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The Acoustic Raindrop Effect at Mexican Pyramids: The Architects' Homage to the Rain God Chac?

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Summary

Mesoamerican pyramids have been in the center of attention ever since their discovery by westerners because of their architectural beauty, their physical connection to ancient Indian cultures, their relationship to astronomy and religion or simply because of their monumental size and attractive decor for tourist pictures. An acoustic effect first encountered by Declercq (reported in J. Acoust. Soc. Am. 116(6), 3328-3335, 2004) is the raindrop effect. When visitors climb the colossal staircase of Maya pyramids, their footsteps are transformed into sound having distinct frequencies similar to raindrops falling in a bucket filled with water. The current paper reports in situ experiments followed by numerical simulations of the raindrop effect together with a physical explanation. In addition to numerical simulations, a rule of thumb formula is extracted from the calculations that enable the prediction of the acoustic raindrop frequency at any other pyramid in Mexico. If the raindrop effect is a phenomenon that was intentionally incorporated in the construction of the Maya pyramids, such as the pyramid in Chichen Itza, then it was most probably related to the rain god Chac for which there is ubiquitous archaeological evidence decorated on the pyramid itself.

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1. Concise introduction to the acoustics and the cultural-historical background

The purpose of this section is to sketch the background of the studied phenomenon in terms of its general importance in the framework of history and culture.

There are many pyramids in Mexico. They are all step pyramids. Some have distinct different 'floors' (big steps or levels), like the ones at Teotihuacan, others look more like Egyptian pyramids without distinctive 'floors', such as the El Castillo pyramid at Chichen Itza (see right side of Figure 1). The El Castillo pyramid is believed to have served as a temple to the god Kukulkan (the Maya name for Quetzal Coatl), or the feathered serpent, see for example Figure 2. It can be found in the Dresden Codex [1, 2, 3, 4, 5, 6, 7] (kept by the 'Sächsische Landesbibliothek', the state and university library in Dresden, Germany) that the Quetzal Coatl was connected to the Resplendent Quetzal, nowadays Mexico's national bird [8].

Special acoustic effects, where the pyramid produces an echo in response to a handclap, that resembles the chirping Resplendent Quetzal bird, have been studied by a number of scientists, including Lubman [9, 10, 11, 12, 13], Declercq [14, 15, 16], Van Kirk [17], Bilsen [18], Trivedi [19] , Elizondo-Garza [20] and Beristain [21]. The different studies show that there is most likely an acoustic connection between the pyramid's staircase and the Resplendent Quetzal chirp. As Lubman stated, it is as if the staircase forms a recording of the Quetzal chirp. However there are also well-known archeological connections. Indeed the pyramid contains sculptures of plumed serpents running down the sides of the northern staircase.

There are many historical and astronomical reports [22, 23, 24, 25, 26, 27, 28, 28, 29, 30, 31] that focus on aspects not of particular interest to acoustics, that show that the pyramid undoubtedly served as a calendar system connecting astronomical events and bodies to the temporal cycles on Earth.

Observation of the particular shape of pyramids like the El Castillo pyramid also reveals a distinctive mismatch between the staircases and the outermost beauty of the geometrical pyramid that they cover. This is because the in-

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Figure 1. Left: the Coo waterfall in Belgium. Each of the 4 staircases of the El Castillo pyramid look like waterfalls originating from the top of the pyramid. Right: The pyramid of Chichen Itza. Center: the mask of Chac enlarged (pictures taken by Declercq).

clination of the staircases differs from the inclination of the pyramid's walls themselves. What could have been the reason for constructing staircases at a different inclination than the walls of the pyramid? One explanation is that this difference in inclination is made to produce the specific features of the descending serpent during the solar eclipse [32]. However the effect is only visible on one side of the pyramid whereas there are a total of four of such staircases on the pyramid. An unprejudiced person may perhaps see a resemblance between the pyramid's staircases and waterfalls. It is as if the four staircases are solidified waterfalls coming from 4 gates at the top of the pyramid as can be seen in Figure 1. Within that framework, it is interesting to know that, according to Roman Piña [33] Chichen Itza is Mayan for 'at the mouth of the well of the water magician' ('*itz*' means 'magician' and '*ha*' means 'water').

