A Report on

Experimental investigation of the acoustics of a liquid jet impinging on a solid surface

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By

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Experimental investigation of the acoustics of a liquid jet impinging on a solid surface

Abstract: It is a common observation that a liquid jet emerging from an orifice and impacting a solid surface has a distinct acoustic signature. In this study the mechanisms for this sound production are investigated experimentally. The details of the flow structure at the point of impingement are captured using high speed video with simultaneous sampling of the acoustic signals. The two are synchronized in time and correlated to try and understand the flow structures responsible for the various distinct sounds that are observed. It is found that two separate mechanisms for sound production exist: one due to the impact of water droplets on the wetted surface and the second due to resonance of air bubbles entrained due to the falling jet. The work is expected to be a first step in a comprehensive treatment of the acoustics of unstable liquid jet impingement on solid surfaces.

1. Introduction

The liquid jet impinging on a solid surface is a very common occurrence such as water emerging from a faucet and falling of rain. Interestingly, the acoustics of this impact are influenced by the breakup of the liquid jet before it reaches the surface. This break up happens due to the growth of small perturbations that exist in any natural system. Joseph Plateau [1] first characterized this instability in 1873 through experimental observation, building on the work of Savart. He noted the instability arose when the liquid column length exceeded the column diameter by a factor of about 3.13 (Plateau, 1873). Lord Rayleigh [2] later corroborated Plateau's work, giving an analytical explanation of this physical observation. This instability is now referred to as the Rayleigh-Plateau instability [3].

A closely related phenomenon to the one considered here is the impact of individual droplets on a liquid surface. Investigations of this have been carried for nearly a century. Worthington [4] was the first to flash photograph this as early as 1890. Several theories were put forward by Mallock [5] and Bragg [6]. These mostly related the sounds produced to the resonance of open-ended cavities at the water surface. Minnaert [7] proposed an alternative theory which explained the sounds based on radial oscillations of an air bubble in a liquid. The first comprehensive investigations of the sounds produced by droplet impacts were made by Franz [8], in which he showed that drop impacts behave like dipole sources of sound. There are several other experimental works which study this phenomenon most notable of which are [9, 10]. For the case of liquid impact on solid surfaces however, few previous works exist which study the acoustics of the phenomenon. Thus an investigation of the acoustics along with the dynamics of the impact is carried out in the current work to better understand and explain this phenomenon.

2. Experimental Procedure

The experimental setup (Fig. 1) is used to produce and maintain a water jet using a nozzle of fixed diameter. Water is supplied to the nozzle from a constant head tank with a head of roughly 2 m, via a butterfly control valve which is used to maintain a specified flow rate. The water jet is made to fall onto a glass plate through a height so that the Rayleigh-Plateau instability sets in and the jet breaks up before the impact. This height can be adjusted by raising or lowering the stand on which the nozzle is mounted. The glass plate used is sufficiently heavy so as to avoid any secondary sounds due to resonant forced vibrations of the plate. After falling onto the plate, water is made to drain in a controlled manner into a large reservoir. Drainage is very important since uncontrolled flow of water from the plate onto the reservoir causes a set of secondary sounds which would contaminate the acoustic data. The glass plate is mounted on a tripod stand which in turn sits on a raised platform. The raised platform is mounted on the base of the reservoir with its top surface just above the water level in the reservoir. The flow circuit is completed using a submarine pump which pumps water back to the constant head tank, whose drainage area is once again connected to the water reservoir.

2.1. High speed video and Photography

An inclined mirror arrangement (Fig. 1 (b)) along with a high speed camera (MotionPro X3) is used to view the bottom surface of the glass plate. The mirror is placed on the raised platform below the plate while the camera is mounted on a tripod and focused carefully on the image from the mirror. Since, a fairly high frame rate is used to capture the images (1000-3000 frames per second), powerful and focused lighting is used. Providing adequate lighting in the right direction is one of the main challenges in this experimental setup, and it is worthwhile to design the lighting arrangement carefully. While capturing the bottom view two 85 W Compact Fluorescent Lamp (CFL) lamps are suspended on either side of the liquid impact point on the plate. Augmenting these, a LED lamp with parabolic focusing arrangement was placed 90 degree separated from the two CFL lamps. After obtaining a steady jet at a specified flow rate, the camera was triggered and images captured at a maximum rate of 3000 fps. This was found to be sufficient in resolving the flow structures of the impact.

