | 1.061 | 2.948 | 2.691 | 3.152 |

| Relative Stdev of EDT with freq | | | | |
|---|---|---|---|---|
| SD | KV | BB | OK | PE |
| 2.6118 | 0.4241 | 0.7089 | 0.2341 | 1.5736 |
| 2.6168 | 1.2347 | 0.1967 | 2.1776 | 0.1967 |
| 0.8822 | 2.4128 | 2.1269 | 1.9472 | 2.1415 |

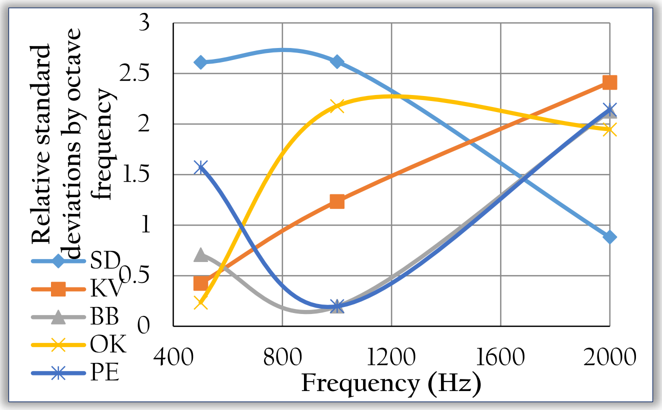


Figure 6 : Relative standard deviation by octave frequency for all temples for 500 Hz, 1 kHz, 2 kHz

It is observed that for three temples, the relative standard deviation value increases at high frequency while for two temples it reduces with frequency. Also, the spread in the relative standard deviation values is more at lower frequency octaves while the spread reduces considerably at high frequencies.

— Differences between EDT and RT values

To establish reasons for differences between EDT and RT values, here we use the parameters $C_{80}$ and $C_{50}$ the early to late sound index, commonly referred to as the 'clarity' of sound. In Figure 7(a) (all five graphs), $C_{80}$ values are plotted against EDT for the mid frequency octaves 500 Hz to 2 kHz, while figure 7(b) (all five graphs) shows the variation of $C_{50}$ values with EDT for the mid frequency octaves. A common observation for all temples is that with increase in early decay time, the early to late sound index goes on decreasing.

$C_{50}$ values are positive when early sound is higher than the reverberated energy, while $C_{80}$ values are generally negative and are defined for enclosures meant for music.

Table 7 : C80 and C50 values for all temples with corresponding values of EDT for frequency range 125 Hz to 2 kHz

| Parameter | Temple | Frequency (Hz) | | | | |
|---|---|---|---|---|---|---|
| | | 125 | 250 | 500 | 1000 | 2000 |
| EDT | SD | 0.83 | 0.79 | 10.51 | 10.53 | 3.55 |
| | KV | 0.5 | 0.99 | 0.45 | 1.31 | 2.56 |
| | BB | 1.21 | 1.17 | 2.09 | 0.58 | 6.27 |
| | OK | 0.62 | 0.71 | 0.63 | 5.86 | 5.24 |
| | PE | 13.67 | 5.92 | 4.96 | 0.62 | 6.75 |
| C80 | SD | 3.14 | 2.33 | -15.8 | -15.81 | -10.67 |
| | KV | 7.86 | 1.59 | 10.57 | 3 | 2.15 |
| | BB | -1.35 | -3.6 | -1.28 | 7.58 | -27.06 |
| | OK | 4.95 | 6.36 | 7.29 | -13.78 | -36.91 |
| | PE | -16.31 | -12.55 | -14.11 | 10.67 | -36.81 |
| C50 | SD | 0.16 | -2.25 | -17.79 | -17.79 | 11.68 |
| | KV | 2.93 | -3.61 | 3.77 | 0.48 | 1.23 |
| | BB | -2.83 | -10.09 | -3.83 | 2.02 | -28.78 |
| | OK | 0.23 | -1.08 | -2.85 | -17.81 | -39.31 |
| | PE | -18.05 | -15.91 | -16.09 | -3.67 | -38.82 |

