SHOCK WAVES AND THE SOUND OF A HAND-CLAP — A SIMPLE MODEL

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The aerodynamics of the impact between two human hands in a hand-clap is examined, in particular in relation to the hand profile which may be either nearly complementary between the two hands, giving a nominally flat impact, or else domed so that there is a significant enclosed volume. It is shown that shock waves are generated in nearly all hand-claps, with the addition of a Helmholtz-type resonance in the case of domed impacts. As can be judged by simple listening, a flat clap produces broad-band sound that typically extends to about 10 kHz while the spectrum of a domed clap usually has a subsidiary maximum somewhere below 1 kHz and then declines with frequency more rapidly than does the flat clap.

INTRODUCTION

While the Zen koan of 'the sound of one hand clapping' aims to encourage meditation, the practical human two-hand-clap is an emotive communication gesture used in many gatherings such as concerts or lectures. A brief experimental study shows that the sound can vary from a dull thud through a low-frequency pulse to a sharp high-frequency snap, selection between these sounds being controlled by the shape of the hands on impact. A simple semi-quantitative examination of the impact dynamics shows that, for those configurations of the hands that produce a loud sharp sound, the generation of shock waves is involved. It is the purpose of the present brief paper to examine this process.

There is little in the way of previous studies to refer to, despite the ubiquity of clapping. A 1987 study by Repp [1] examined the sound spectra for different hand configurations, but concentrated on perceptual psychophysics rather than on physical acoustics. A later study by Hargather et al. [2] noted the presence of shock waves in some handclap sounds and examined them by schlieren photography, but again did not investigate the underlying physics.

VARIETIES OF IMPACT

While the surface profile of the human hands is rather complex, a quick self-experiment shows that, in order to produce a loud sound as is generally desired, the two hands are oriented so that the more protuberant part of the profile — the ridge below the fingers or the fingers themselves — is brought into collision with the recessed palm of the other hand. Because the flesh of the hand is softly elastic, the collision is generally terminated by complete contact over the impact area, though it is possible to arch the hand so that some enclosed cavity remains. The flesh of the hands is also sufficiently damped by its cellular structure that acoustic vibration of the solid structures can be ignored, so that sound production is entirely due to the enclosed air.

Since the hands are not flat, there are several possible simplified geometries of this enclosed air, as shown in Figure 1.

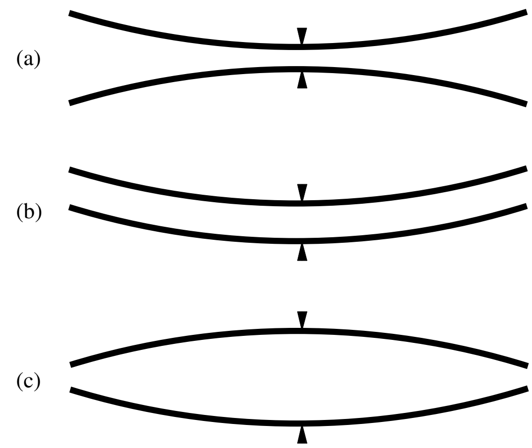

Figure 1. Three simplified geometries for impact of two hands during a clap. (a) very little sound produced, (b) a sharp clap sound with no resonance, (c) a sharp loud clap with a low-frequency resonance. There may be vents left at the edges.

If the hands are brought together where both surfaces are convex, as shown in Figure 1(a), then experiment shows that almost no sound is generated. If the relative positions and orientations of the hands are chosen so that the surface shapes are complementary, as in Figure 1(b), then the sound is a sharp high-frequency snap with no audible resonant component. If, however, the hands are cupped as in Figure 1(c), then there is a sharp sound with emphasized low-frequency components, the central frequency of which can be altered by adjusting the curvature of the hands, and thus the enclosed cavity volume, and also perhaps the geometry of the exit opening.

DYNAMICS OF A FLAT IMPACT

While the hand surfaces are generally somewhat curved, as idealized in Figure 1, any matching curvature of the two hands, as in Figure 1(b), has very little acoustic effect. An initial simplified model can therefore consider the impact of two planar surfaces in order to approximate the actual sound from a sharp clap. This model can then be modified to incorporate an enclosed volume that does not collapse under the force of the impact. These two possibilities will be considered in order.