While the high speed video camera was used to capture the flow structures from a bottom view, a Nikon D90 camera is used to capture the flow structures in the jet before impact. To provide adequately focused lighting the CFL lamps were mounted on a stand with a parabolic mirror and placed to illuminate the jet from the front. The jet is photographed against a backdrop of blue PVC cloth which was essential to provide the contrast needed to view the jet. The experiments were primarily carried out at night and further, a white PVC cloth with a diffusely reflective surface was used as a shroud in all experiments to eliminate noise due to ambient light (see Fig. 1(a)).

2.2.Capturing acoustics

The sound produced is captured using a EASUN super-unidirectional cardioid condenser microphone mounted on a stand and aimed at the point of impingement. Audio data is acquired and processed on a personal laptop computer using the open source software AUDACITY, which is also used for Fast Fourier Transform (FFT) of the signal. To remove ambient noise from the audio recording, the microphone is used to record the small amount of noise present in the room. This noise is then eliminated using the built in noise removal software in AUDACITY. The video and audio tracks are synchronized using a simple method, described here. A simple circuit is put together which is capable of producing a flash of light using an LED and a sharp high pitched beep simultaneously when a switch is triggered. The sound signal clearly registers on the audio track and the LED was placed so as to be observable in the corner of the high speed camera image. Thus the exact frame number when the light first flashes can be determined and matched to the audio track position corresponding to the beep. In this way a simultaneous record of the flow structures of impact along with the corresponding audio signals are recorded.

