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Nondestructive characterization of musical pillars of Mahamandapam of Vitthala Temple at Hampi, India

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This paper presents the first scientific investigation on the musical pillars of the Vitthala Temple at Hampi, India. The solid stone columns in these pillars produce audible sound, when struck with a finger. Systematic investigations on the acoustic characteristics of the musical pillars of mahamandapam (great stage) of the Vitthala Temple have been carried out. The 11 most popular pillars that produce sounds of specific musical instruments are considered for the investigations. The sound produced from these 11 most popular musical pillars was recorded systematically and different nondestructive testing techniques such as low frequency ultrasonic testing, impact echo testing, and *in situ* metallography were employed on the musical columns of these pillars. The peak frequencies in the amplitude spectrum of the sound produced from various columns in these pillars are correlated with the dimensional measurements and ultrasonic velocity determined using impact echo technique. The peak frequencies obtained experimentally have been found to have excellent correlation with the calculated flexural frequencies based on the dimensional measurements and ultrasonic velocities of the columns.

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I. INTRODUCTION

The Vitthala Temple is the most magnificent of the religious edifices at Hampi, one of the world heritage sites in India. The Vitthala Temple stands on the southern bank of the Tungabhadra River and it portrays the high watermark of perfection of the Vijayanagara Kingdom style. The existence of the temple is traced at least to 1422–1461.[1] The temple stands in a large rectangular enclosure (164 m × 94.5 m). One of the unique features of the Vitthala Temple is the musical pillars on the mahamandapam (great stage) of the temple. The mahamandapam of the temple is reported to contain 56 pillars, each 3.6 m high, 40 of which are regularly disposed to form an aisle.[1] The remaining 16 form a rectangular court in the center. Each pillar is a massive composite sculptural unit measuring as much as 1.5 m across and has a group of monolithic sculptures. All the structures in the temple, including the musical pillars, are made of granite stone. The solid stone columns in these pillars produce audible sound, when struck with a finger. The musical columns in the pillars are of different size, shape, length, and width, which make them produce sounds of different musical instruments. It is said that the Bahamani invaders burnt the temple in the 15th century, damaging many pillars. These musical pillars have been a great attraction and surprise for tourists from all over the world. However, no systematic acoustic analysis of these pillars has been reported so far.

The present study is the first attempt to scientifically investigate the acoustic properties of the musical columns in the pillars of the mahamandapam of the Vitthala Temple and correlate them with the dimensional and nondestructive measurements.

II. EXPERIMENTAL DETAILS

The present study is concentrated on the 11 most popular pillars, which are believed to produce sounds of specific musical instruments. The details of these pillars and their locations are given in Table I and Fig. 1, respectively.

A. Dimensional measurements

Details of the locations of the pillars and the musical columns in the pillars were systematically recorded and all the pillars were photographed using a digital camera from various directions to record the details, to assist in analyzing the musical notes from different pillars. Figure 2(a) shows a photograph of the mahamandapam taken from southwest direction showing the pillars and the musical columns in the pillars. The close-up view of one of the musical columns toward the east in pillar 2 (Table I) is shown in Fig. 2(b).

Dimensional measurements were carried out on each musical column of the 11 pillars shown in Table I. The pillars were found to have larger dimension at the bottommost portion and it decreased almost continuously to the minimum at the uppermost portion. The diameter of the columns was measured at the lowest (maximum) and uppermost portions (minimum) by measuring the circumference with 0.5 mm ac-

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TABLE I. Details of the 11 pillars examined in depth.

