Capillary Wave Phenomenon

by

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Contents

Abstract

A special, unstudied class of capillary wave is studied experimentally. The wave phenomenon has a v-shaped wake pattern that trails a leading point source, which typically look like 'water beetle tracks' across water. Using digital cameras, the phenomenon is tracked both in the lab and the field. High speed videos are used to obtain qualitative descriptions of the phenomenology of the wave patterns forced by air moving over the fluid. Velocities are calculated for the point source and wake field in two fluids; water and mineral oil. Point speeds are as expected given the fluid properties and wake speeds seem to agree with known dispersion relation calculated phase speeds. The wave is found to be a forced wave that is likely the result of a moving air pressure structure over the fluid.

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Chapter 1

Background

1.1 The Capillary Wave Phenomenon

Ripples observed on the surface of a puddle or pond are most often classified as capillary waves. Unlike larger gravity waves, surface tension provides the restoring force for such waves. Both types of waves are forced by pressure or stress of the air over the water. Waves can also be forced by a displacement of the surface, e.g. by dropping a stone into water. Surface gravity waves are thought to develop from capillary waves and such waves play an important role in the energy transfer between the atmosphere and puddles, ponds, lakes and oceans.

When a gust of wind blows over a calm surface of water, the first signs of a surface disturbance on the water are capillary waves. [1] A small breeze results in the creation of dark patches on the water known as cat's paws. Similarly gusts also form wavelets, that are seen as ripples. They form 'remarkably regular diamond-shaped patterns', that quickly dissipate as the gust dies out. [1] Complex patterns of such waves are often observed in nature. Presumably due to the superposition of varying capillary actions and wavelets, these patterns change quite unpredictably with time.

The question arises whether or not all observed patterns consist of capillary waves showing such regular patterns.

Typical capillary waves generally have a front or a wave train. Waves like these are often formed on the forward face of short gravity waves.

Figure 1.1: Capillary waves forming on the forward face of short gravity waves. [2]

Similar capillary waves occur on their own without the gravity waves as seen in Figure 1.1. An observer would recognize such disturbances as a result of some solid body transferring energy to the water, for example the rings of waves that propagate radially outward when a pebble is tossed into a pond. These same ripples can also result from a light gust of wind on a calm surface.

Figure 1.2: Capillary waves often show a wave train. [3]

These capillary waves have been observed, and their dynamics understood, for a long time. Under this classification of capillary wave however, there exists a form of wind-generated wave that does not exhibit the same general shape or type of propagation traits of a 'typical' wave. As seen in Figure 1.3, this class of wave appears to have a v-shaped wake trailing behind some unknown propagating object. These waves resemble the pattern of a wake that results from a water beetle's trek across a small body of water, yet they clearly move much too quickly to be caused by an insect. This wave resembles that resulting from a small body moving through fluid. In this case the leading front seems to be a point source.

While the typical pattern is a v-shaped wake, other varied patterns do also occur. On occasion, the point source follows a curved path resulting in a curved wake pattern. We have also observed the point source produce circular eddies at various points along its path. The main difference between these special waves and typical capillary waves is that these waves are single waves that do not exhibit a wave train, or show a regular

Figure 1.3: The Capillary Wave phenomenon. This event was captured in the field, occurring naturally. The red arrow indicates the point source. The v-shaped wake is barely visible to the left of this point source.

pattern of ripples.

Resulting naturally from a strong gust of wind, these waves are readily apparent on puddles or small bodies of water. When trying to generate these waves in the lab, it becomes obvious that the wind required has to be in the form of a short, brisk gust. Usually such wind conditions in nature tend to accompany persistent winds which produce gravity waves, on large bodies of water, that obscure the waves in question. Thus more ideal conditions exist in smaller bodies of water where gravity waves do not have enough room to develop and mask the affects of these irregular capillary waves.

When an appropriate gust of wind blows over the water, the wave phenomenon develops and quickly propagates over the surface of the water and dissipates after a short period of time, roughly 0.1s on a one square meter body of water. We have observed these events to persist for longer periods of time, but only on larger bodies of water.