Indeed water has been, and still is, very important for the growth and continuation of civilization on the dry peninsula of Yucatan [34, 35, 36, 37, 38, 39, 40, 41, 42]. There is also archeological evidence for the connection of the El Castillo pyramid to the rain god (or water god) Chac [43]. In fact, a close look at the pyramid uncovers the presence of a mask of Chac on top of the pyramid (on all four sides). This is also shown in Figure 1. There are also other curved elements at two faces of the temple related to the same Deity [44].

Furthermore, Chac was the unification of 4 separate gods based in the four cardinal directions [45]: 'Chac Xib Chac' (or Red Chac of the East), 'Sac Xib Chac' (or White North Chac), 'Ek Xib Chac' (or Black West Chac) and 'Kan Xib Chac' (or Yellow South Chac). These 4 separate gods also correspond to the 4 staircases of the pyramid. Even more, according to Thompson [46] the God Chac is depicted 134 times in the Dresden Codex.

Declercq *et al.* [14] have reported what is now widely known as the 'raindrop effect', a phenomenon which Declercq had discovered, together with a colleague during a visit to Chichen Itza on the occasion of the first Pan-American meeting of the Acoustical Society of America in 2002. If the raindrop would have been an intentional acoustic effect incorporated by the builders of the pyramid, then it is most likely the acoustic fingerprint (or recording) of Chac, the rain god. The effect involves footsteps, produced by people climbing the immense staircase of the El Castillo pyramid, to be transformed into the sound of raindrops falling in a bucket filled with water, at least to an observer seated on the lower stairs of the pyramid. Without any measurement, but with the memory of this particular sound in his mind, Declercq *et al.* [14] mentioned the effect in a paper about the Quetzal echo and produced a preliminary simulation. The simulation showed that the effect was probably due to the diffraction of sound, causing sound of a particular frequency to propagate along the stairs down towards the observer.

The current paper investigates this raindrop effect more thoroughly and compares in-situ recordings with new numerical simulations.

2. Acoustic experiments

The awareness of the raindrop effect originates from December 2002, when Declercq and a colleague were sitting on the lower step of the El Castillo pyramid in Chichen Itza. They heard the sound of raindrops falling in a bucket of water, and not the sound of footsteps, while people were climbing the stairs higher up. We have performed experiments to study the effect quantitatively and found a similar effect if one is sitting higher up and people are climbing the pyramid lower down. The new experiments also reveal that the raindrop effect is actually only detectible very near the surface of the staircase and is best perceived in between the steps.

In what follows, we present the recorded measurements of the 'raindrop effect' caused by two Mexican pyramids: the Moon Pyramid of Teotihuacan and also the El Castillo Pyramid at Chichen Itza. Both pyramids were chosen because of their significant staircase reaching from the base to the top of the pyramid. In each of the experiments we measured the sound in between two of the lower pyramid