Pillar number as per Fig. 1	Musical instruments they are correlated to	Number of musical columns in the pillar	Total height range (mm)	Diameter range (mm)	Ultrasonic velocity range (m/s)	Frequency range of the sound produced (Hz)		Average time for decay of amplitude to 1/20 of the peak in autocorrelation function (ms)
						Lower	Higher	
2 (east side)	Saptaswara (seven notes)	8	960–1180	75.6–99.5	5300–5500	243–396	687–1000	226
2 (north side)	···	6+1 (Cut)	960–1140	89–104	5250–5430	296–372	738–967	130
3	Panchtala (five tones)	9	870–950	62.5–100.5	4600–5300	442–588	1046–1280	215
4	Jaltarang (water instrument)	7	880–920	90.0–130	5400–5500	495–780	–	266
5	Mridanga (percussion instrument)	5	910–985	98–106.5	5300–5500	444–457	1148	178 (114–284)
11	Ghanta (bell)	6	910–985	102.7–111.2	5400–5740	533–656	953	500
14	Ghatam (earthern pot, (percussion instrument)	12	1220–1250	102.7–122.5	5300–5600	305–454	774	300
16	Veena (sting instrument)	4	830–980	100.3–106.6	5200–5500	745–821	···	250
24	Tabla (percussion instrument)	10	1115–1120	97.3–107.0	5200–5600	296–407	···	188
3A	Damaru (small percussion instrument)	9	1170–1220	97.1–106.6	5200–5700	273–375	739–786	258
5A	Kerala Mridangam (percussion instrument)	5	1080–1130	115–122	5500–5600	338–412	783–901	295
20A	Shankha (shell)	5	940–1065	95.5–1127.5	5200–5450	399–471	983–1060	332
15A	Damaged				4200	680–760		91

curacy. The total length of the columns was also recorded with the same accuracy. The shape of the columns was also recorded.

B. Nondestructive testing

Different nondestructive testing techniques, i.e., low frequency ultrasonic testing, impact echo testing, and *in situ* metallography were employed on the musical columns. Low frequency ultrasonic testing was carried out to assess the internal structure of the pillar. Impact echo testing was carried out to measure the impact wave velocity in the columns and *in situ* metallography was carried out to identify the material of the column and presence of microcracks, if any.

1. Low frequency ultrasonic testing

A microprocessor-based ultrasonic flaw detector (Panametrics-NDT EPOCH-IV, Olympus NDT Inc., MA, USA) along with a pair of ultrasonic transducers of 500 kHz was used in through transmission mode to inspect the musical columns. One of the transducers was used to generate the sound waves. The transducer was coupled to the musical columns using grease as couplant. The time of travel of ultrasonic waves through the diameter of the columns was determined by observing the arrival of the ultrasonic waves in the receiver transducer, placed on diametrically opposite sides.

2. Impact echo testing

Impact echo technique involves introducing a transient stress pulse into a test object by mechanical impact and monitoring the surface displacements caused by the arrival of reflections of the pulse from internal defects and external boundaries.[2,3] The pulse consists of compression (P) and shear (S) waves that propagate into the object along spherical wave fronts, and a Rayleigh (R) wave that propagates along the surface. The bulk waves are reflected by internal defects and boundaries and the reflected waves propagate back to the surface. At the top surface, the waves are reflected again and they propagate into the test object. Thus a transient resonance condition is set up by multiple reflections of waves between the top surface and internal flaws or external boundaries. The frequency of P-wave arrivals at the transducer is determined by transforming the time domain signal into the frequency domain using the fast Fourier transform technique. The frequencies associated with the peaks in the resulting amplitude spectrum represent the dominant frequencies in the waveform. The specimen thickness or the depth of a flaw,