Considering the required conditions for development, it is not surprising that these waves are only observed intermittently in the field. For this reason, it is more effective to study the waves in the lab where the waves can be generated repeatedly.

We have been unable to find any previous research done on this class of capillary wave. The process by which they are formed is not yet known, nor the means by which they propagate.

There is no apparent reason why these waves must be capillary waves and not gravity waves. The mechanism used to generate these waves may or may not restrict the disturbance to this class of wave (capillary). Before trying to fit these waves into a model there is some theory that is useful to review.

First, it is necessary to review the characteristics of regular capillary waves and note their comparisons to this special case. Second, current wind wave generation models become important for two reasons. While these models are less than complete, fitting these capillary waves into a model will improve, in general, the understanding of the phenomenon and lead towards development of a dynamical model. In doing so it is also helpful to look at general fluid properties such as turbulence and vorticity which are possibly important to the formation of these waves.

1.2 Theory

1.2.1 Wave Theory of Capillary Waves

Water waves of any type are described as a boundary value problem. The water-air surface acts as a ‘free’ surface, which differs from a solid boundary. Solid boundaries cannot sustain pressure variations and must maintain a uniform pressure thus producing a boundary condition that the pressure be constant. Free surfaces can sustain pressure variations and these pressure variations can be related to velocity and height of an ideal fluid as described by the following Equation,

$$\frac{\partial\varphi}{\partial t} + \frac{1}{2}(u + v)^2 + \frac{P}{\rho} + gz = C(t) \tag{1.1}$$

where the pressure, P, is no longer constant. Here φ is the velocity potential and is defined by $u = \nabla\varphi$. The variables u, w, C(t), are velocity in the x and y directions and integration constant respectively. Equation 1.1 is the time-dependent general form of the Bernoulli equation . [4]

For capillary waves, as already mentioned, surface tension provides the restoring force. Surface tension is a boundary property at the surface of the water because of the absence of strong molecular bonding above the molecules that sit at the surface. The surface molecules feel as great an intermolecular force as do the interior molecules. As a result there is a different arrangement of force on these surface molecules to keep them in place, leaving a tension between these water molecules at the interface.

If capillary waves have short wavelengths for which surface tension is more important than gravity as the restoring force then such a boundary condition invokes a modification to the Bernoulli equation (1.1), which can be rewritten as,

$$\frac{\partial\varphi}{\partial t} + \frac{1}{2}(u + v)^2 - \frac{\sigma}{\rho}\frac{\partial^2\eta}{\partial x^2} + \frac{P}{\rho} + gz = C(t). \tag{1.2}$$

Here σ and η are the tension per unit length and the displacement of the water from equilibrium respectively [4]. If the surface tension per unit length σ is dominant then Equation 1.2 becomes,

$$\frac{\partial\varphi}{\partial t} + \frac{1}{2}(u + v)^2 - \frac{\sigma}{\rho}\frac{\partial^2\eta}{\partial x^2} + \frac{P}{\rho} = C(t) \tag{1.3}$$

where the gravity term is neglected.

1.2.2 Capillary Waves

The linearized solution to the wave problem in the presence of surface tension for $z = 0$ is,

$$\frac{\partial\varphi}{\partial t} = \frac{\sigma}{\rho}\frac{\partial^2\eta}{\partial x^2} - g\eta \tag{1.4}$$

where σ is the surface tension.

The dispersion relation for these waves is given by the following equation,

$$\omega = \sqrt{k(g + \frac{\sigma k^2}{\rho}) \tanh(kH)}. \tag{1.5}$$

The phase velocity of these waves $c = \frac{\omega}{k}$ is given by [4],

$$c = \sqrt{(\frac{g}{k} + \frac{\sigma k}{\rho}) \tanh(kH)}. \tag{1.6}$$

The phase velocity versus wavelength shows that there is a minimum phase velocity at roughly $\lambda = 1.73$ cm with $c_{min} = 23.2$ cm/s or 0.232 m/s. For wavelengths of less than 7 cm, the surface tension is the dominant force and the waves, or ripples, are pure capillary waves for which,

$$c = \sqrt{\frac{2\pi\sigma}{\rho\lambda}}. \tag{1.7}$$

The speed of these waves depends only on wavelength $(\frac{1}{\lambda})^{1/2}$, the density $(\frac{1}{\rho})^{1/2}$ and the surface tension $\sigma^{1/2}$. Note that the shorter waves travel more quickly than do longer waves.