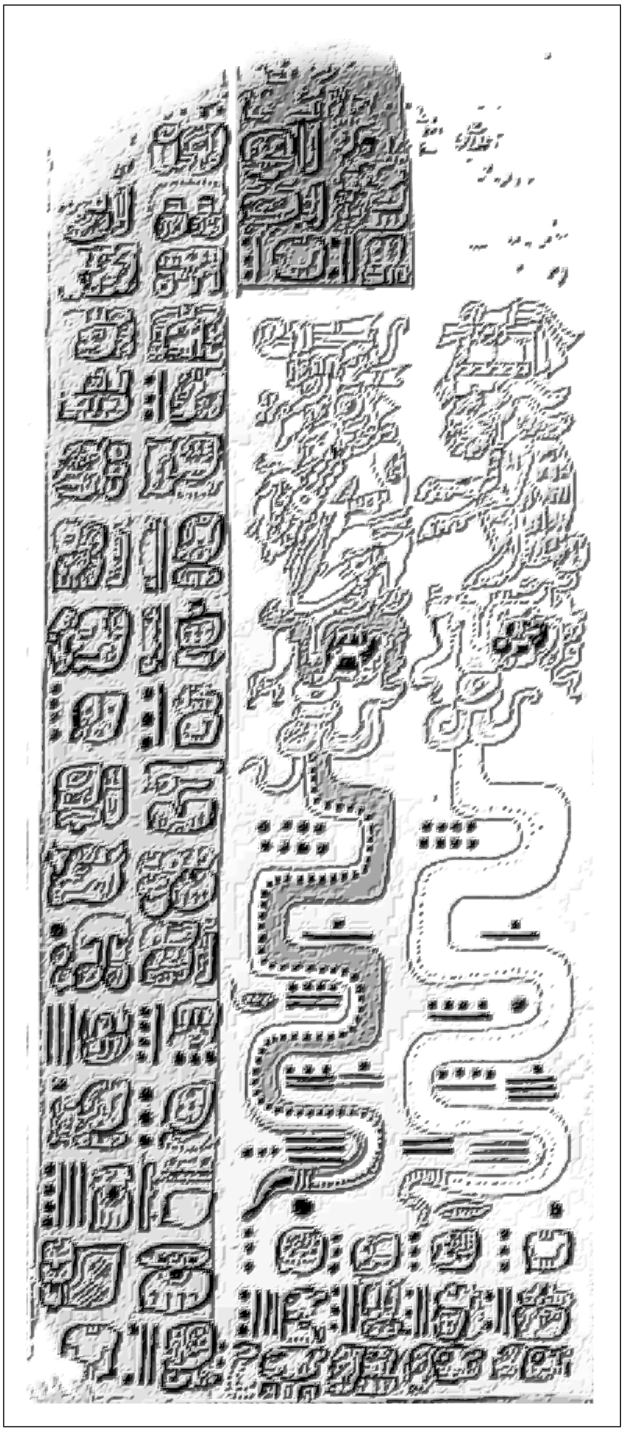

Figure 2. God Chac in Dresden Codex.

steps while a student was climbing the pyramid higher up. All measurements were made during the night in order to avoid interference of sound caused by chirping birds or other visitors.

2.1. Measurements at Teotihuacan

In [14] a value ‘q’ is introduced to characterize the steps of the pyramid and is related to the step periodicity Λ (crucial for the diffraction effect) as $q = \Lambda/\sqrt{2}$. For Teotihuacan, we have measured the steps and found a mean value for the step parameter $q = 0.298$ m.

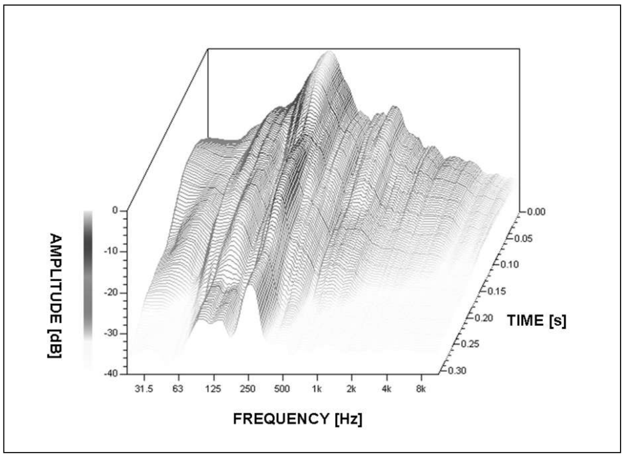

Figure 3. Analyses of the Teotihuacan raindrop effect record: sonogram.

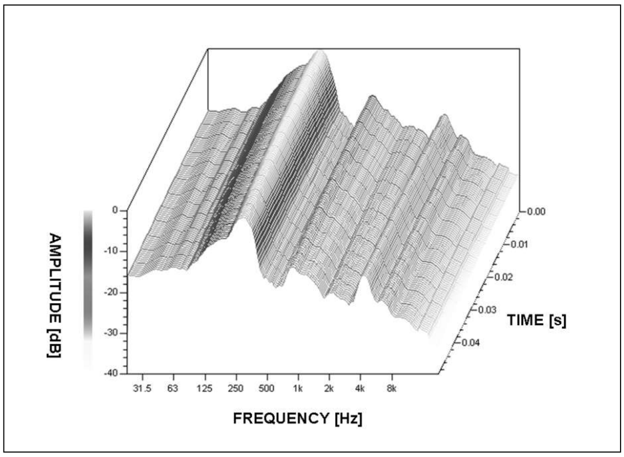

Figure 4. Analyses of the Chichen Itza raindrop effect record: sonogram.