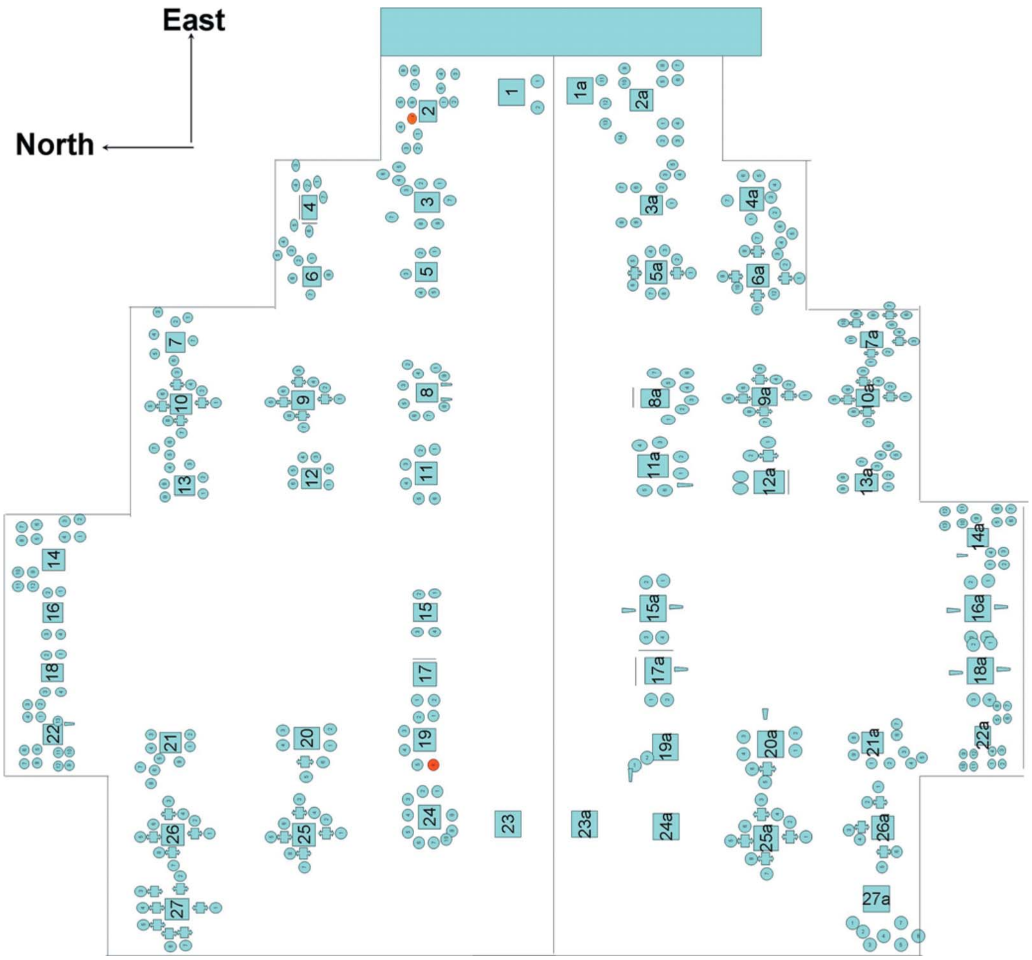

FIG. 1. (Color online) Plan of the mahamandapam indicating the pillars and the musical columns in them.

where waves are reflected between two materials/air interfaces, can be calculated using a simple formula which relates the depth, d, to the frequency of wave reflections, f, and to the P-wave speed, C_P:

$$d = \beta C_P / 2f, \tag{1}$$

where β is a structure factor depending upon the shape of the specimen. For cylindrical structures, β is equal to 0.92.[3]

An in-house developed impact echo system with a commercial receiver was used for measurement of impact wave velocities in the musical columns. Impact wave velocity measurements were carried out on all the musical columns of the 11 pillars mentioned earlier.

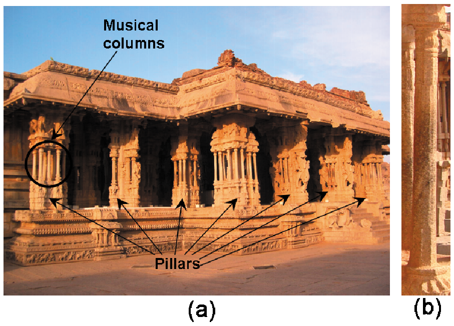

FIG. 2. (Color online) Photograph of (a) the mahamandapam taken from the southwest direction showing the pillars and the musical columns in the pillars and (b) one of the musical columns toward the east in pillar 2 (see Table I).

3. *In situ* metallography

In situ metallographic studies were carried out for identification of the type of material and to study the presence of microcracks/pores, if any, in the musical columns. It was carried out at two locations, i.e., the broken portions of two of the musical columns, one each in pillars 2 and 19. An *in situ* grinding machine was used for polishing the broken surface of the musical columns under continuous flow of water. A replica of the polished surface was taken using a replica tape to observe the features under an optical microscope.