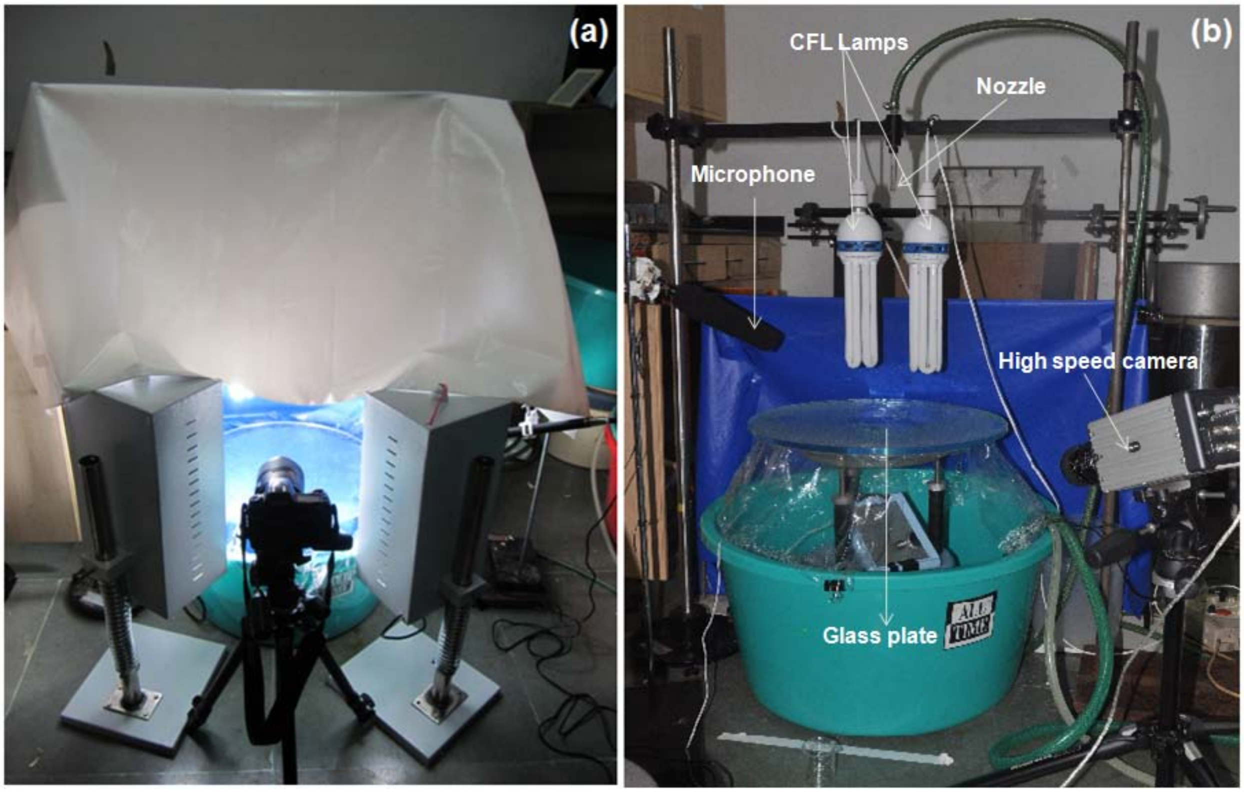


Fig. 1. (a) Experimental setup for still photographs (b) for high speed video

3. Results and discussion

3.1.Flow structures before impact

Analysis of the still photographs of the jet before impact revealed two main kinds of flow structures. At low flow rates (2-3 ml/s) the jet is in the form of a train of droplets (Fig. 2), though it appears continuous to the naked eye. The impingement of these individual droplets is however not independent of one another since the flows setup by the last drop is seen to interact with those of the next one. The second type of flow structure is seen at higher flow rates (3-6 ml/s). Here the liquid is in the form of a continuous central strand with regions of positive curvature at intervals (see Fig. 3). These strands exist just before the liquid breaks up into droplets and secondary droplets. It is observed at certain locations that this breakup occurs with a train of secondary droplets (Fig. 3) formed which are not fully separated from one another. At even higher flow rates (>6 ml/s) the jet may not breakup completely before impinging on the plate (Fig. 4). It should be noted that these discussions of flow rate are based on a nozzle diameter in the range 3-9 mm and for flow rates where the jet breaks up at most just before reaching the plate. As expected the breakup point of the jet for a fixed nozzle diameter was observed to descend with flow rate.

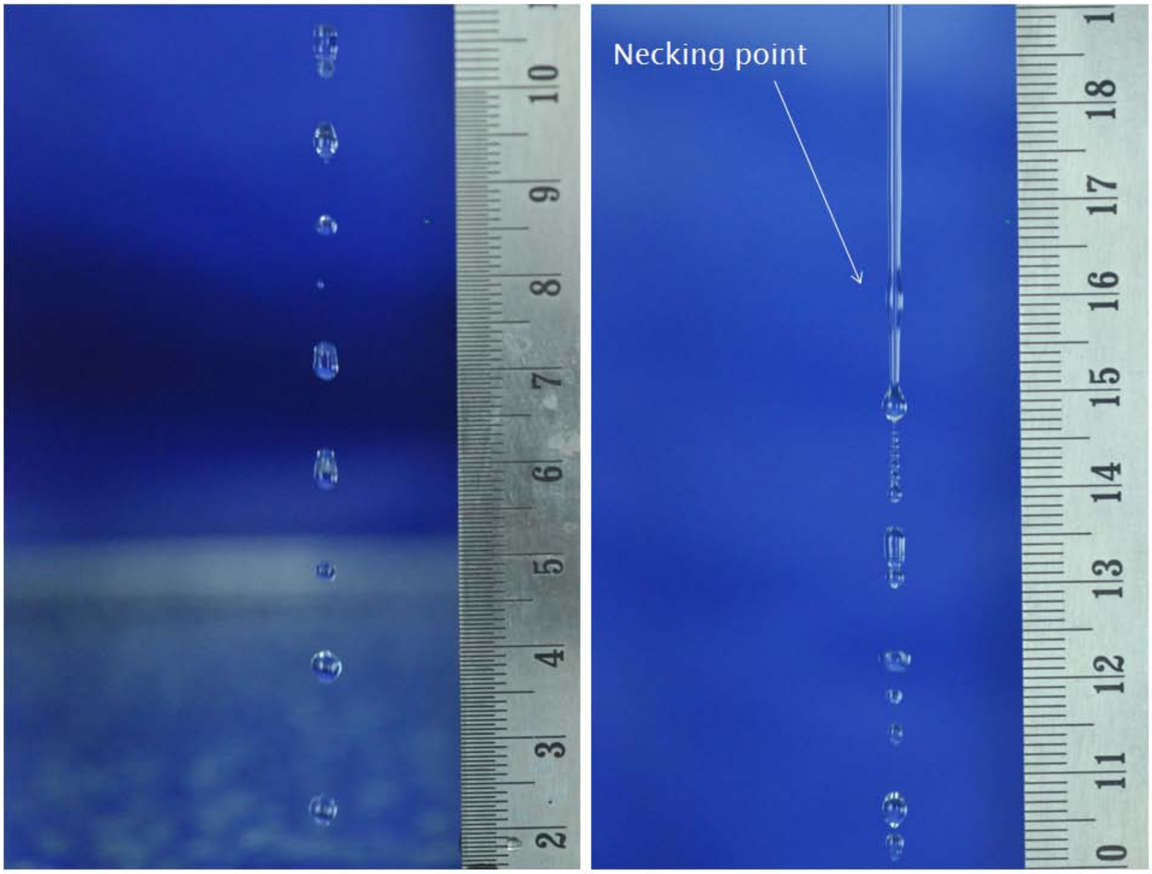


Fig. 2. Flow structure at low flow rates (<2 ml/s)