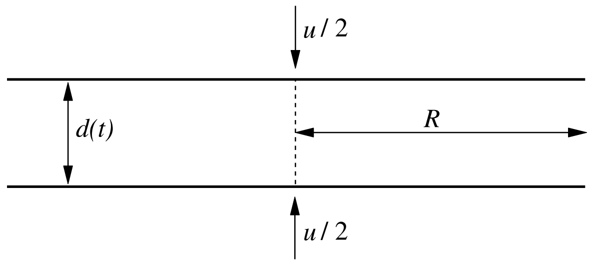

Figure 2. Simplified geometry for a planar-impact clap. Two circular planes of radius R are approaching each other at speed u.

Consider the simple case of two rigid circular plates of radius R moving towards each other along their common axis with velocity u as shown in Figure 2. Ignoring compression for the moment, when the spacing between the plates is d the air between them is expelled from the cylindrical ring around their edges at a speed v where

$$v = \frac{\pi R^2 u}{2\pi R d} = \frac{Ru}{2d}. \tag{1}$$

If the initial spacing between the plates at time $t = 0$ is d_0, then this can be written

$$v = \frac{Ru}{2(d_0 - ut)} \tag{2}$$

which reaches the speed c of sound in air after a time

$$t_0 = \frac{d_0}{u} - \frac{R}{2c}. \tag{3}$$

For an exit speed v significantly less than the speed of sound c, the excess pressure Δp between the plates can be described by the Bernoulli equation

$$\Delta p = \frac{\rho v^2}{2} = \frac{\rho R^2 u^2}{8d^2} = \frac{\rho R^2 u^2}{8(d_0 - ut)^2}. \tag{4}$$

For simplicity we assume this equation to apply up to the speed of sound. Using the assumed data in Table 1 gives a pressure of 120 Pa when the disc spacing is 1 mm, rising to 12 kPa for a spacing of 0.1 mm. Such a narrow uniform spacing is unrealistic, particularly for a handclap, and one might consider a configuration in which only a fraction β of the vent perimeter remained open near the conclusion of the clap. This would raise the exit velocity by a factor $1/\beta$ and so raise the internal pressure by a factor $1/\beta^2$ which could easily be greater than 10 and increase with time. The pressure in the cavity between the plates thus rises increasingly rapidly with time, as also does the exit airspeed until it reaches the speed of sound.

When the exit speed v reaches the speed of sound c, not all the compressed air escapes and the excess pressure Δp between the discs increases more rapidly. The rate of decrease of the cavity volume is $\pi R^2 u$ and the rate of escape around the edges is $2\pi Rcd$. If p_0 is normal atmospheric pressure and $\gamma \approx 1.4$ the adiabatic constant for air, then the rate of pressure rise in the cavity is approximately

$$\frac{d\Delta p_2(t)}{dt} \approx \gamma p_0 \left(\frac{\pi R^2 u - 2\pi Rcd}{\pi R^2 d} \right) \tag{5}$$

where the subscript 2 has been used for this approximation. Using the result in equation (2) then gives

$$\frac{d\Delta p_2}{dt} \approx \gamma p_0 \left(\frac{u}{d_0 - ut} - \frac{2c}{R} \right). \tag{6}$$

Integrating this expression over the time range from t_0 to t gives

$$\Delta p_2(t) \approx \gamma p_0 \log \left(\frac{d_0 - ut_0}{d_0 - ut} \right) - \frac{2\gamma p_0 c(t - t_0)}{R}. \tag{7}$$

This equation (7) has $\Delta p_2 = 0$ at the changeover point $t = t_0$, which is clearly not correct, but a more realistic solution is that

$$\begin{aligned} \Delta p(t > t_0) &= \Delta p_1(t_0) + \Delta p_2(t) \\ &\approx \Delta p_1(t_0) + \gamma p_0 \log \left(\frac{d_0 - ut_0}{d_0 - ut} \right) - \\ &\quad \frac{2\gamma p_0 c(t - t_0)}{R} \end{aligned} \tag{8}$$

for $t > t_0$. This gives a smooth transition between the subsonic and supersonic regimes at $t = t_0$. The prediction of the combined equations (4) and (8) is plotted in Figure 3 for the arbitrary but realistic set of parameter values shown in Table 1.