C. Analysis of the sound waves from the musical columns

The sound produced by striking at the center of the musical columns with thumb was recorded in a laptop computer using a capacitor-type computer microphone for each of the musical columns in the pillars. Schematic of the experimental setup for recording the sound waves is shown in Fig. 3. Specific software was developed in LABVIEW with features for recording the sound waves and for online and offline analysis of the sound pattern in time and frequency domains.

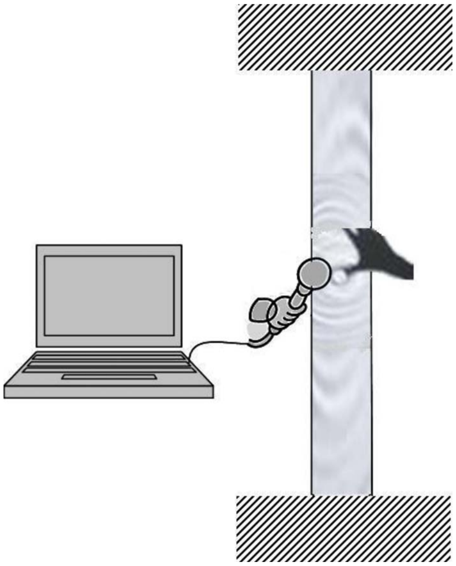

FIG. 3. (Color online) Schematic of recording of the sound produced by tapping on the musical columns with the thumb. Sound is recorded in a laptop computer using a capacitor microphone.

The sound waves were recorded at 22 kHz digitization with 16 bit resolution. A typical time domain signal, the corresponding amplitude spectrum, and the autocorrelation function are shown in Figs. 4(a)–4(c), respectively. Peak frequencies [as in Fig. 4(b)] and amplitude decay rate of the sound produced were analyzed for each of the musical columns. Half the width of the autocorrelation function at 1/20 of the peak amplitude has been used as a parameter related to the decay rate of the sound produced [Fig. 4(c)]. This parameter provides the time required for the decay of the amplitude to 1/20th of the peak amplitude and hence represents the attenuation/damping characteristics of the sound produced in the pillar. A higher value of this parameter indicates lower rate of attenuation/damping in the pillar and hence better coupling of the sound waves. The width of the autocorrelation in place of that of the sound signals is used to avoid error arising from the noise during the recording. Prior to recording the sound waves produced by the musical columns, the quality of the performance of the microphone was verified by recording and analyzing the sound waves produced by using a signal generator and a standard speaker.

III. RESULTS AND DISCUSSION

A. Detailed plan of the mahamandapam

Figure 1 shows the plan of the mahamandapam of the Vitthala Temple showing the placement of the pillars and musical columns in them. The mahamandapam is reported to consist of 56 main pillars.[1] However, only 54 main pillars could be observed during the detailed study, as shown in Fig. 1. These pillars are symmetrically placed on the north and south sides of the mahamandapam. In this paper, the pillars are referred to with numbers as shown in Fig. 1. Out of the 54 pillars, 4 pillars (1, 23, 23A, and 24A) are totally damaged and do not have any musical column now. The remaining pillars consist of different numbers of musical columns in the range of 4–15 numbers in each pillar.

