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Physical Mechanisms Underlying the Acoustic Signatures of Breaking Waves

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Scientific Report
DRDC-RDDC-2016-R150
August 2016

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Abstract

The characteristic sound of breaking waves is an integral component of the ambient noise along the coastline. The underwater sound generation from breaking waves has been thoroughly studied, but very little work has been published on the airborne sound caused by breaking waves. Acoustic recordings from a field study were analyzed in an attempt to determine the sound generation mechanisms. A microphone was deployed at Osborne Head, Nova Scotia from June to August 2011 on a grassy cliff above a beach with abundant breaking wave activity. Photographs, weather and ocean wave data were collected to assist in interpreting the audio recordings. Individual breaking wave events were located in the data and their one-third-octave band spectra were analyzed. The levels in the 40 to 200 Hz bands increased by 10 to 25 dB as the wave breaking occurred, with the largest increases observed for frequencies less than 100 Hz. The power spectra of the breaking waves revealed a harmonic structure for frequencies below 200 Hz. The band-level increase and the harmonic structure in the power spectrum was used to postulate that the breaking wave mechanism which give rise to its characteristic sound is the large collapsing air volume present for wave heights greater than 1 m. An approximate resonance frequency was calculated by modelling the wave as a pipe closed at one end, and the resonance frequency coincided with typical maxima found in the power spectra.

Significance for defence and security

Breaking waves along the shoreline can potentially mask airborne anthropogenic sounds, whether it is undesirable sound from human activity (e.g., offshore firing exercises, wind farms) or sounds from activities that should remain covert. Understanding the physical mechanisms that underlie airborne wave-generated sounds could allow for predictions of the resulting spectrum, which could be used for predicting the probability of detecting human activity near shore areas.

Résumé

Le son caractéristique des déferlantes fait partie intégrante du bruit ambiant le long de la côte. Les sons produits sous l'eau par les déferlantes ont été étudiés de façon exhaustive, mais très peu de travaux ont été publiés sur les sons aériens causés par ces vagues. On a analysé les enregistrements acoustiques obtenus dans le cadre d'une étude sur le terrain pour tâcher de déterminer les mécanismes de production des sons. De plus, un microphone a été installé à Osborne Head, en Nouvelle-écosse, de juin à août 2011, sur une falaise herbeuse surplombant une plage où l'activité des déferlantes est importante. Des photos, des données sur la météo et sur les vagues océaniques ont été recueillies pour faciliter l'interprétation des enregistrements audio. Les données contiennent en outre les enregistrements de certaines déferlantes et on a analysé leurs spectres de bande de tiers d'octave. Les niveaux dans les bandes de 40 à 200 Hz augmentent de 10 à 25 dB lorsque la déferlante survient, et on observe la hausse la plus importante dans les fréquences inférieures à 100 Hz. Les spectres de puissance des déferlantes montrent une structure harmonique dans les fréquences inférieures à 200 Hz. Par ailleurs, l'augmentation au niveau de la bande et la structure harmonique dans le spectre de puissance ont été utilisées pour établir que le mécanisme des déferlantes qui produit le son caractéristique est l'important volume d'air qui se comprime à l'intérieur des vagues d'une hauteur supérieure à 1 m. On a calculé une fréquence de résonance approximative en modélisant l'onde comme un tuyau bouché à une extrémité, et la fréquence de résonance coïncide avec le maximum qu'on retrouve généralement dans les spectres de puissance.

Importance pour la défense et la sécurité

Les déferlantes le long de la côte peuvent éventuellement masquer les sons anthropiques aériens, que ce soit un son indésirable attribuable à l'activité humaine (p. ex., exercices de tirs en mer, parcs éoliens) ou les sons produits par des activités devant rester secrètes. La compréhension des mécanismes physiques sous-jacents aux sons aériens produits par les vagues permettrait de prédire le spectre résultant, information qui pourrait permettre de prédire la probabilité de détection de l'activité humaine à proximité des régions côtières.

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1 Introduction

The purpose of this study is to unite two areas of research: ambient noise near the ocean surface and the physics underlying how waves break along the shoreline. Both topics have been extensively studied over the last century and much progress has been made in understanding these subjects and finding connections between them. This study will focus on plunging waves and the underlying physical mechanisms producing the airborne sound heard when listening to waves break along the shore.