Table 1. Model parameters

Cavity radius	R	3 cm
Initial spacing	d_0	1 cm
Impact speed	u	1 m/s
Closing time	d_0/u	10 ms
Supersonic onset time	t_0	9.96 ms
Duration of shock wave		0.04 ms

When this prediction is compared with a sound recording using real human hands, however, a new phenomenon appears, as shown in Figure 4. The smooth increase in pressure in the initial part of the graph agrees at least qualitatively with equation (4), and there is then a sudden change to a plateau of duration about 1 ms and then a broadband oscillatory signal with maximum frequency around 10 kHz and with a duration of about 5 ms. A possible explanation for this behavior is that the plateau is the duration of a simple shock wave exit and the subsequent oscillation is due to propagation of shock waves across the rather irregular geometry of the space between the hands. Depending upon the geometry of the closing hands, there are normally a few passages and apertures of about 5 mm height upon impact, and for a closing speed of about 1 m/s this implies an oscillation duration of about 5 ms, which is in approximate agreement with the measurements in Figure 4. From this figure the peak spacing in the waveform is about

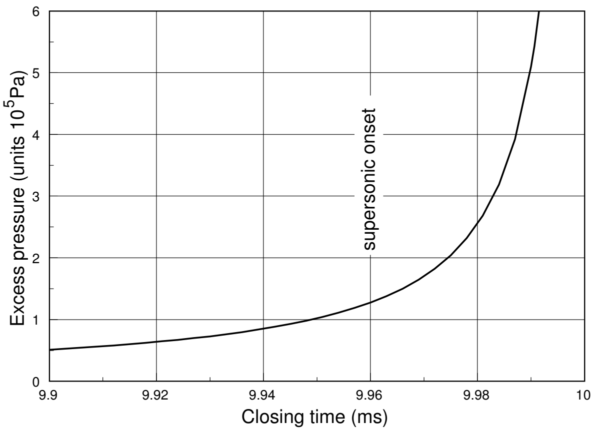

Figure 3. Increase in pressure between flat hands for the parameter values in Table 1. Normal atmospheric pressure is about 10^5 Pa.

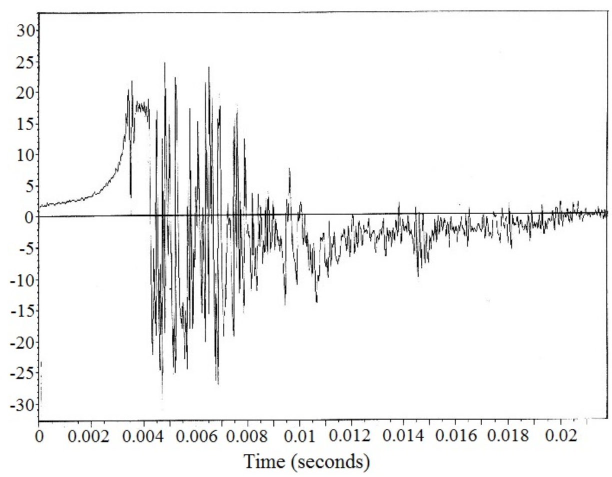

Figure 4. Waveform for a flat clap between two hands. The amplitude scale is arbitrary but the scan duration is 22 ms.

1 mm which corresponds to a time duration of about 0.2 ms. Since the irregular shallow cavity between the hands is typically about 6 cm in diameter, consideration of a circular wave approximation [3] suggests resonance frequencies of about 4, 10, 15, ... kHz, each of these being greatly broadened by the irregular shape of the cavity. Spectral aspects of the flat impact will be considered after discussion of the dynamics of a cupped impact in the next section.

DYNAMICS OF A CUPPED IMPACT

When we consider the impact of two cupped hands, as in Figure 1(c), the geometry of the impact is of greater significance. Generally the two hands will make an initial impact that leaves an opening of moderate size in one place, so that shock waves are not generated at this stage. The geometry is then essentially that of a Helmholtz resonator with volume V vented through an opening with cross section S and effective wall thickness l. This has a resonance frequency

