Sounds of Leidenfrost drops

Tanu Singla$^{1,2}$ and M. Rivera$^1$

$^1$Centro de Investigación en Ciencias-(IICBA),
UAEM, Avenida Universidad 1001,
Colonia Chamilpa, Cuernavaca, Morelos, México

$^2$Tecnológico de Monterrey, Calle del Puente 222,
Colonia Ejidos de Huipulco, Tlalpan, Ciudad de México, México

(Dated: February 25, 2020)

Abstract

We show that when a drop of water is maintained in its Leidenfrost regime, a sound in the form of periodic beats emits from the drop. The process of beat emission involves two distinct frequencies. One is the frequency of beats itself; this relates to the frequency of the oscillations of the drop. Second is the frequency of the sound in every beat which is emitted when one oscillation in the drop occurs. Experiments have been performed by placing a drop of water over a concave metallic surface and the beats of the drop were recorded by fixing a microphone above the drop. A video camera was also fixed above the drop to record its oscillations. Simple analytical techniques like Fourier and wavelet transforms of the audio signals and image processing of the videos of the drop have been used to gain insight about mechanism of beat emission process. This analysis also helped us in studying the dependence of frequencies, if any, on the radius of the drop and the substrate temperature.
Leidenfrost effect explains how a drop of liquid after coming in contact with a surface, at a temperature much higher than the boiling point of the liquid, floats over a cushion of liquid vapors between the drop and the surface. This effect is known to the scientific community since 1751 and it gained popularity in 1952 when Holter et al. [1] accidently found the oscillating patterns in the drop. Since then, interest in people to study this effect has not subsided and a plethora of research is being reported even until today; inverse Leidenfrost effect [2], Leidenfrost wheels [3], about fate of Leidenfrost droplets [4], Leidenfrost levitation [5], granular Leidenfrost effect [6], Leidenfrost effect in hydrogels [7, 8], self propelled Leidenfrost drops [9] are to name a few.

Oscillations in liquid drops due to distinct perturbations in itself is a widely explored topic. It is known that under small perturbations, frequencies of the resonance modes of liquid drops follows the relation \( f_d \propto r_d^{-3/2} \), where, \( r_d \) is the radius of the drop [10]. Following this idea, Shen et al. studied the dynamics of acoustically levitated drops as a function of \( r_d \) [11]. This was followed by Bouwhuis et al. [12] where they studied frequencies of oscillations of a liquid drop floating over an air cushion. In a completely different scenario, in 1996, Yoshiyasu et al. [13] studied the behavior of water drop on a vertically oscillating plate. One of the principle findings of this work was that the frequency of the oscillations of the drop was half of the frequency of perturbation; i.e. the drop behaved like a parametric oscillator. Our group has also reported oscillations of liquid metal subjected to different perturbations [14–17]. Despite the fact that the liquid drops in these works were subjected to different perturbations, due to the identical underlying hydrodynamic principles, similar star shaped oscillations were observed in all cases.

In the case of Leidenfrost drops, the vapor layer trapped between the drop and the hot substrate plays a crucial role in its dynamics. The geometry and dynamics of the vapor layer have been studied using interference imaging technique [18, 19] and the dependence of the vapor layer thickness on the drop radius was established. In another interesting study, the thickness of the vapor layer was calculated using electrostatic methods [20]. Ma et al. [21] have reported different oscillating modes (“Leidenfrost Stars”) in various liquids. Contrary to popular belief, they further reported that in the case of Leidenfrost effect, the resonant frequencies of the drop do not depend on its radius. Moreover, similar to the drops on vertically vibrated plate, mentioned earlier, the frequency of the vapor layer beneath the drop has been reported to be double the frequency of oscillations of the drop.
Here we introduce a new phenomenon; the emission of beats from a Leidenfrost drop. We show that when a drop of water was kept on a substrate with temperature much higher than the boiling point of water, a sound in the form of periodic beats was emitted from the drop. It was observed that, when the size of the drop was large, beats were emitted only when the drop oscillated in one of the star configuration modes. In contrast to large drops, where beats were observed only for Leidenfrost stars, beats were also detected in small drops, even though the stars cannot be observed in drops of these sizes. It was further observed that the beats emitted from the drop (both large and small) can be decomposed into two frequencies: the frequency of the beats ($f_b$) which is related to the fix interval of time between two consecutive beats and the frequency of sound ($f_s$) emitted in every beat. In the present work, we study both components of frequencies ($f_b$ and $f_s$) as a function of the drop radius ($r_d$) and the substrate temperature.