For waves, the difference between breaker types and the role of wave height, water depth, and the bathymetry slope in forming a wave is well understood [1]. In the case of a plunging breaker, the wave will rise in height as it approaches the shallow water near the shore and will eventually reach a critical point where it begins to overturn [2]. The collapsing water from the unstable wave (known as the 'jet') will fall and strike the surface in front of the wave at a location known as the plunge point. The plunging jet will either be reflected or swept back into the wave by the quickly moving surface [2, 3]. During this process a plunging wave will entrain a cavity of air which will briefly be kept stable by the inward pressure gradient in the entrained tube [2].

Underwater air bubbles are created in a variety of ways, including the collapse of the air cavity, the splash of the plunging jet and by the highly turbulent region near the front of a wave [3]. It is well known that plunging waves create a plume of bubbles beneath the surface as it breaks [4, 5]. High- and low-frequency underwater sound is emitted from these plumes by single bubble oscillations and collective volume oscillations of the entire plume, respectively [6]. The emission spectrum of these plumes has been well documented [7, 8] and appears the 100 Hz–50 kHz region of the spectrum. Bubbles will also form over the entire surface of a breaking wave where they will oscillate and burst. The airborne sound from the bubbles bursting at a water surface has been studied by Spiel [9] who found the acoustical emissions to be in the 5–50 kHz frequency range.

Despite the extent of research done on these topics, very little is known about the airborne sound generated by breaking waves. Bolin and Åbom have proposed a model in which the volume oscillations of the bubble plume and single bubble oscillations are responsible for the sound produced from plunging and spilling waves, respectively [10]. Their measurements and model results show reasonable agreement, but not enough to fully describe the underlying processes. They conclude that the main airborne sound generating mechanisms remain a mystery.

This report aims to elucidate the physical mechanisms underlying the acoustic signature of breaking waves. Acoustic data from a field study done along the coast of Nova Scotia will be analyzed in an attempt to advance the discussion on sound-generating physical processes found in breaking waves.

2 Methods and data selection

Recordings were made of breaking waves at Osborne Head, Nova Scotia, Canada (44.612°N, 63.420°W) from June 1 to August 22, 2011. A microphone was situated on a cliff 6 m above a rocky beach that experiences abundant breaking wave activity. The instruments were approximately 20–30 m away from the high water mark. Five minutes of uncompressed audio data sampled at 25.6 kHz were recorded every half hour. A camera mounted on a nearby building acquired photographs of the surf zone every five minutes. Directional wave spectra and significant wave height (SWH) were measured at a location 800 m from the microphone site, while weather data were obtained from a weather buoy 12.5 km SE of the microphone site (due to problems with the installation of the on-site weather station).

Since plunging waves are the focus of this study, an algorithm was created to determine which audio clips most likely contained plunging breaking wave events. Thirteen isolated plunging breaking wave events were selected from the data set, with SWH ranging from 0.8 m to 1.8 m. Eight spilling waves events were selected from the same audio files as the plunging breakers to provide a comparison. Each wave was selected in times of low wind speed in order to avoid unwanted background noise. Relatively few audio samples fit the wind and wave criteria (likely because high waves are correlated with high wind speeds), making our sample size small compared to the size of the entire data set. The time of the wave break was determined by listening to the audio clip and manually marking the time the plunging water jet was heard making contact with the surface.

The plunging wave phenomenon produces impulsive sounds, with large instantaneous power increases in the acoustic signal. When time-averaged, the impulse signals from the breaking wave are drowned out by the ambient coastline noise. To isolate the plunging breaking wave event, only short time intervals surrounding the wave break are considered. All audio samples were high-pass filtered using a cutoff frequency of 20 Hz to remove all infrasound and the ensuing data analysis was done in Python using the Scikits Audiolab library [11].

3 Results

3.1 Variability

Time series of the one-third-octave band levels were constructed by first calculating the power spectral density (PSD) using a Fast Fourier Transform (FFT) of the pressure signal in lengths of 0.4 seconds (10240 samples) using a Hanning window and then summing the energy in each one-third-octave band with nominal centre frequen-