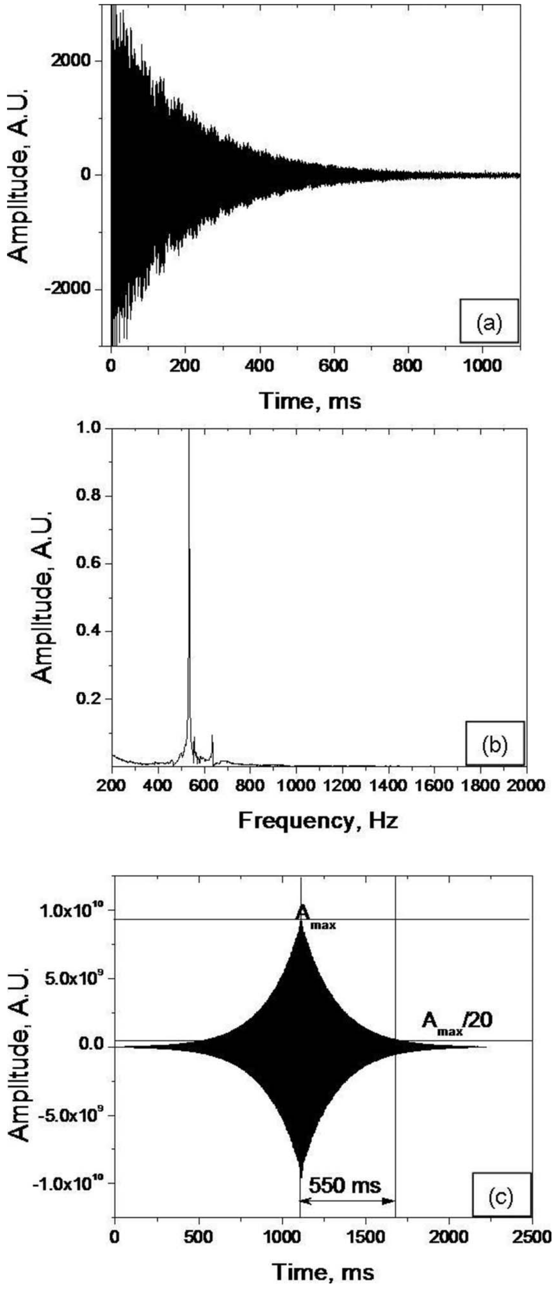

FIG. 4. (a) The time domain signal for the sound produced by tapping on one of the musical columns in pillar 16, which is popularly known to produce the sound of a bell. The amplitude spectrum and autocorrelation function of (a) are shown in (b) and (c), respectively. The time for decay of amplitude to 1/20 of the peak in autocorrelation function is also shown in (c).

B. *In situ* metallography

Figure 5 shows typical microstructures observed on the broken columns in pillars 2 and 19, respectively. The microstructures at both places are found to be similar to that of a typical granite stone.

C. Dimensional measurements

Table I also provides the range of length and the average diameter of each musical column of the 11 pillars. The columns were found to have larger dimension at the bottommost regions and it decreased almost continuously to the mini-

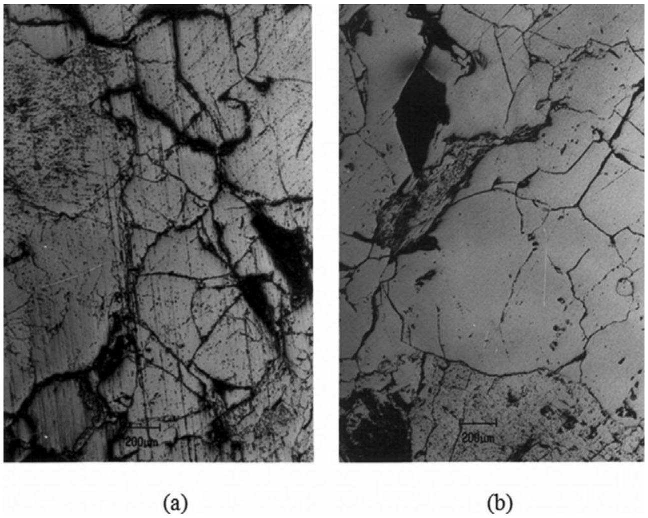

FIG. 5. Typical as polished microstructure in cut surface of the musical columns: (a) Pillar 2 and (b) pillar 19.

mum at the uppermost regions in most of the columns. The maximum variation in the diameter of the columns was found to be about 10% across about 1 m length of the column from the bottom to the top portion. In view of this, the columns are considered as cylindrical and the average diameter is reported and used for all the calculations.

D. Low frequency ultrasonics and impact echo testing

The low frequency ultrasonics and impact echo testing indicated that the musical columns are solid shafts in nature. Ultrasonic velocity in the musical columns is found to be in the range of 4800–5500 m/s in almost all the pillars, as can be seen in Table I. However, ultrasonic velocity in columns of a few of the pillars (pillars 15, 15A, 17) that exhibited damage (presumably by fire) is found to be much lower, i.e., in the range of ~3800 to 4200 m/s.