Fig. 1(a) shows the experimental setup that was used to record the beats of water drop. Experiments were performed by placing a drop of water on a concave surface (8cm radius of curvature) of aluminum. The concave surface helped us in keeping the drop stationary so that sound could be recorded. A heater from Thermo Scientific was used to keep the substrate at high temperature. The temperature of the substrate was obtained by using a FLUKE's thermocouple fixed with the substrate. A microphone (48KHz sampling rate), connected to a regular smartphone, was held near the boundary of the drop to record the sound. A video camera (240fps) was fixed above the drop to record the videos. Fig. 1(b) shows some images of different geometrical patterns in the drop. As already mentioned, these are the modes of the drop which emit periodic beats. Fig. 1(c) shows a timeseries of an audio signal recorded from one of the experiments. This timeseries consists of two components: periodic spikes and interspike intervals. The spikes represent the beats emitted from the drop and the interspike interval part is the background noise. The duration of the interspike intervals for any audio signal corresponds to $f_b$. The background noise in the audio signal can have sources of various origins like electrical noise from the microphone, the noise from the environment etc. We must mention here that the analysis of the audio signals has been done by only filtering out the high frequency components of the background noise. Low frequency components of the noise could not be removed because the amplitude of the noise (in this frequency range) was comparable to the amplitude of the signal of interest and it was difficult to filter noise without altering the audio signal, and henceforth changing $f_s$. In
Fig. 1(d) timeseries representing the oscillations of the drop has been shown. A video of the drop was first recorded and the method of cross correlation [17] was further employed on this video to obtain this timeseries. Finally, in Fig. 1(e), frequency spectra of timeseries shown in (c) and (d) have been shown; blue curve represents the spectrum of the audio signal and the orange curve represents the spectrum of the oscillations in the drop. It can be seen that the principle frequency of the oscillations in drop \( f_d \) is almost half the frequency of the beats \( f_b \). This is similar to the result reported by Ma et al. [21] where they showed that the frequency of the oscillations of a Leidenfrost drop \( f_d \) is half the frequency of the vibrations in the vapor layer \( f_v \) underneath. The identical nature of \( f_b \) and \( f_v \) indicates that the vapor layer is responsible for the emission of beats from the drop, i.e. when vapors escape from the layer beneath the drop, they interact with the surrounding air to produce the beats.

![Fig. 1](image-url)

FIG. 1: (a) Experimental setup that was used to study the beats of Leidenfrost drops, (b) Some examples of the geometric patterns that result in the beat emission phenomenon, (c) An example of the audio signal of the beats emerging from the drop, (d) timeseries corresponding to geometric oscillations in the drop, and (e) Fourier transforms of the timeseries shown in (c, and d).

As already mentioned, the beats of the drop can be decomposed into two frequencies: \( f_b \) and \( f_s \). \( f_b \) was obtained by employing Fourier transform technique on the audio signals
recorded from the experiment. However, $f_b$ and $f_d$ are identical and it has been reported earlier that $f_b$ is not a function of the drop radius but of capillary length of the fluid used \[21\]. Therefore, $f_b$ that we obtained for different modes of oscillations did not vary with the drop radius and had similar values (results not shown) as reported in previous works. To obtain the frequency of the sound ($f_s$), method of wavelet transforms was used. Without going into much details about wavelet transforms, this technique allowed us to decompose the audio signals into frequency components at different times and a 2 dimensional frequency-time spectrum was obtained. In Fig. 2(a), an audio signal consisting of two consecutive beats has been shown. The wavelet transform of this signal is shown in Fig. 2(b). The information about frequencies present in the signal at any time moment can thus be obtained from these wavelet transforms; dark red color corresponding to the major frequencies and blue color corresponding to the insignificant frequencies of the signal. Therefore, the frequency of sound ($f_s$) in each of the beats can be obtained from these islands in the wavelet transform, which in the present case is $f_s \approx 100 Hz$.