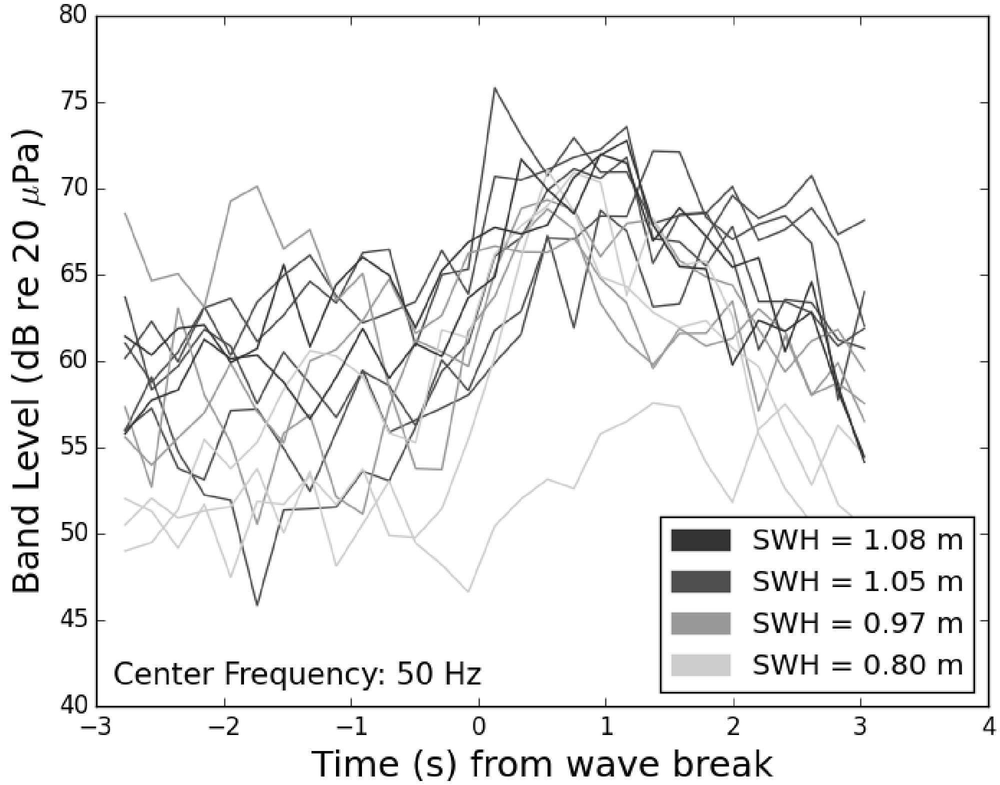

Figure 1: *Time series of the band level in the one-third-octave band centred at 50 Hz for all plunging waves considered in this study.*

cies ranging from 40 Hz to 2500 Hz[1]. The sliding window for each one-third-octave band level estimate was overlapped by 50% with the previous estimate to provide estimates every 0.2 s. Figure 1 is a time series of the one-third-octave band level centred at 50 Hz. Higher band levels typically correspond to larger significant wave height, but that is not always the case. The time-series plots of the other band levels are similar to Figure 1, with large variability in band level (± 10 dB) and waveform surrounding the break.

Determination of the airborne sound-generating mechanisms is complicated due to the large variability between each of the individual plunging waves. When considering a single plunging wave, the power in each band increases near the instant the wave breaks, but not all bands have similar responses. The increase in level will differ in timing and magnitude, and sometimes a band level will remain mostly unchanged as the wave breaks. The variability is also present when considering the ensemble of

[1] Upper and lower band limits for the n^{th} band with centre frequency $10^{n/10}$ were calculated according to the formula $10^{(n\pm0.5)/10}$ [12].

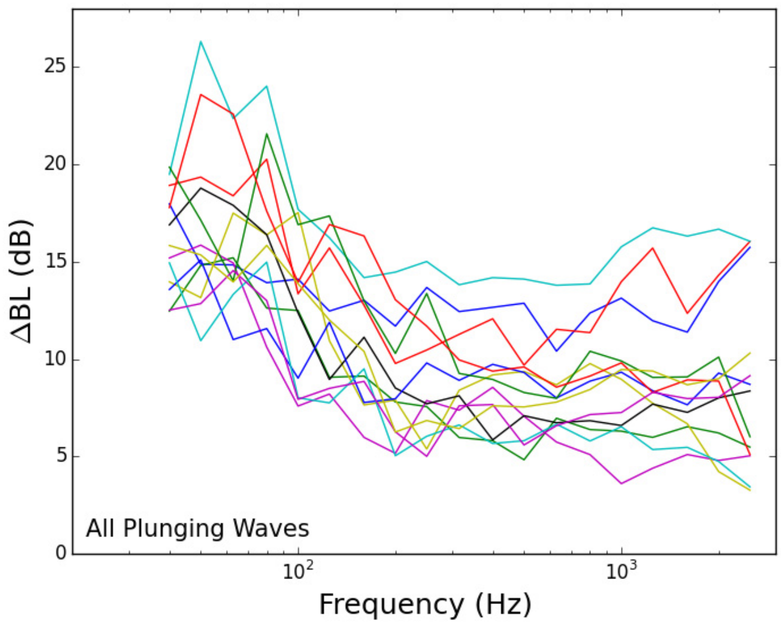

Figure 2: *Band level increase at the wave break for all plunging breaking waves.*

wave breaks. A single band will often show differences in the increase in magnitude between wave breaks, with some bands experiencing a considerable increase in one audio clip, then experiencing little to no increase in another audio clip.