E. Analysis of the sound produced from the musical columns

The sound pattern for one of the columns of pillar 11 (popularly known to produce the sound of a bell), the corresponding frequency spectrum, and its autocorrelation function are shown in Fig. 4. A detailed analysis of the frequency content of the sound generated in different columns of various pillars has been carried out. The frequency range of the sound generated in different pillars is also given in Table I. In a few of the pillars, frequency corresponding to higher overtone has also been observed, as given in Table I. The average time for decay of amplitude to 1/20 of the peak in autocorrelation function (ms) corresponding to various columns in the pillars is also given in Table I. Proper coupling between the musical columns led to a large duration (~500 ms) of sound waves produced by the columns. The duration of the sound waves corresponding to a damaged pillar, which did not produce any musical sound, is also given in Table I for ready comparison. It can be seen very clearly that the duration of the sound produced is much higher for the pillars producing musical sounds as compared to the damaged one. Further, the duration of the sound is also found to be different in different musical pillars. Pillar 11, which is known to produce the sounds of bells, exhibited the highest duration of sound waves (>500 ms). The sound produced from the columns in this pillar exhibited almost exponential decay of the sound amplitude [Fig. 4(a)], inharmonic component [Fig. 4(b)], and nearby peaks [Fig. 4(b)] in the amplitude spectrum. These are the characteristic features of the bell-like sound.[4] Further, different musical columns in the same pillar produced sounds of different frequencies, usually in an increasing order in a sequence. Hence, when these columns are struck in a sequence, they produce the effect of playing of a musical instrument in increasing tone. A few of the columns, which have rectangular cross section, produce different sounds when struck on the two perpendicular sides. By considering the two moments of inertia in the two perpendicular directions for the rectangular columns, the ratio of the flexural resonance frequencies would be equal to the ratio of the thickness and the breadth (area moment of intertia, $I \propto bt^3$; and $f^2 \propto I$).[5] The frequency of the sound produced by striking the musical columns in the pillars is presumed to be tailored by adjusting the height and diameter of the columns. The correlation among the dimensions, ultrasonic velocity, and frequency of the sound waves generated in different columns is discussed in the following.

F. Correlation among dimensions of columns, velocity, and peak frequencies

For the sake of simplicity in the correlation, the conical (less than 10% variation in diameter over about 1 m length) columns are considered as cylinders. The diameter is taken as the average of the minimum and maximum diameters at top and bottom portions of the columns, respectively. For homogeneous columns with uniform cross section, bending and torsional vibrations can be described by a fourth- and a second-order partial differential equation, respectively. The equation of motion for the bending modes is given by[5,6]

$$EI\frac{\partial^4 y}{\partial x^4} + \rho A\frac{\partial^2 y}{\partial t^2} = 0, \tag{2}$$

where E is the Young's modulus, I $(=\pi D^4/64)$ is the area moment of inertia, ρ is the mass density, A $(=\pi D^2/4)$ is the cross-sectional area and D is the diameter. Here, x is the coordinate in the longitudinal direction of the column and $y(x)$ is the excursion from the rest position of the length element at x. A general solution for Eq. (2) can be written as

$$y(x,t) = (a_1 e^{kx} + a_2 e^{-kx} + a_3 e^{ikx} + a_4 e^{-ikx})e^{i\omega t}. \tag{3}$$

Here, $\omega = 2\pi f$ is the angular frequency and $k = 2\pi/\lambda$ is the flexural wave number. Inserting Eq. (3) in Eq. (2) yields the following generalized dispersion relation:

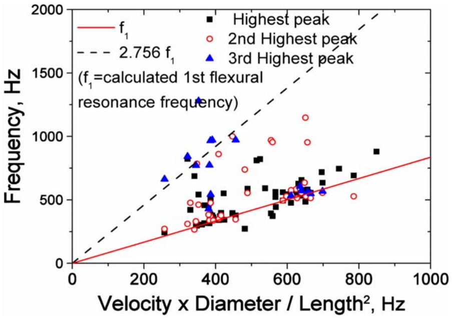

FIG. 6. (Color online) Variations in the peak frequencies with (velocity $\times$ diameter/length^2) for 87 columns in the 11 pillars. Solid and dashed lines show the variations in the first (f_1) and second (f_2) flexural resonance frequencies, respectively, with (velocity $\times$ diameter/length^2) as per Eqs. (8) and (9).