The reported signals were recorded at a sample rate of 44.1 kHz. We have applied a sonogram analysis using Hanning windowing of 8192 samples wide. A sonogram shows the evolution of the frequency spectrum as a function of time.

Figure 3 shows the sonogram of the in situ recorded raindrop pulse at Teotihuacan. The sonogram shows that the main amplitude is situated at 271.86 Hz for all times depicted. The shape of the flanks of that peak is depending on time and so is the overall amplitude. The peak at 271.86 Hz means that the main frequency present in the Raindrop effect is actually 271.86 Hz.

2.2. Measurements at Chichen Itza

For Chichen Itza [14], the mean value for q is 0.263 m. We have followed the same experimental procedure as in Teotihuacan.

Figure 4 shows the sonogram of the in situ recorded raindrop pulse at Chichen Itza. We only show the time interval that highlights the peak as we figured out that the time evolution as given in Figure 3 for Teotihuacan plays a role, but does not change the position of the amplitude peak. The sonogram shows that the peak amplitude is situated at 304.69 Hz.

3. Numerical simulations of acoustic phenomena

We have used the same material parameters as in Declercq *et al.* [14]. Therefore the material properties in the humid Yucatan air have been taken as $\rho = 1.1466\,\mathrm{kg/m^3}$ for the density and $v = 343\,\mathrm{m/s}$ for the sound velocity. Those for the limestone [47] staircase have been taken as $\rho = 2000\,\mathrm{kg/m^3}$ for the density, $v_l = 4100\,\mathrm{m/s}$ for the longitudinal wave velocity and $v_s = 2300\,\mathrm{m/s}$ for the shear wave velocity. Visco-elastic damping effects have not been taken under consideration.

Simulation of the interaction of sound with the staircase is performed using a plane wave expansion technique, i.e. Rayleigh's theory of diffraction [48, 49, 50, 51]. The incident sound field (displacement field) is given by

$$\boldsymbol{N}^{\mathrm{inc}} = A^{\mathrm{inc}}\varphi^{\mathrm{inc}}\left(\mathrm{i}k_x^{\mathrm{inc}}\boldsymbol{e}_x + \mathrm{i}k_z^{\mathrm{inc}}\boldsymbol{e}_z\right). \tag{1}$$

The reflected ($\zeta = r$) and transmitted longitudinal ($\zeta = d$) sound fields are given by

$$N^{\zeta} = \sum_m A_m^{\zeta}\varphi^{m,\zeta}\left(\mathrm{i}k_x^{m,\zeta}\boldsymbol{e}_x + \mathrm{i}k_z^{m,\zeta}\boldsymbol{e}_z\right), \quad \zeta = r, d. \tag{2}$$

Finally, the transmitted shear sound field is written as

$$N^s = \sum_m A_m^s \boldsymbol{P}^{m,s}\varphi^{m,s}, \tag{3}$$

with

$$\varphi^{\tau} = \exp\left[i\left(k_x^{\tau}x + k_z^{\tau}z\right)\right] \tag{4}$$

and

$$k_x^{m,s}P_x^{m,s} + k_z^{m,s}P_z^{m,s} = 0. \tag{5}$$

In order for the sound fields described in (1)–(2) to be the incident and diffracted sound on the air-solid interface formed by the staircase, it is necessary to determine the unknown coefficients A_m^r, A_m^d, $A_m^s P_x^{m,s}$ and $A_m^s P_z^{m,s}$. For this reason we impose continuity of normal stress and normal displacement along the interface. The corrugated surface is given by a function $z = f(x)$. Periodicity of the corrugation yields

$$f(x + \Lambda) = f(x), \tag{6}$$

with Λ the corrugation period. For further use, we define the function $g(x, z)$ as

$$g(x, z) = f(x) - z. \tag{7}$$

Along the interface we have $g(x, z) = 0$.