However, the variability is not overly surprising since no two breaking waves sound similar. Three main distinct types of sound are heard in the audio clips: the 'whoomphing' or bellowing sound heard in plunging waves, the crashing sound also heard in plunging waves, and the spilling sound (a 'shhhhh' sound) inherent in all waves but heard in plunging waves after the wave break. The relative levels of these sounds accounts for the uniqueness of each breaking wave.

3.2 Band-level change

Since the power in each band increases as a wave breaks, a signature of the more dominant sound generating mechanisms can be identified by the differences in how each band responds during a wave break. The band-level change (ΔBL) across a wave break was calculated for each one-third-octave band by taking minimum band level before the break (BL_{min}) and the maximum band level after the break (BL_{max}) and taking their difference ($\Delta BL = BL_{max} - BL_{min}$). Figures 2 and 3 are plots of the band-level change for plunging and spilling waves, respectively.

Figure 4 compares the average band-level change between the two types of waves.

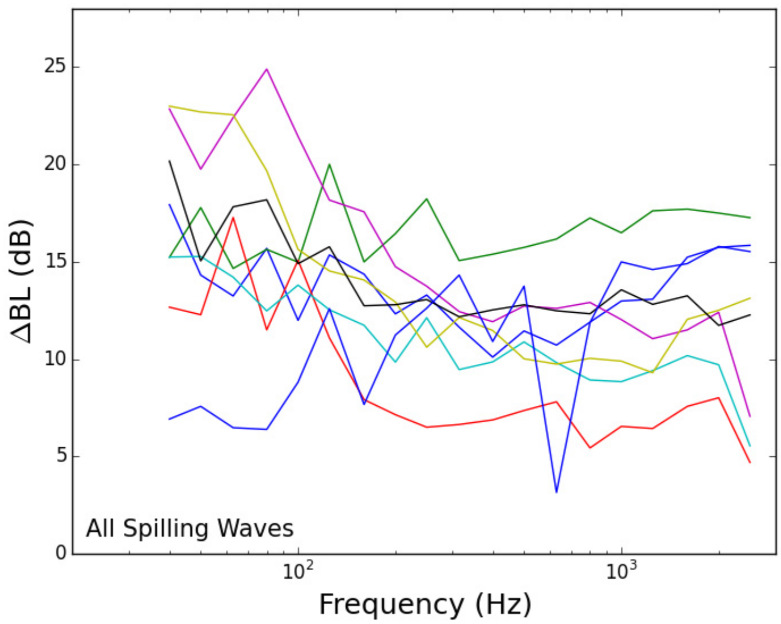

Figure 3: *Band level increase at the wave break for all spilling waves.*

Plunging and spilling waves exhibit similar band level changes in the low frequency regime ($f < 200\ Hz$), but differ at frequencies above 200 Hz. Spilling waves show a greater band-level increase than plunging waves in the frequencies above 200 Hz, which is reasonable since the prominent noise in a spilling wave sounds higher in pitch than that of a plunging wave. The mechanism producing the spilling sound is still unclear.

As for the bands below 200 Hz, the sound source appears to differ between the plunging and spilling breakers. There is little to no ambient wind noise in the audio clips, so it is unlikely that the low frequency sound is emitted from anything other than the waves. For plunging waves, the low frequency sound is heard as the familiar 'whoomphing' or bellowing noise produced just as the wave breaks. For the spilling breakers a constant low rumble is heard as the wave surges up the beach, similar in pitch to the bellowing sound of a plunging wave. Since both plunging and spilling waves do not seem to noticeably exhibit similar low-frequency sounds, it is likely that the large low-frequency band-level change in each type of wave (see Figure 4) is generated by different mechanisms.

3.3 Rise and relaxation time

A plunging wave is a rapid event, with most of the interactions and sound emission commonly lasting less than 2–3 s. Conversely, a spilling wave is a gradual event where