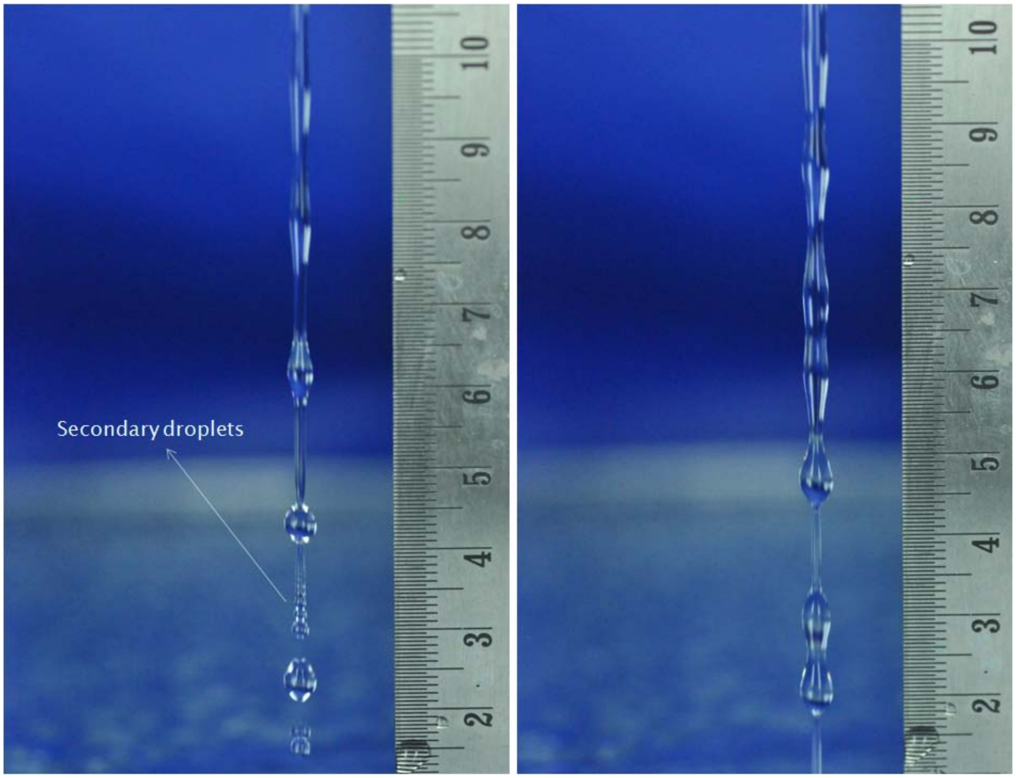


Fig. 3. Flow structure at medium flow rates (3-6 ml/s)