The stress tensor T^{τ} ($\tau = 1$ in air, $\tau = 2$ the solid), is calculated as

$$T_{ij}^{\zeta} = \sum_{\eta} \lambda^{\tau}\varepsilon_{\eta\eta}^{\tau}\delta_{i,j} + 2\mu^{\tau}\varepsilon_{i,j}^{\tau}, \tag{8}$$

in which λ^{τ} and μ^{τ} are Lamé's constants.

The strain tensor ε^{τ} is calculated as

$$\varepsilon_{i,j}^{\tau} = \frac{1}{2}\left(\partial_i N_j^{\tau} + \partial_j N_i^{\tau}\right). \tag{9}$$

We also incorporate the dispersion relations for longitudinal waves,

$$k^{\zeta} = \sqrt{\frac{\rho\omega^2}{\lambda^{\tau} + 2\mu^{\tau}}}, \tag{10}$$

with = ζ = “inc” or “m, r” and for shear waves

$$k^{\zeta} = \sqrt{\frac{\rho\omega^2}{\mu^{\tau}}}, \tag{11}$$

with $\zeta = s, 2$ for shear waves in the solid.

The dispersion relations (10) and (11) reveal the value of k_z corresponding to each of the values for k_x for the different diffraction orders. The sign of k_z is chosen according to the well-known ‘Sommerfeld conditions’ stating that each of the generated waves must propagate away from the interface and demanding that whenever k_z is purely imaginary (evanescent waves), its sign must be chosen such that the amplitude of the wave under consideration diminishes away from the interface.

Continuity of normal stress and normal displacement everywhere along the interface between air and solid yield

$$\left(\boldsymbol{N}^{\mathrm{inc}} + \boldsymbol{N}^r\right)\nabla g = \left(\boldsymbol{N}^d + \boldsymbol{N}^s\right)\nabla g \quad \text{along } g = 0, \tag{12}$$

$$\sum_j T_{ij}^1(\nabla g)_j = \sum_j T_{ij}^2(\nabla g)_j \quad \text{along } g = 0. \tag{13}$$

Relations (5), (12) and (13) result in 4 equations that are periodical along the x-axis. A discrete Fourier transform with repetition period is eminent and each of the Fourier components on both sides of the equations are then equal to one another.

Straightforward calculations ultimately result in 4 continuity equations

$$\begin{aligned}
&A^{\mathrm{inc}}I^{\mathrm{inc},p}i\left(-(k^1)^2 + k_x^{\mathrm{inc}}k_x^p\right)\\
&+\sum_m A_m^r I^{m,r,p}i\left(-(k^1)^2 + k_x^m k_x^p\right)\\
&+\sum_m A_m^d I^{m,d,p}i\left(-(k^{d,2})^2 + k_x^m k_x^p\right)\\
&-\sum_m A_m^s P_x^{m,s} I^{m,s,p}\left(k_x^P - k_x^m\right)\\
&+\sum_m A_m^s P_z^{m,s} I^{m,s,p}\left(k_z^{m,s}\right) = 0,
\end{aligned} \tag{14}$$

$$
\begin{aligned}
&-A^{\mathrm{inc}} I^{\mathrm{inc},p} \rho_1 \left(k^p - k_x^{\mathrm{inc}}\right) \\
&\quad - \sum_m A_m^r I^{m,r,p} \rho_1 \left(k_x^p - k_x^m\right) \qquad (15) \\
&\quad + \sum_m A_m^d I^{m,d,p} \rho_2 \Big[- k_x^m + \Big(1 + 2\frac{(k_x^m)^2 - (k^{d,2})^2}{(k^{s,2})^2}\Big) k_x^p \Big] \\
&\quad + \sum_m A_m^s P_x^{m,s} I^{m,s,p} i \rho_2 \Big[1 - \frac{k_x^m k_x^p}{(k^{d,2})^2} \\
&\qquad\qquad + \Big(\frac{1}{(k^{d,2})^2} - \frac{1}{(k^{s,2})^2} \Big) (k_x^m)^2 \Big] \\
&\quad + \sum_m A_m^s P_z^{m,s} I^{m,s,p} \rho_2 (k_z^{m,s}) \Big[\Big(\frac{1}{(k^{d,2})^2} - \frac{1}{(k^{s,2})^2} \Big) k_x^m \\
&\qquad\qquad - \Big(\frac{1}{(k^{d,2})^2} - \frac{2}{(k^{s,2})^2} \Big) k_x^p \Big] = 0,
\end{aligned}
$$