$$EIk^4 - \rho A\omega^2 = 0 \quad \text{or} \quad \omega = k^2\sqrt{\frac{EI}{\rho A}} \quad \text{or} \quad f = \frac{k^2}{2\pi}\sqrt{\frac{EI}{\rho A}} \tag{4}$$

$$f = \frac{k^2}{2\pi}\sqrt{\frac{EI}{\rho A}} \quad \text{or} \quad f = \frac{(kl)^2}{2\pi l^2}\sqrt{\frac{EI}{\rho A}},$$

where, l is the length of the column. As the columns analyzed in the present study are clamped at both the ends, the boundary conditions are

$$y = 0, \quad \frac{\partial y}{\partial x} = 0 \quad \text{at} \quad x = 0, \quad x = L. \tag{5}$$

These boundary conditions lead to the following frequency equation:

$$(\cos kl)(\cosh kl) = 1. \tag{6}$$

For Eq. (6), the first (f_1) and the second (f_2) flexural resonance frequencies can be derived as

$$f_1 = 0.89\frac{D}{L^2}\sqrt{\frac{E}{\rho}}, \tag{7}$$

$$f_2 = 2.7564 f_1. \tag{8}$$

Equation (7) can be reduced to the experimentally measured quantities, i.e., frequency, d, L, and V_L by substituting

$$\sqrt{\frac{E}{\rho}} = V_L\sqrt{\frac{(1+\nu)(1-2\nu)}{(1-\nu)}},$$

where ν is the Poisson's ratio. The values of ν for granites are reported to be in a range of 0.1–0.33.[7] As the ν is not measured experimentally for the columns, ν=0.215 (mean value for granites) is considered for the correlation. Substituting these values in Eq. (7) leads to

$$f_1 = 0.84 DV_L/L^2, \tag{9}$$

where D and L are in meters and V_L is in meters per second.

Based on Eq. (9), the variation in the peak frequency with DV_L/L^2 is plotted in Fig. 6 for 87 columns in 11 pillars. In a few of the pillars, more than one peak (up to three peaks) was observed in the frequency spectra. The frequencies corresponding to the highest amplitude, the second highest amplitude, and the third-highest amplitude are shown as square, circular, and triangular data points in Fig. 6. The average diameter of the top and bottom regions of the column is used in the correlation. For columns with square cross section (about 10 out of 87 columns analyzed), average thickness is used in place of the diameter. For the same range of DV_L/L^2, the calculated first and second flexural resonance frequencies are also plotted in Fig. 6 for ready comparison. The calculated resonance frequencies are found to be in good agreement with those observed experimentally. This indicates that the sound produced in the columns is essentially arising due to the flexural mode of vibrations. The deviations from the calculated frequencies for a few of the columns could be attributed to the structural factors, such as localized damage to the columns, varied shape or diameter over its length, interference from the nearby columns, or varied integrated geometries of the columns with the base and top structures. Further, as the columns can be excited to produce audible sound by striking with the thumb, it indicates that the driving point impedance of the columns is extremely low. This aspect is being investigated separately.

IV. CONCLUSION

This study reports the first scientific investigation on the acoustic properties of the musical columns in the pillars of the mahamandapam of the Vitthala Temple at Hampi, a world heritage site in India. The study was concentrated on the 11 most popular pillars, which are widely known to produce sounds of different Indian musical instruments. Various nondestructive techniques, such as low frequency ultrasonic testing, impact echo testing, and *in situ* metallography, were employed on the musical columns of the pillars. The *in situ* metallography revealed the microstructure of the pillars to be similar to a typical granite microstructure. The low frequency ultrasonic and impact echo testings revealed that all the musical columns are solid shafts. Further, ultrasonic velocity was found to be almost uniform in all the good pillars. The velocity in the damaged pillars is found to be considerably lower as compared to that in the good pillars. The frequency of the sound produced from the musical columns could be correlated well with the calculated flexural resonance frequencies based on the dimensions (height and diameter) and the velocity of the sound waves in the columns.

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