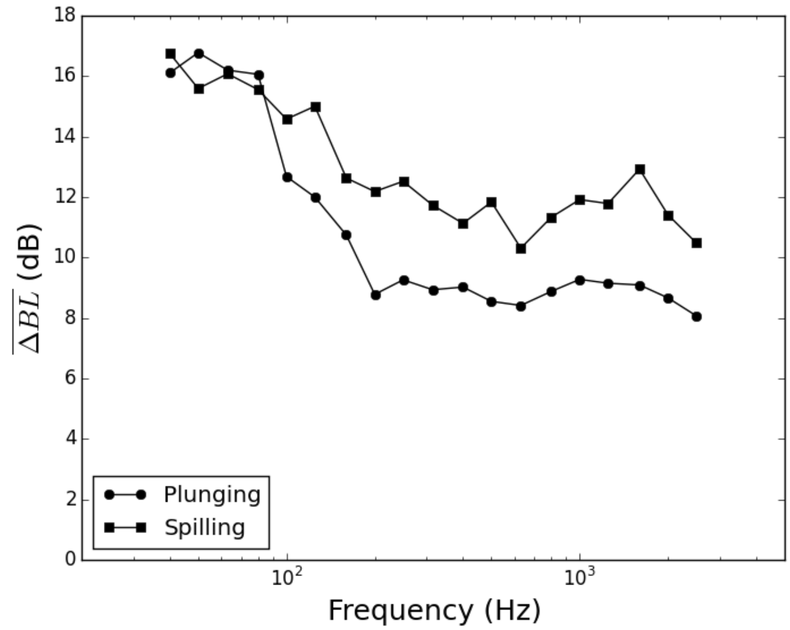

Figure 4: *Average band-level change for plunging and spilling waves.*

the band power slowly increases to a maximum as the wave surges up the beach, taking much longer to dissipate its energy. The difference can be characterized by defining a rise time (T_{rise}) and a relaxation time (T_{relax}) for each wave. The rise time is defined as the time interval between the minimum band level before the wave break and the maximum band level after the wave break. The relaxation time is defined as the time interval between the peak band level after the wave break to the point where the band level has dropped by 3 dB.

Figure 5 shows the average rise and relaxation time for plunging and spilling waves. It is clear from Figure 5 that spilling waves take significantly longer (2–3 s more) to reach their maxima. This strengthens the hypothesis that the low-frequency sound-generating mechanisms between plunging and spilling waves are unique, since similar sound-generating mechanisms would also likely have similar temporal responses. The relaxation time for frequencies less than 200 Hz are comparable between plunging and spilling waves, which is curious and a better understanding of the low-frequency airborne sound-generating mechanisms is needed for both plunging and spilling waves to explain this similarity. For frequencies above 200 Hz, the spilling wave relaxation time is greater than that of the plunging wave by 0.5–1.0 s. This is mostly likely because of the prominent spilling-wave sound being generated in this frequency range and the slower energy dissipation in spilling waves versus plunging waves.

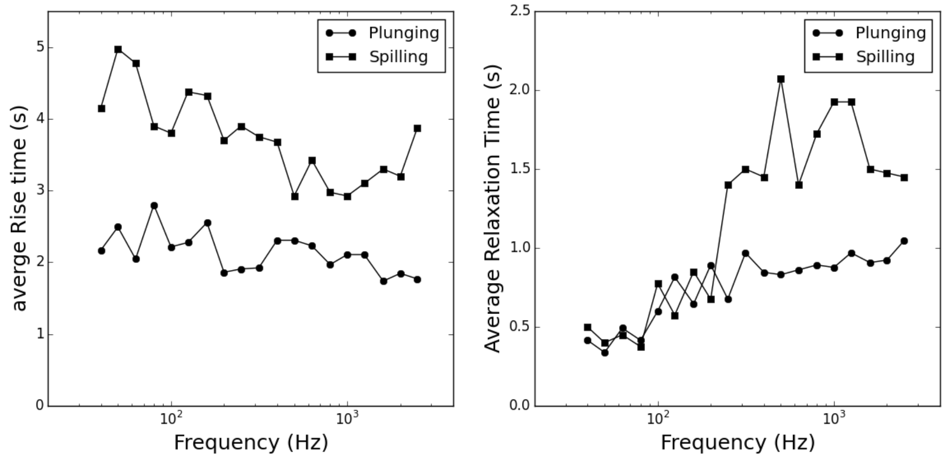

Figure 5: *Average rise time for plunging waves.*

3.4 Spectral analysis: organ pipe analogy

Plunging waves produce short bursts of sound which often last less than 2–3 s, as described in Section 3.3. Therefore, when examining longer spectral averages (e.g., minutes or longer) of breaking wave noise, the individual plunging wave signatures are not noticeable against the background noise from many waves of different types overlapping in time and space. In order to better characterize the sounds produced by plunging breaking waves, power spectra using time intervals of 0.4 s surrounding the break were calculated using Welch's method [13] with window lengths of 0.2 s and a 50% overlap.