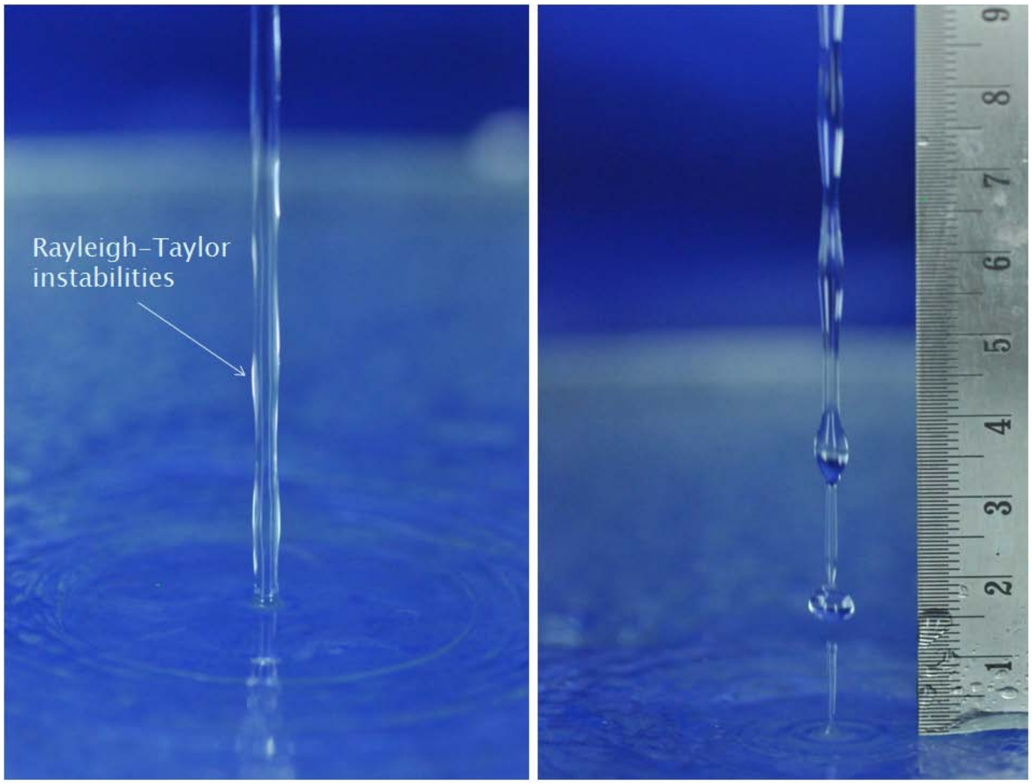
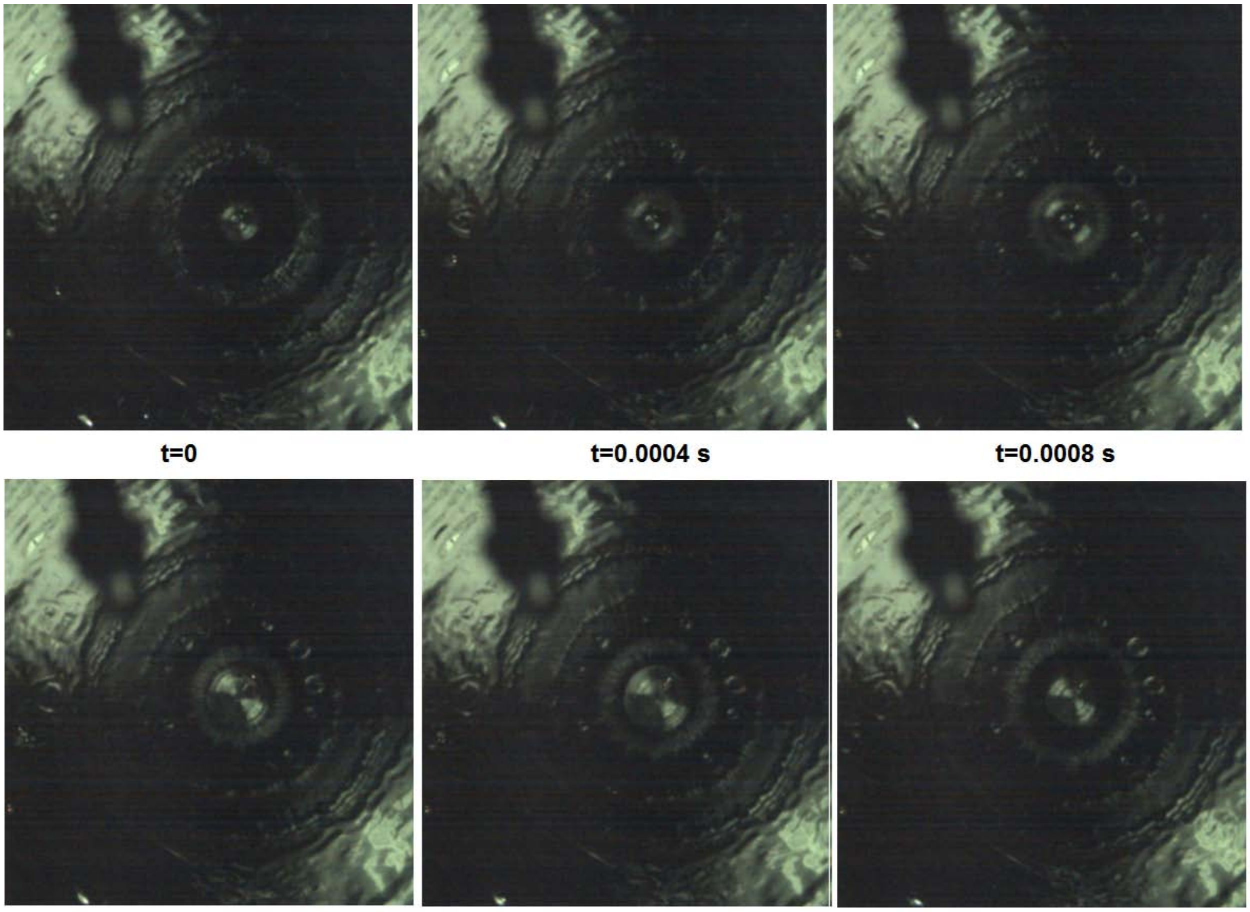


Fig. 4. Flow structure at higher flow rates (>6 ml/s)