Fig. 3(a-d) show audio signals of a single beat for different drop sizes at substrate temperature 500°C. The respective wavelet transforms of these signals have been shown in Fig. 3(e-h). These transforms show an inverse relationship between $f_s$ and $r_d$. We already know, the source of the beats is the vapor layer underneath the drop (Fig. 1). Moreover, it is known that the thickness of the vapor layer beneath the drop is directly proportional to $r_d$ \[18\]. Therefore, as the thickness of the vapor layer reduces in size, the vapors escape with
FIG. 3: Audio signals with corresponding wavelet transforms for four different drop sizes ($r_d$) and substrate temperature of 500°C. $r_d$ for (a-d) were: (a) 1.69cm, (b) 1.42cm, (c) 0.61cm, (d) 0.33cm. 

higher velocities from the layer and interact differently with the surrounding air to produce sounds of higher frequencies. This scenario is similar to the situation where a gas contained in a chamber escapes from a small hole and the frequency of the sound produced is inversely proportional to the size of the hole [22]. It can be argued that the pressure of the vapor layer can be another parameter controlling $f_s$. However, due to limited knowledge about the variation of vapor pressure with $r_d$, the dependence of $f_s$ on the vapor pressure remains an open question. Another interesting fact that can be observed from Fig. 3 is how the profile of audio signals changes as $r_d$ reduces. This behavior of the audio signals indicates different mechanism of beat emission in these cases; which is due to the fact that the morphology of the vapor layer for the drops with big $r_d$ could be quite distinct from that of small $r_d$.

The dependence of the frequency of sound ($f_s$) on the temperature of the substrate has been shown in Fig. 4. To explore this dependency, audio signals for several beats at different drop sizes ($r_d$) were obtained at three different temperatures. The $f_s$ of these audio signals along with corresponding errorbars were then plotted on Fig. 4. While this image holds the fact that $f_s$ is inversely proportional to $r_d$, nothing definite can be commented on the dependence of $f_s$ on the substrate temperature. Moreover, as there exists a lot of background
noise in the audio signals, clean audio signals could be extracted and then analyzed only for few drop sizes. This, however, does not mean that beats were not detected at other drop sizes.

FIG. 5: Audio signal of beats when \( r_d \) was very small such that it does not exhibit geometric oscillations, (b) frequency spectrum of the audio signal shown in (a)

We now show results for beat emission from a small drop in which Leidenfrost stars cannot be observed. An example of an audio signal for this scenario along with its frequency spectrum have been shown in Fig. 5 (a), and (b). The frequency spectrum shown in (b) has been obtained by manually removing the noise from the audio signal shown in (a). As can be seen in the frequency spectrum, the principle frequency of the beats in this case is around 180Hz; shows that this mechanism of beat emission is distinct from the mechanism
when the beats were emitted in the star configuration modes \( f_b \approx 23Hz \). Furthermore, on
closer inspection, it was observed that the drop in this case executed vertical bounces. A
similar case was reported for sound emitted due to hyrdogel spheres bounces \cite{7,8}. It was
showed that the high frequency “gap oscillations” created by the impact of the sphere on
the surface are responsible for this sound. Hence, the timeseries shown in Fig. 3(a) is the
result of these gap oscillations occurring between the water drop and the substrate. \( f_s \) of
the beats was also calculated for this case, and it had a value of \( f_s \approx 1KHz \) (results not
shown).

In conclusion, using basic experimental setup we showed the existence of periodic beats
emerging from a Leidenfrost drop. In \cite{23} Philippe Brunet speculated the possible existence
of sounds from Leidenfrost drops. However, Philippe mentioned if sounds with \( f_v > 50Hz \)
can be generated from the drops. In our results, while the sound emission has been observed,
\( f_v \) remained in the order of 23Hz (which is the typical vapor layer frequency of the Leidenfrost
stars).