Figure 6 is a power spectrum of the plunging wave with the most notable bellowing sound of all the waves in the data set. Most of the power is concentrated in the low-frequency portion of the spectrum, with a moderately sharp drop in power (10–15 dB) occurring near 200 Hz. A harmonic structure is observed in the low-frequency range, with pronounced peaks occurring at 34 Hz, 48 Hz, and 78 Hz that are accompanied by second (and possible third) harmonics. Other plunging waves in the data set display similar harmonic structure in the same frequency range, but with maxima occurring at different frequencies. The fact that no two power spectra share a similar set of low frequency maxima is another way in which the large variability between the waves is expressed.

A plunging wave will first break in the middle and proceed to collapse in both directions from where the plunging jet first struck the water. The manner in which this happens forces air and aerated water through the opening in the side of the wave, a phenomenon known to surfers as 'wave spit'. We propose that air travelling through the entrained air tube excites the resonance frequencies of the tube and is potentially

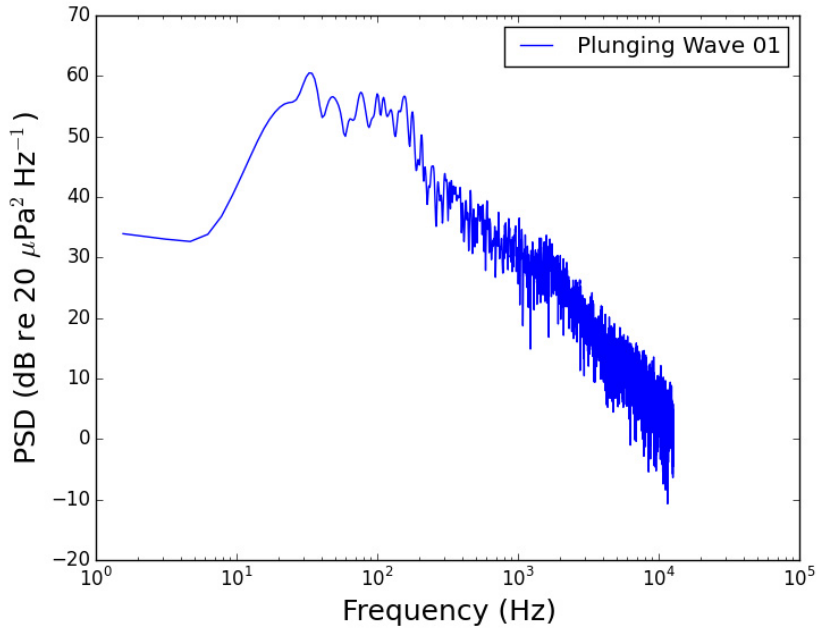

Figure 6: *Power spectrum of the 0.4 seconds after the break of a plunging wave.*

responsible for the low-frequency bellowing noise made by plunging waves. The forcing function described here is much like the forcing function in a flue-type organ pipe and a rough approximation of the resonance frequencies of the wave can be made by modelling the air tube entrained by the plunging wave as a cylinder that is closed at one end. The fundamental frequency f_0 of a closed cylinder is

$$f_0 = \frac{c}{4(L + 0.6R)} \tag{1}$$

where L and R are, respectively, the length and radius of the cylinder, and c is the speed of sound in air [14]. Photographs of the surf zone and knowledge of the SWH were used to estimate the dimensions of the wave. Using values of $L = 1.0$ m and $R = 0.25$ m in Equation 1 yields a fundamental frequency of $f_0 = 75$ Hz. Every plunging wave spectrum observed has a distinct maximum at or near this frequency, with additional peaks at integer multiples of the fundamental frequency. The particular wave shown in Figure 6 also has other low-frequency peaks, e.g., near 34 Hz, suggesting that the collapsing volume may have been longer than 1.0 m, or that several regions of different volumes were collapsing simultaneously.

As mentioned earlier, there is a great variability between each wave which is recognized in every type of analysis conducted in this study. Prominent peaks rarely occur at the same frequencies in the power spectrum, meaning the sound generating