$$
\begin{aligned}
&A^{\mathrm{inc}} I^{\mathrm{inc},p} \rho_1 \left(k_z^{\mathrm{inc}}\right) \\
&\quad + \sum_m A_m^r I^{m,r,p} \rho_1 \left(k_z^{m,r}\right) \qquad (16) \\
&\quad + \sum_m A_m^d I^{m,d,p} \left(k_z^{m,d}\right) \rho_2 \Big(- 1 + \frac{2}{(k^{s,2})^2} \left(k_x^m k_x^p\right) \Big) \\
&\quad + \sum_m A_m^s P_x^{m,s} I^{m,s,p} i \left(k_z^{m,s}\right) \rho_2 \\
&\qquad \cdot \Big[\Big(\frac{1}{(k^{d,2})^2} - \frac{1}{(k^{s,2})^2} \Big) k_x^m - \frac{k_x^p}{(k^{s,2})^2} \Big] \\
&\quad + \sum_m A_m^s P_z^{m,s} I^{m,s,p} i \rho_2 \Big[\Big(\frac{1}{(k^{d,2})^2} - \frac{1}{(k^{s,2})^2} \Big) (k_z^{m,s})^2 \\
&\qquad\qquad + 1 - \frac{k_x^m k_x^p}{(k^{s,2})^2} \Big] = 0,
\end{aligned}
$$

$$
\left(A_m^s P_x^{m,s} k_x^{m,s} + A_m^s P_z^{m,s} k_z^{m,s}\right) \delta_{m,p} = 0. \qquad (17)
$$

$\delta_{m,p}$ in (17) is Kronecker's delta.

The grating equation (similar to the one in optics) determines k_x^m and k_x^p as

$$
k_x^\beta = k_x^{\mathrm{inc}} + \beta \frac{2\pi}{\Lambda}, \qquad \beta = m, p \in \mathrm{Z}. \qquad (18)
$$

The Fourier transformation also leaves integrals within the equations (14)–(16):

$$
I^{\mathrm{inc},\eta} = \frac{1}{k_z^{\mathrm{inc}}} \int_\Lambda \exp\left[\mathrm{i}\left(k_x^{\mathrm{inc}} - k_x^\eta\right) x + k_z^{\mathrm{inc}} f(x) \right] \mathrm{d}x, \qquad (19)
$$

$$
I^{m,\zeta,\eta} = \frac{1}{k_z^{m,\xi}} \int_\Lambda \exp\left[\mathrm{i}\left(k_x^m - k_x^\eta\right) x + k_z^{m,\xi} f(x) \right] \mathrm{d}x. \qquad (20)
$$

The integrals (19) and (20) can be solved numerically or analytically.

In other words, an incident plane waves is considered that interacts with the interface. The formulation described above then delivers the amplitudes of the diffraction orders in reflection and transmission. The experiments are performed in the air, therefore we only focus on the numerical results for the reflection amplitudes A_m^r as a function of the frequency.

In [14] Declercq *et al.* have numerically estimated the frequency of the raindrop effect, applying the described procedure, for sound diffracted by means of sound perpendicularly incident on the staircase. For Chichen-Itza they found a result of 920 Hz. Given the measurements reported in the current paper, this has clearly been an overestimation of the exact frequency. At that time there were no measurements to compare with except for a memory of what Declercq had experienced when he visited Chichen Itza. It was mentioned [14] that the actual footstep must be far more complicated than a normal incident sound wave, still for simplicity only normal incident waves were considered. Furthermore the numerical results were only considered valuable in that range of frequencies where evanescent waves turn into bulk waves because it was believed that the raindrop effect was actually caused by skimming bulk waves in air.