3.2. Flow structures after impact

These are studies using the high speed camera images from the bottom of the plate. At low flow rates the high speed video seemingly resembles that of individual drop impacts, with the important distinction that the flows setup on the plate interact with each other for consecutive droplets as explained above. In these images the entrainment of air leading to bubble formation can be clearly observed (Fig. 5). When sampled at a large enough frame rate it is seen that even at steady conditions and constant flow rate of the jet, the actual impact appears to be a stochastic process. Impact occurs in a series of random splashes which throw up a crown-like ring of droplets. The liquid after impinging on the plate travels as a thin film and does so with radial velocities of order 0.01 m/s. The bubbles formed are convected with this velocity and thus move much slower in relation to the splashing structures which evolve at the rate of jet impingement (~ 1 m/s).



t=0 t=0.0004 s t=0.0008 s

t=0.0012 s t=0.0016 s t=0.002 s

Fig. 5. Evolution of a ring of bubbles over an interval of 2 milliseconds at a flow rate of 70 ml/s

3.3.Correlation of flow structure and acoustics

On carefully listening, one can clearly make out two distinct types of sound produced by the impinging jet. One is the continuous ‘pitter-patter’ type sound which stays constant with time both in its nature and amplitude. The other sounds are a seemingly random splash type sound which is of noticeably higher loudness and pitch compared to the previous type. On plotting the amplitude of the sound signal versus time both these observations can easily be corroborated. The first type of sound is seen as the continuous and small amplitude waveform (Fig. 6 (a) region A), whereas the second type has a distinct decaying sinusoid signature (Fig. 6 (a) region B) with amplitude which is an order of magnitude greater.

Synchronization of video and audio data allows determination of the acoustic signal corresponding to a given flow structure to within experimental error. It is reasonable to expect that the irregular splash sound is caused due to a flow structure which by itself is not formed at a regular frequency but occurs at random times. The entrainment of air leading to small, radially moving bubbles is one such candidate. That such bubbles produce sounds has been shown theoretically by Minnaert [7]. In his model the radial oscillations of the bubble immediately after its formation result in its distinct acoustic signature. The resonant frequency of a bubble inside the bulk fluid is given by,

$$\nu = \frac{1}{2\pi a}\left(\frac{2\kappa p_0}{\rho}\right)^{1/2}$$

where a is the radius of the bubble, κ the polytropic exponent of the gas inside the bubble (in this case, air), $p_0$is the ambient pressure which is well approximated in this case by atmospheric pressure and ρ is the liquid density. While the above relation applies to bubbles inside the liquid bulk, Strasberg [11] has shown that the resonant frequency increases as the bubble gets near to the liquid surface.

By counting and noting down the frame number and time elapsed in the video at which the bubbles form and doing the same for the splash signature in the audio track, we can estimate the correlation between the two events. To within experimental error, it is found that the two events are coincident in time, however further quantitative data is needed to establish this connection more rigorously. Here, error can result from the following: 1) the minimum resolution in time is limited by the frame rate of the high speed camera. 2) There is an uncertainty of the order of a few milliseconds in the audio track as to the exact initiation of the beep.

Flow and sound signals were analyzed for a few characteristic flow rates. Here the range of flow rates for a nozzle of 5 mm diameter is found to be lying in the following three regimes.

1) <1.8 ml/s: No jet formation. Liquid falls as separate drops from the nozzle.
2) 1.8-8ml/s: Jet is formed which breaks up before reaching the plate.

3) > 8 ml/s: Jet impinges the plate before breaking up and thus does not cause any perceptible sound.

Fig. 6 (a) shows the time trace of sound signal amplitude in which a number of intermittent high amplitude signatures are observed. Frequency spectrum of the same signal is given in Fig. 6 (b). A few peaks are observed at low frequencies which correspond to the sound signatures lying in region A. The higher frequency peaks in the range 3000-16000 Hz correspond to region B in Fig. 6 (a). This is established by performing separate FFT analysis for the signals in region A and B. Frequency spectrum of region A shows only the low frequency peaks, while that of region B shows both low and high frequency. The frequency spectrum (Fig. 7) of the sound for a higher flow rate impingement shows a similar trend but has more number of peaks in a higher frequency region when compared to a lower flow rate. Also, the rate of occurrence of high amplitude signatures which correspond to the splashing sounds also increases (Fig. 7 (a)). Both these are in keeping with the fact that the rate of entrainment increases with increasing flow rate.