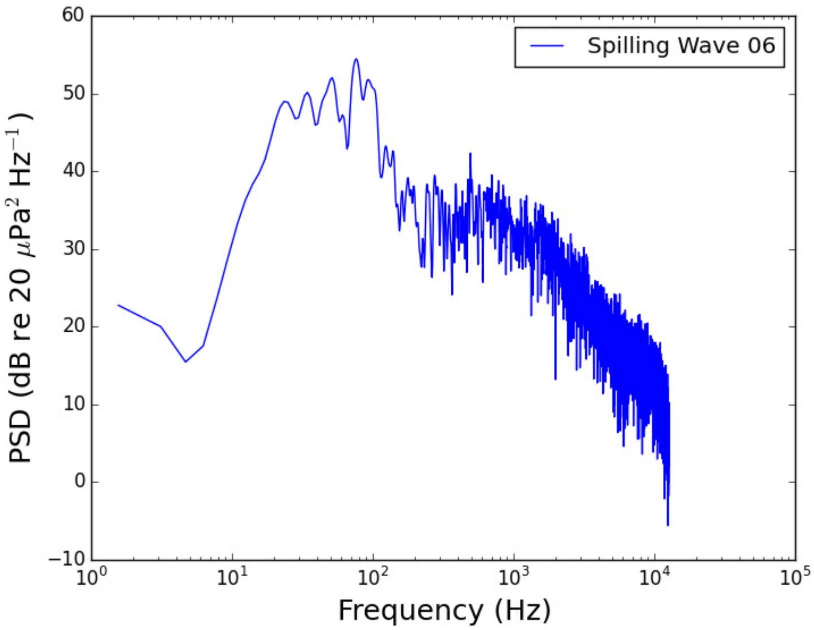

Figure 7: *Power spectrum of the 0.4 seconds after the break of a spilling wave.*

mechanisms must be somehow altered between waves. The flue pipe analogy provides and explanation for this variation, since the resonant frequencies of the entrained air tube depend on the geometry of the plunging breaker which would change between waves.

As a comparison, Figure 7 is a power spectrum of the 0.4 s after the break of a spilling wave, calculated using the same method as the plunging waves. The low-frequency maxima are similar to that of a plunging wave; however, closer inspection of the spilling wave spectra reveals that the harmonic structure in the low frequency maxima is less common than in plunging wave spectra. For example, the additional peaks in Figure 7 do not occur at any integer multiples of a fundamental frequency.

The power in the low-frequency bands (100 Hz and below) is approximately 10 dB less for spilling waves than plunging waves. For mid-frequencies (200–2000 Hz) the plunging wave power spectrum decreases and quickly resembles background noise. The spilling wave spectrum typically experiences a power drop near the 100 Hz band, approximately 100 Hz lower than the frequency at which the plunging wave spectra display a comparable drop. The power in the mid-frequencies of the spilling spectra plateaus and will often have distinct peaks that are absent for plunging waves, which further suggests that the sound-generating mechanisms specific to spilling waves produce sounds in the mid-frequency range.

3.5 Alternate sound-generating mechanisms

Other mechanisms have been proposed to explain the airborne sound generating mechanisms of breaking waves, including underwater bubble oscillations and water jet impact. These are discussed in the following sub-sections.

3.5.1 Underwater bubble oscillations

As mention in Section 1, Bolin and Åbom proposed that sounds from breaking waves could be due to the emission of sound by the individual and collective oscillations of the bubble plume beneath the wave. Bolin and Åbom's measurements and calculations yield broad peaks with maxima near the 200 Hz and 1000 Hz bands for the plunging and spilling waves, respectively. Both spectra show decreasing power for frequency bands below 200 Hz that is most likely due to their power spectra being averaged over five minutes of continuous audio recordings.

Bolin and Åbom's model for collective bubble oscillations produced by plunging waves predict that most airborne sound is emitted in the 100–300 Hz frequency range. The spectra of the plunging waves shows heightened activity compared to the spilling waves in the 100–200 Hz frequency band. This suggests that heightened activity in the this frequency range may be due to the collective bubble oscillations of the underwater bubble plume.

3.5.2 Water jet impact

Another possible mechanism for sound generation from plunging waves is the plunging jet impacting the water surface. The psychoacoustics field has produced many comprehensive analyses on the acoustic properties of small artificial waterfalls and fountains that can be used to mask urban noise. A recent study done by Galbrun and Ali [15] investigated the airborne sound produced by a 1.0 m-wide plain-edge waterfall at a height of 1.0 m falling onto a water surface. This scenario is very similar to the plunging jet striking the water in a plunging breaker. An octave-band spectrum of the waterfall showed that most of the airborne sound was emitted at a frequencies over 1 kHz, which is due to oscillations of the air entrained by water falling and breaking the surface. Galbrun and Ali's spectra also included peaks in the 100–200 Hz frequency range which they do not provide an explanation for. It seems plausible that this sound is produced by the impact of the falling water onto the water beneath, since there are no other obvious mechanisms in which sound could be produced in this scenario. It is then possible that a similar water impact mechanism is present in plunging waves and is contributing to the power seen in the spectrum in the 100–200 Hz range.