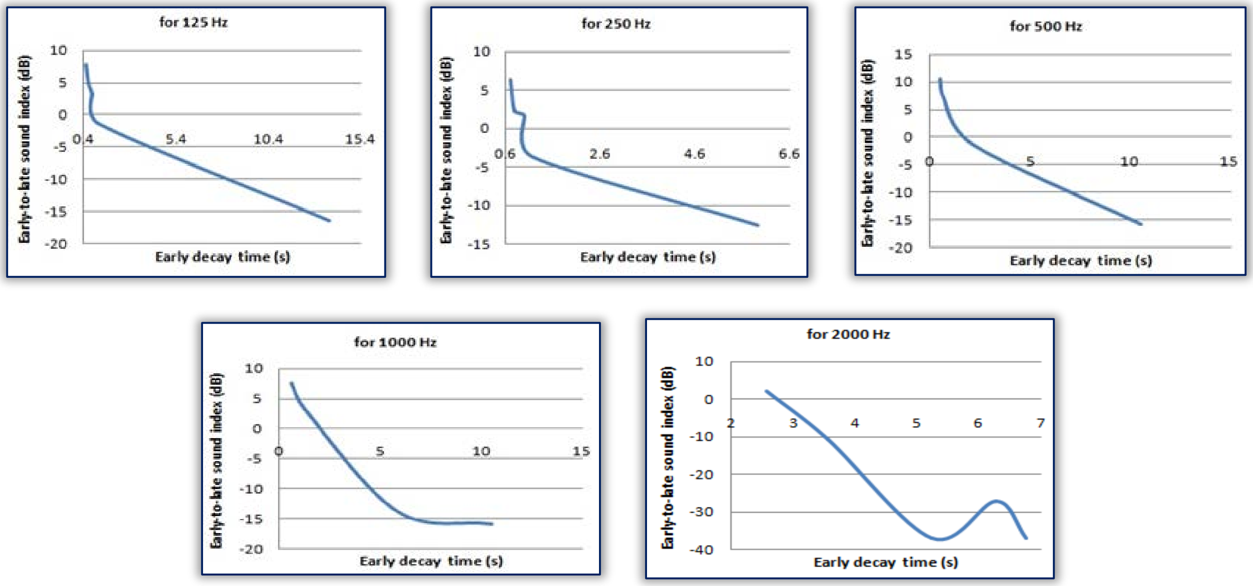


Figure 7 (a) : Early-to-late sound index ($C_{80}$) with EDT for mid-frequency octaves 500 Hz, 1 kHz and 2 kHz

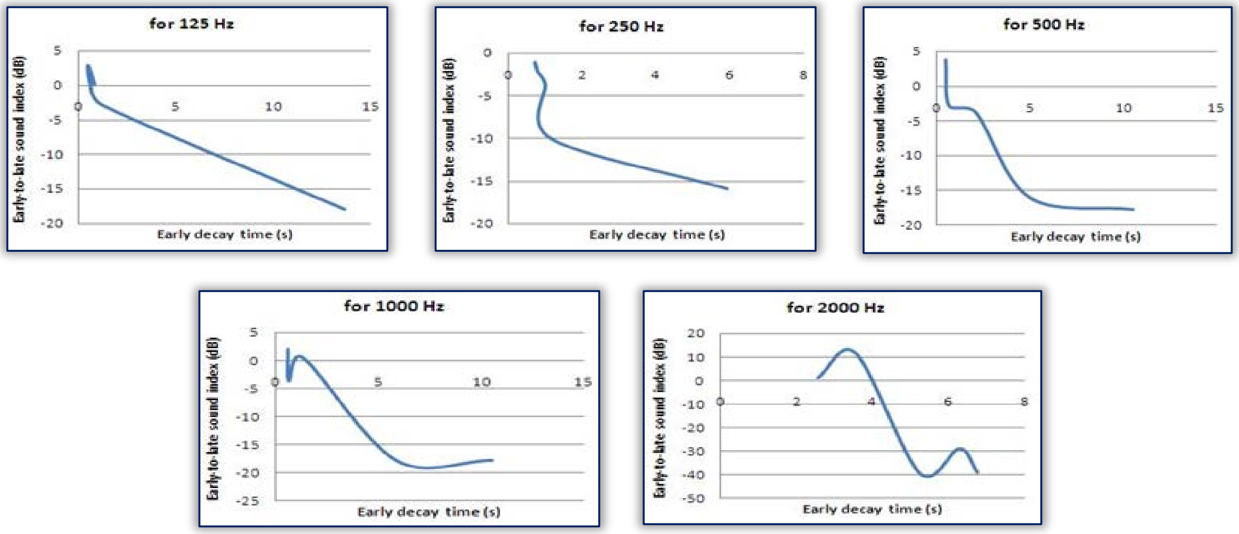


Figure 7 (b) : Early-to-late sound index ($C_{50}$) with EDT for mid-frequency octaves 500 Hz, 1 kHz and 2 kHz