$$f = \frac{c}{2\pi}\left(\frac{S}{Vl}\right)^{1/2} \tag{9}$$

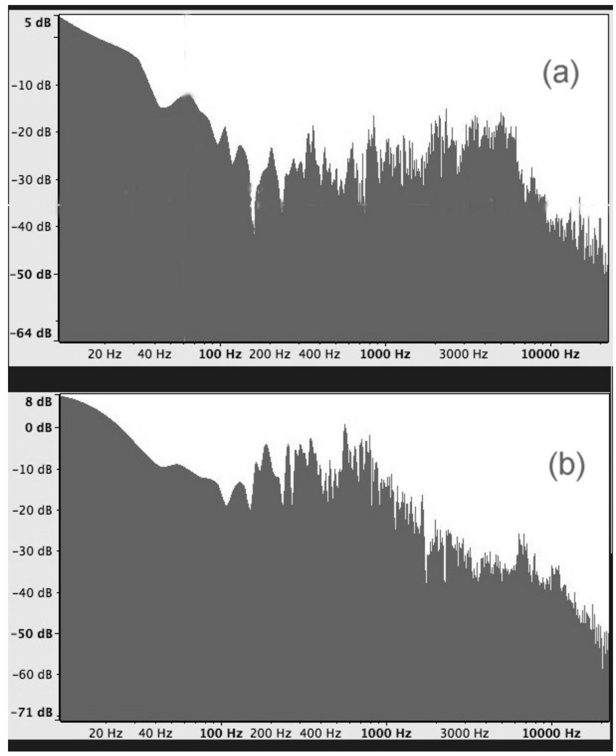

Figure 5. (a) Spectrum of the sound of a nearly-flat clap. (b) Spectrum of the sound of a cupped clap with the same hands. The sound pressure reference level is arbitrary and the frequency scale is logarithmic from 10 Hz to 20 kHz. Note that the level range in (b) is different from that in (a).

where c is the speed of sound in air. As the hands move closer together and compress their contact areas, the height of both the enclosed volume and the opening decrease about linearly with time. The airflow through the aperture has a constant value, however, so that it ultimately reaches supersonic speed and generates a shock wave. If the aperture does not close, however, no such shock is generated and there is simply a radiated pulse at the resonance frequency of the vented cavity.

In a typical case the enclosed volume V is about 100 cm^3, the total aperture cross-section S about 1 cm^2 and the aperture length l about 1 cm, giving a resonance frequency of about 500 Hz. The initial impact velocity may be higher than 1 ms^{-1}, but this slows once contact is made, allowing rather more than 0.01 s during which several oscillation cycles can occur before the final shock impulse. Because of the short duration of this resonant pulse, it is expected to produce a rather broad-band sound centered on this frequency.

SPECTRAL ANALYSIS

Measurements of the sound of nominally flat and cupped natural handclaps were made in an anechoic environment. Because of the variability of hand profile and impact position there is large variability from one clap to another but one was nearly flat and the other had a deep cup. The measured spectra are shown in Figure 5. Both spectra show a decline of about 20 dB for a frequency increase of a factor 10, so that the sound amplitude varies about as $1/f$. It is clear that the main difference is that the nearly-flat hand-clap has a subsidiary intensity maximum in the range 1–10 kHz while the deep-cupped clap has a subsidiary maximum in the range 0.1–1 kHz. This is about what is expected from what is heard of the sound and confirms the general explanation presented above.

CONCLUSIONS

The overall conclusion of the study is that shock waves produced by the rapid impact of two human hands appear to play a prominent part in the emitted sound. Because of the irregular shape and soft texture of the hands such shock waves appear to be generated to some extent in most cases, but their magnitude is much greater in the impact of a pair of nominally flat hands where the impact area is large rather than in cupped hands where there is a much smaller impact area. The extent to which shock waves are present in the sound of impacting cupped hands depends greatly upon their shape, which can be controlled by the person clapping. As is expected, a flat handclap has a large proportion of radiated sound in the frequency range 1–10 kHz while a cupped handclap has this maximum in the range 0.1–2 kHz, again under the control of the person clapping.

ACKNOWLEDGEMENTS

This brief study of handclaps was provoked by my supervision of a University student project on Aboriginal clapsticks carried out by David Johnston. Handclaps are actually not significant in Aboriginal music or dance however, because the impacting objects are usually cylindrical clapsticks or more often boomerangs, the surfaces of which are convex as in Figure 1(a). The sound in these cases then results mainly from vibration of the two objects involved in the clap impact. I am also grateful to John Smith for help with the sound spectra and to Joe Wolfe for helpful comments and suggestions.

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