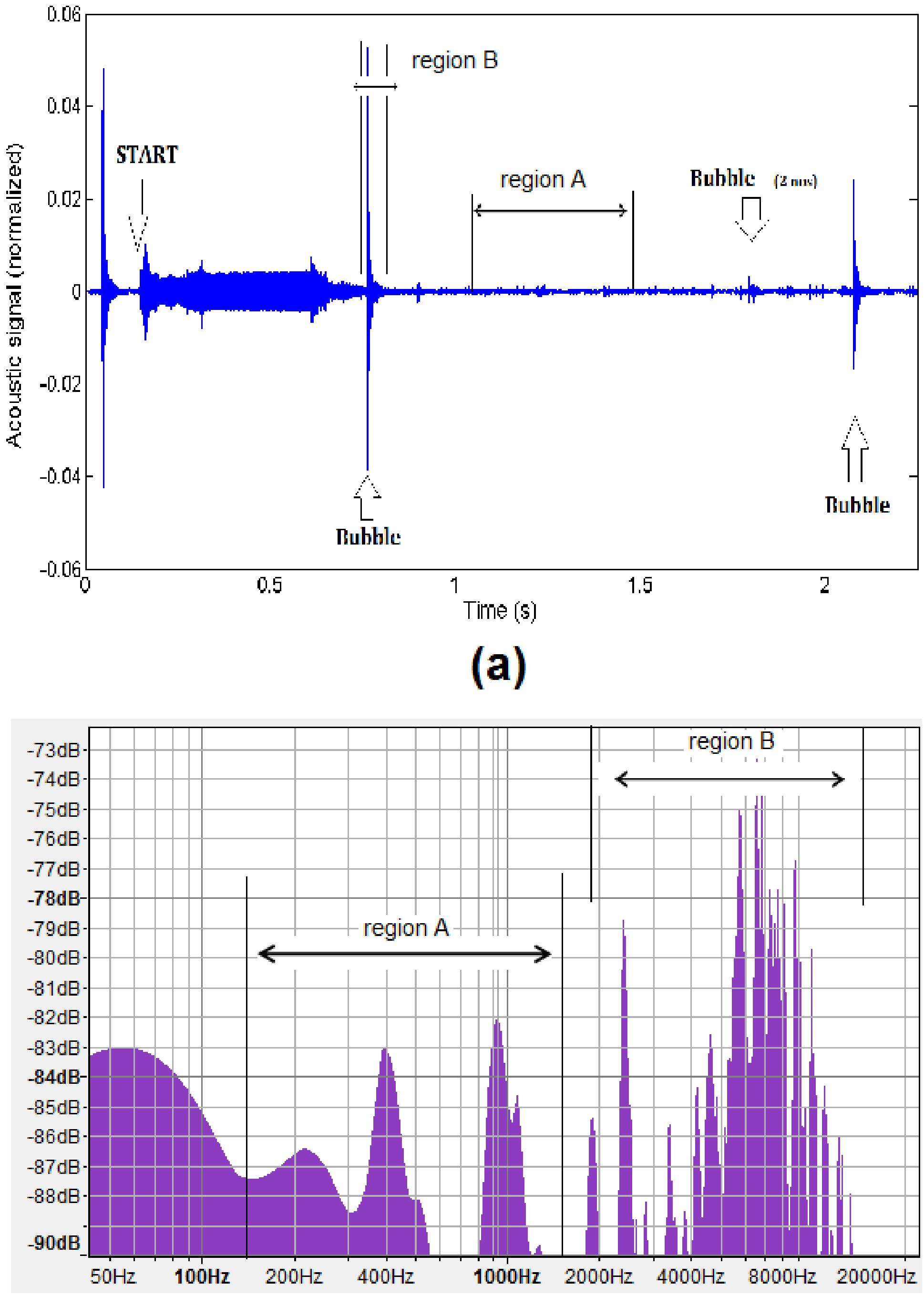


Fig. 6. (a) Acoustic signal amplitude vs time (b) Frequency spectrum of the sound, for a flow rate of 3 ml/s