New numerical simulations, having the new experimental results in mind, show that we should not focus on skimming bulk waves, but on evanescent waves (surface waves) and that we should not limit the simulation to perpendicularly incident sound but extend it to oblique incident sound. Indeed, the new experimental observations have shown that the raindrop can only be observed very near or even in between the stairs; therefore it is likely that evanescent waves are involved. Furthermore a footstep on a stair is actually directing sound perpendicular to the stair itself and not perpendicular to the staircase. Therefore oblique incident sound waves must be considered in order to study the effect. For obliquely incident sound, we found that the threshold frequency corresponding to the transition from evanescent waves to bulk waves, is lower than for perpendicularly incident sound but this frequency is still too high compared with the experiments. If however we do not limit our study to (skimming) bulk waves and if we also consider evanescent waves, it is interesting to study the amplitude of these evanescent waves. For that purpose Figure 5 shows the numerical result for the diffracted zero order sound waves and also the diffracted first order sound waves. As expected the zero order diffracted waves show an amplitude drop at the threshold frequency where the first order diffracted waves turn from evanescent waves into bulk waves. A similar effect was also seen in the simulations for normal incidence reported in [14]. The first order diffracted waves are evanescent for low frequencies and within that evanescence regime they show considerable amplitude values for certain frequencies. The amplitude peak for the first order diffracted waves at Chichen Itza was found to be 308.70 Hz and 272.55 Hz at Teotihuacan if we consider an angle of incidence of 85 degrees measured from the direction perpendicular to the staircase. As a matter of fact, the peak positions were almost unchanged for angles around the almost grazing angle of incidence of 85 degrees and were significantly increased for smaller angles (80 degrees or less). If we compare these results with the experimental values, we find rather good agreement. It actually means that it is precisely that portion of the incident sound generated at around 85 degrees

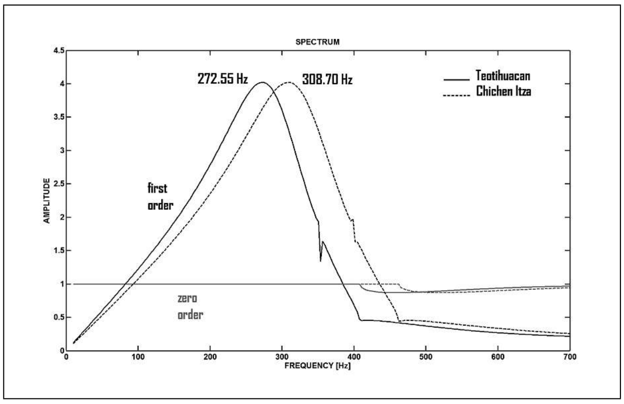

Figure 5. Estimated frequency for raindrop effect in Chichen Itza and Teotihuacan pyramids.

that causes evanescent surface waves to be originated that pass the pass-band staircase and result in 'transmitted' frequencies corresponding to the raindrop frequency and are detected by the observer.

The reported numerical simulations are based on the grating equation, but also on the continuity of normal stress and normal displacements on the corrugated surface. Therefore if we want to predict the raindrop frequency for any given pyramid, we must perform the entire calculation and then find the peak value of the amplitude of first order sound. There is however a rule of thumb possible to estimate the raindrop frequency, if we ignore dispersion effects of evanescent waves. In Figure 5, we clearly see that the shift of the peak is comparable to the shift of the threshold frequency where 'evanescence' turns into 'skimming bulk'. We know [52, 53, 54, 16] that the threshold frequency is determined by the dispersion equation of sound in air and by the grating equation. For first order diffracted sound, this results in (1)

$$f_{\text{treshold}}\left(1 - \sin\theta^{\text{inc}}\right) = \frac{v_{\text{air}}}{\sqrt{2}q}, \tag{21}$$

with f_{treshold} the threshold frequency, for θ^{inc} the angle of incidence and for v_{air} the sound velocity in air. The formula is extendable to any skimming wave (not just a skimming bulk sound wave in air at the threshold frequency) generated at its corresponding frequency. If we suppose that the evanescent wave that is responsible for the raindrop effect, has a velocity that does not depend on the step periodicity of the staircase, i.e. if we ignore dispersion effects, then we find