Table 8 : EDT – RT ratio and C80 values comparison for all temples for frequencies 500 Hz, 1 kHz and 2 kHz

| | 500 | | 1000 | | 2000 | |
|---|---|---|---|---|---|---|
| | EDT:RT | C80 | EDT:RT | C80 | EDT:RT | C80 |
| SD | 0.83 | -15.8 | 0.83 | -15.81 | 0.13 | -10.67 |
| KV | 0.94 | 10.57 | 1.01 | 3 | 0.03 | 2.15 |
| BB | 1.22 | -1.28 | 1.53 | 7.58 | 2.96 | -27.06 |
| OK | 2.42 | 7.29 | 0.39 | -13.78 | 0.49 | -36.91 |
| PE | 1.08 | -14.11 | 3.1 | 10.67 | 0.6 | -36.81 |

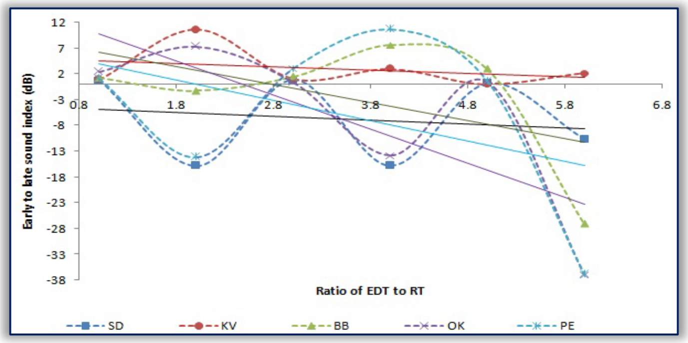


Figure 8 : Early to late sound index vs EDT-RT ratio for all temples for 500 Hz, 1 kHz and 2 kHz

Figure 8 shows the relation between early-to-late index and EDT-RT ratio for all temples in the mid-frequency octaves 500 Hz, 1 kHz and 2 kHz. The curves are also fitted as shown in the figure. It is seen that there is a negative correlation between the early-to-late index and EDT-RT ratio.

## 4. CONCLUSIONS

It is observed that in Siddheshwar Dhom and Kashivishweshwar temples, mean EDT values are shorter than RT. This means that the strongest reflections are coming from large surfaces which do not form the actual temple enclosure. These surfaces are nearby pillars which extend from the floor to the ceilings. Further, in such places, the decay curve must be steep in its first stage and thereafter flatten out and attain a value in accordance with the reverberation time of the enclosures. The entire space inside temples shows a "coupled enclosures effect". This also shows that the early energy is directed more towards the rear side of the temples than on the front side. However, in none of the temples, mean EDT is much smaller than RT and hence, there is always some amount of 'liveliness' in every temple. For Omkareshwar temple, the EDT-RT ratio is close to 1. Thus, the decay curve in this case must be more linear. This shows that this temple space is more diffused, because a diffuse enclosure is characterized by a linear decay. Higher RT values may be accepted for musical performances if the enclosure is well diffused. Figure 5 also shows that in Siddheshwar Dhom and Kashivishweshwar, large part of first reflections are directed towards the devotees in the hall and only a small part reaches the people ringing the bell while in other temples, the sound field is more diffused.

It is observed that Kashivishweshwar temple shows positive $C_{50}$ for most of the frequency octaves whereas Siddheshwar Dhom temple shows negative $C_{80}$ values for most of the frequency octaves.

The authors therefore conclude that out of the temples under consideration, Kashivishweshwar temple is more suited to speech, like prayers or religious preaching whereas Siddheshwar Dhom temple is best suited for activities like musical performances or prayers with musical accompaniments. A high value of the early to late index ($C_{80}$) may be due to either a high level of early sound or a low level of late sound, and either of these may also result in low values for the early decay time. The corresponding causes of high values for the EDT relative to the RT may be due to weak early sound or a high level of late sound.

Future work may include using few suitable materials in combination, though temporarily, to alter the surface coatings of the temples to make temples appropriate for music and speech both, however care should be taken to preserve the heritage temples and not hamper the quality of original materials that were used for construction.

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