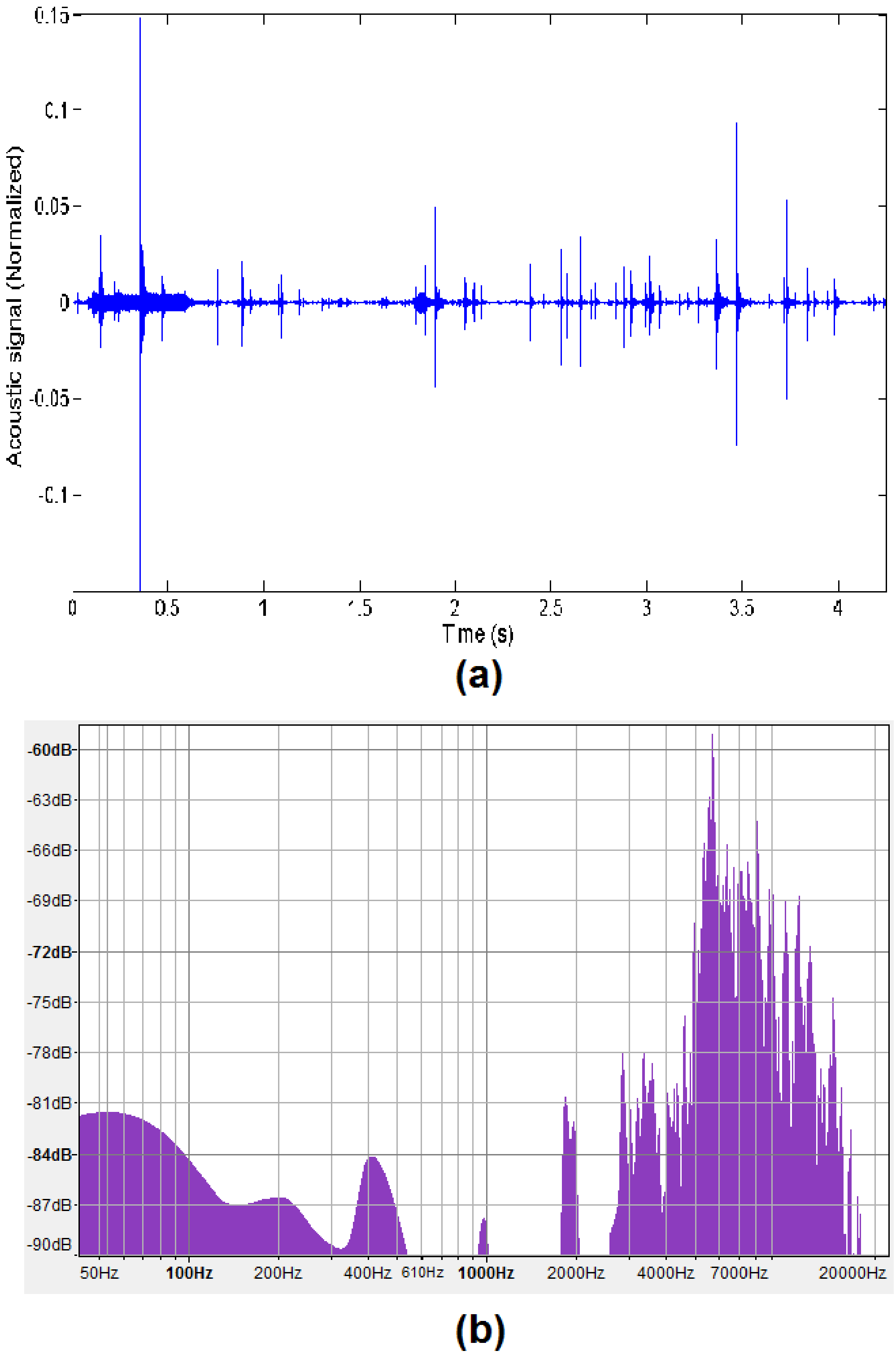


Fig. 7. (a) Acoustic signal amplitude vs time (b) Frequency spectrum of the sound, for a flow rate of 6 ml/s

4. Conclusions and future work

In this work a basic setup is constructed to study the acoustics of a liquid jet impinging on a solid wall. The main aim of the experiment is to finely resolve the flow structures before, at and after impingement simultaneously with the acoustic signals due to the flow. This is achieved using a still camera to capture the flow before impingement, a high speed camera for flow structures at the impact point and a high sensitivity microphone for the sound. The data from the high speed camera were synchronized using a simple circuit that emits light and sound simultaneously on triggering a switch. Based on these studies it is found that two types of sounds are produced, namely the impact sound which results in a characteristic pitter-patter type effect and the splashing sound resulting from bubble formation due to air entrainment. The former is in the lower end of the frequency spectrum (100-1000 Hz), whereas the latter is characterized by higher frequencies (3000-16000 Hz). These high frequencies are in keeping with Minnaert's theory of resonant frequencies of a bubble. It is also observed that the splashing signatures in the audio track correspond to bubble formation events in the high speed video, lending further evidence to the theory that splashing is due to bubble formation. For future work, it remains to be seen about the exact cause of the impact sound. A few theories exist which try to explain this based on vibrations of the liquid drop itself. Further, a more sophisticated synchronization needs to be developed which reduces uncertainty in matching video and audio tracks. Work is ongoing to characterize the effects of temperature, surface tension and viscosity on the acoustics and flow structures. These will be reported in a future work

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