We used simple but powerful analytical techniques to qualitatively study the beats. These
techniques allowed us to provide an insight about the process of beat emission, which oth-
erwise could have required complicated experimental measures; typically used to study Lei-
denfrost drops. We showed that the vapors escaping from the layer beneath the drop are
responsible for producing the beats and that the frequency of the sound in every beat is
inversely proportional to \( r_d \). We also intended to show the dependence of the frequencies on
the substrate temperature, which unfortunately due to the presence of background noise in
the audio signals was difficult to establish. Finally, we showed that the gap oscillations of a
bouncing water drop can result in the emission of periodic beats from the drop.

TS acknowledges PRODEP-SEP, México for the postdoctoral fellowship.

\[1\] N. J. Holter and W. R. Glasscock, The Journal of the Acoustical Society of America 26, 253
(1954).

\[2\] R. S. Hall, S. J. Board, A. J. Clare, R. B. Duffey, T. S. Playle, and D. H. Poole, Nature 224,
266 (1969).

\[3\] A. Bouillant, T. Mouterde, P. Bourrianne, A. Lagarde, C. Clanet, and D. Quéré, Nature Phys.
[4] S. Lyu, V. Mathai, Y. Wang, B. Sobac, P. Colinet, D. Lohse, and C. Sun, Science Advances 5, eaav8081 (2019).
[5] A. Hashmi, Y. Xu, B. Coder, P. A. Osborne, J. Spafford, G. E. Michael, G. Yu, and J. Xu, Scientific Reports 2, 797 (2012).
[6] P. Eshuis, K. van der Weele, D. van der Meer, and D. Lohse, Phys. Rev. Lett. 95, 258001 (2005).
[7] S. R. Waitukaitis, A. Zuiderwijk, A. Souslov, C. Coulais, and M. van Hecke, Nature Physics 13, 1095 (2017).
[8] S. Waitukaitis, K. Harth, and M. van Hecke, Phys. Rev. Lett. 121, 048001 (2018).
[9] H. Linke, B. J. Alemán, L. D. Melling, M. J. Taormina, M. J. Francis, C. C. Dow-Hygelund, V. Narayanan, R. P. Taylor, and A. Stout, Phys. Rev. Lett. 96, 154502 (2006).
[10] L. Rayleigh, Proc. R. Soc. 29, 71 (1879).
[11] C. L. Shen, W. J. Xie, and B. Wei, Phys. Rev. E 81, 046305 (2010).
[12] W. Bouwhuis, K. G. Winkels, I. R. Peters, P. Brunet, D. van der Meer, and J. H. Snoeijer, Phys. Rev. E 88, 023017 (2013).
[13] N. Yoshiyasu, K. Matsuda, and R. Takaki, Journal of the Physical Society of Japan 65, 2068 (1996).
[14] D. K. Verma, A. Q. Contractor, and P. Parmananda, J. Phys. Chem. A 117, 267 (2013).
[15] E. Ramírez-Álvarez, J. L. Ocampo-Espindola, F. Montoya, F. Yousif, F. Vázquez, and M. Rivera, J. Phys. Chem. A 118, 10673 (2014).
[16] J. L. Ocampo-Espindola, E. R. Ivarez, F. Montoya, P. Parmananda, and M. Rivera, Journal of Solid State Electrochemistry 19, 3297 (2015).
[17] T. Singla, D. K. Verma, J. F. Tovar, A. Figueroa, F. Vzquez, F. B. Yousif, and M. Rivera, AIP Advances 9, 045204 (2019).
[18] J. C. Burton, A. L. Sharpe, R. C. A. van der Veen, A. Franco, and S. R. Nagel, Phys. Rev. Lett. 109, 074301 (2012).
[19] T. A. Caswell, Phys. Rev. E 90, 013014 (2014).
[20] T. Roques-Carmes, A. Domps, P. Marchal, and L. Marchal-Heussler, Experiments in Fluids 59, 115 (2018).
[21] X. Ma, J.-J. Liétor-Santos, and J. C. Burton, Phys. Rev. Fluids 2, 031602 (2017).
[22] A. B. C. Anderson, The Journal of the Acoustical Society of America 24, 675 (1952).

[23] P. Brunet, Journal of Fluid Mechanics 850, 1 (2018).