$$fq = f'q'. \tag{22}$$

Indeed, if we take the example of Chichen Itza, then $q = 0.263m$ and the simulated raindrop frequency is $f = 308.70$ Hz. If we enter $q' = 0.298m$ (corresponding to the Teotihuacan pyramid), we find a raindrop frequency for Teotihuacan of $f' = 272.44$ Hz, which corresponds almost perfectly to the raindrop frequency of 272.55 Hz found in the exact simulations. Equation (22) is likely to predict the raindrop frequency accurately, at least when dispersion effects for evanescent waves are ignored. From our experience with the plane wave expansion technique we know that dispersion can be ignore in those situations where the plane wave expansion technique is valid, i.e. when the wave length of sound in air is of the same order of magnitude as the step periodicity and the step height. The transition from evanescent to bulk waves naturally occurs in the regime when the wave length of the first order diffracted waves (bulk or evanescent) have a wave length comparable to the step periodicity. Therefore it is right to assume that formula (22) is valid for any pyramid in Mexico because the second condition of validity of the plane wave expansion technique, is always fulfilled since the step heights is always almost equal to the step periodicity. The raindrop frequency can therefore be predicted in confidence by formula (23) which may be useful to other acousticians or archeologists.

$$f_{\text{raindrop}} = \frac{81.1881}{q}. \tag{23}$$

Formula (23) is accurate for limestone staircases where the step height is of the same order of magnitude as the step periodicity.

The velocity corresponding to the raindrop effect can be calculated by means of the grating equation as

$$v_{\text{raindrop}} = \left(\frac{\sin\theta^{\text{inc}}}{v_{\text{air}}} + \frac{1}{qf\sqrt{2}}\right)^{-1} \tag{24}$$

If we enter the properties for Chichen Itza, we find a velocity for the raindrop effect, measured along the staircase, of 122 m/s. Since formula (23) predicts the results very well for the Teotihuacan pyramid as well, we may assume that the raindrop effect on pyramids under similar conditions (steps made of limestone, air around humidity and temperature as in Chichen Itza) propagates along the staircase at the same velocity.

4. The raindrop effect is not caused by the hollowness of the pyramid

It is known that some pyramids are hollow, including the El Castillo pyramid at Chichen Itza. Hollowness of the pyramid may also cause a distinct sound, at much lower frequencies than the raindrop effect, when hit by heavy tools, similar to hitting a brick wall with a heavy hammer. First of all, the effect described here is not due to hollowness because we have encountered the effect both at hollow and solid pyramids. In addition, if hollowness was the cause, it would be heard in all directions; contrary to a typical diffraction effect like the raindrop effect, which causes the phenomena only to be heard at skimming angles. Furthermore the sound would not be 'trapped' by the staircase, as with the evanescence of surface waves, but would also propagate away from it, which is clearly not the case.

Hence it is clear that acoustic effects caused by the hollowness of the pyramid, if they exist, are totally different from what is described here.

5. Conclusions

After an introduction to the pyramid of Chichen Itza and after recalling the existence of a Quetzal echo at the pyramid, we studied the raindrop effect. We explained how this raindrop effect may have been related to the rain god Chac because the latter is depicted several time on the pyramid. Then we presented in situ experiments and indicated the measured frequencies of the raindrop effect at Chichen Itza and also Teotihuacan. Consequent numerical simulations showed that the effect is due to evanescent waves along the staircase propagating at a velocity of 122 m/s. Astonishing agreement between the experimentally found frequencies and the numerically obtained frequencies led to the formulation of a rule of thumb useful to predict the raindrop frequency for any similar Mesoamerican pyramid as long as dispersion effects do not play a significant role for the evanescent waves, which is most likely the case for all Mexican pyramids since the height of the steps is always of the same order of magnitude as the periodicity.

As a final conclusion we would like to highlight that only specific archeological evidence may ever prove whether acoustics played a role in Maya culture [46, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64]. Up until now there are only so called archeological ‘indications’ found, mentioned in this paper, together with acoustic effects that are currently under investigation. The Mexican pyramids, with some imagination, can be considered musical instruments dating back to the Mayan civilization, but we have no evidence that the Mayans have ever played them…

At other locations, mainly at Epidaurus in Greece, there is real evidence of ancient architectural structures for which it is much more likely that they have been constructed mainly according to acoustic principles and for the reason of acoustic performances [48, 65].

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