3.5.3 Relative contributions

The relative sound levels produced by underwater bubble oscillations and water jet impact are not easy to determine based on the scarce information available. Bolin and Åbom do not indicate how sound levels are expected to change with wave height. However, the water jet impact noise is expected to depend on wave height, since in the waterfall study, the A-weighted sound pressure level increased by 3–10 dB when the waterfall height was increased from 0.5 m to 2.0 m [15]. Therefore the relative contribution of both sound generation mechanisms (if present) is not easy to predict without further study.

4 Conclusion

Airborne acoustic data from the coastline near Osborne Head, Nova Scotia was analyzed with the goal of determining the airborne sound-generating mechanisms of plunging breaking waves. Time series of the one-third-octave band levels showed that the power in each one-third-octave band from 40 Hz to 2500 Hz increases the instant a wave breaks. The band-level change for each one-third-octave band was calculated and revealed that band levels near 100 Hz changed approximately 4–8 dB more than higher one-third-octave bands. The difference between high- and low- frequency band-level change was found to be not as significant in spilling waves (3–6 dB).

Rise and relaxation times were calculated for plunging and spilling waves. The average rise time for spilling waves was 1–2 s longer than in plunging waves. The relaxation time was similar between plunging and spilling waves for frequencies less than 200 Hz. For frequencies greater than 200 Hz the relaxation time for spilling waves was 0.5–1.5 s longer than for plunging waves. The differences in rise and relaxation times suggests that the airborne sound is produced by different physical mechanisms for the two types of waves.

Power spectra calculated for plunging waves revealed a harmonic structure for frequencies below 200 Hz. It was hypothesized that sound emitted at these frequencies may be due to air flowing through the open ends of the breaking wave and producing sound much like a flue pipe in an organ. The plunging breaking wave was then modelled as a cylinder which is closed at one end. Physical dimensions determined from inspecting photographs of the breaking waves were used to calculated a representative resonance frequency of $f_0 = 75$ Hz. All plunging waves in the data set had prominent maxima at or near the calculated resonance frequency with some significant second and third harmonics. The flue pipe analogy also helps to explain the variability seen between each of the plunging waves.

It is postulated that the resonance of the entrained air tube may be an important airborne sound-generating mechanism of plunging breaking waves. Other sound-generating mechanisms, such as collective underwater bubble oscillations and the impact of the plunging jet on the water surface, may also play a role in the airborne sound generated by plunging waves.

5 Future Work

A major obstacle in determining the main airborne sound generating mechanisms was the significant variability among breaking waves. For more rigorous analysis to be done, this phenomenon must be tested in a laboratory setting where a large wave tank can be used to generate plunging breaking waves with consistently similar properties. This would greatly diminish the uncertainty on wave geometry during for the breaking waves and also would allow the complete removal of all ambient ocean noise. A plethora of experiments of this nature have been conducted [7]; however, hydrophones were used to study the underwater sound generated by bubble plumes without making concurrent recordings of airborne sound.

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List of symbols / abbreviations / acronyms / initialisms

FFT	Fast Fourier Transform
PSD	Power Spectral Density
SWH	Significant Wave Height

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Dallas, C. A.; Tollefsen, C. D. S.

5. DATE OF PUBLICATION (Month and year of publication of document.)	6a. NO. OF PAGES (Total containing information. Include Annexes, Appendices, etc.)	6b. NO. OF REFS (Total cited in document.)
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The characteristic sound of breaking waves is an integral component of the ambient noise along the coastline. The underwater sound generation from breaking waves has been thoroughly studied, but very little work has been published on the airborne sound caused by breaking waves. Acoustic recordings from a field study were analyzed in an attempt to determine the sound generation mechanisms. A microphone was deployed at Osborne Head, Nova Scotia from June to August 2011 on a grassy cliff above a beach with abundant breaking wave activity. Photographs, weather and ocean wave data were collected to assist in interpreting the audio recordings. Individual breaking wave events were located in the data and their one-third-octave band spectra were analyzed. The levels in the 40 to 200 Hz bands increased by 10 to 25 dB as the wave breaking occurred, with the largest increases observed for frequencies less than 100 Hz. The power spectra of the breaking waves revealed a harmonic structure for frequencies below 200 Hz. The band-level increase and the harmonic structure in the power spectrum was used to postulate that the breaking wave mechanism which give rise to its characteristic sound is the large collapsing air volume present for wave heights greater than 1 m. An approximate resonance frequency was calculated by modelling the wave as a pipe closed at one end, and the resonance frequency coincided with typical maxima found in the power spectra.

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airborne sound; breaking waves; acoustics; wave noise

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