1.2.3 Wind-Water Wave Model

The general model for wind wave generation is not really well established and there is no clearly accepted mechanism to explain their generation. What is currently known, as seen in basic wind generation models, does not explain fully the observed characteristics of waves formed by wind. One present shortcoming in trying to describe how surface gravity waves develop so quickly from a calm surface. A number of wave models exist today, some much more complicated than others. It is best to start with the most basic theory. [5]

The initial waves generated on a calm flat surface are generally considered to be the capillary waves as described above since they begin as waves of very short wavelength. Pressure gradients in the air at the water-air interface are the mechanism by which the first wave are formed on a flat surface of a fluid.

The presence of capillary waves leaves a water surface that is no longer flat. The newly roughened surface of the water allows for further development of waves. Gravity waves can form as the wind continues to blow over this rough surface. Unlike the initial flat surface only allowing the action of normal forces, a surface covered with capillary waves permits tangential forces. The wind can then blow over the water and push behind the small ripples directly forcing the water.

If the wind forces are strong enough and persist for long enough then gravity waves will develop. As this occurs, further wave growth becomes more complicated. With large peaks and troughs at the water-air interface, large pressure differences can develop. If these pressure fluctuations stayed in constant phase with the surface waves then the waves on the surface would grow exponentially. This model, known as the Resonance Model, may explain how waves are able to develop so quickly. This model allows forcing of waves beyond the requirements of turbulent air, whereas the initial development of the capillary waves does not.

1.2.4 Boundary Layer Turbulence

Forcing of waves is clearly related to the structure of the lower atmosphere boundary layer, which is often turbulent. Boundary layers occur at the surface of a fluid in a viscous flow. The reason for this is that one fluid seems to stick to the surface of another. Because the fluid is viscous, this fluid transfers momentum to the surface layer. Thus a thin layer of fluid with lower velocity than the outer flow develops.

This transfer of momentum can be carried to deeper layers of the second fluid. No matter how much momentum is transferred, the relative motion at the interface between the two fluids will remain zero. This is due to the no slip condition. This boundary layer activity is initially laminar, however, this layer does not necessarily remain laminar. These layers move against one another and begin to grow in thickness. As they grow in thickness, mixing begins to become uneven and eddies start to form. Nonlinearities in the flow field cause instabilities which lead to the transition to turbulent flow.

It is in this turbulent boundary layer, in which small scale structures develop and dissipate energy that the forcing conditions for the observed capillary waves likely form. As introduced by Gibson [6], Fossil Turbulence may be a more specific possibility for the description behind this class of wave. Fossil Turbulence is defined as a fluctuation in some hydrophysical field of the fluid caused by turbulence that persists after the flow ceases to be turbulent at the scale of the fluctuation. The remnants from this phenomenon may not be turbulent, but actually conserve the properties or hydrodynamic state of the fluid before turbulence ceased. [6]

The capillary waves of interest may be formed in some turbulent manner and then simply propagate in the absence of turbulence and collapse after some short time. What one might actually be seeing is the propagation of features in the turbulent boundary layer that are carried on the mean flow and force displacements in the air-water interface, possibly through pressure differences rather than surface stress. This would explain the short lifetime and the observed patterns of surface structure.

1.2.5 Boundary Layer Vorticity

Consideration of turbulent motion in air naturally leads to a discussion of vorticity. Vorticity can be defined in terms of elements of fluid in the shape of a line. Two perpendicular fluid lines each rotate and have some average between them. From this rotation develops the net effect, angular velocity of the fluid. Vorticity is defined as twice the angular velocity. [4]

Mathematically, vorticity is related to the velocity vector $u(x,t)$ in Equation 1.8,

$$\omega = \nabla \times u. \tag{1.8}$$

This vorticity vector, ω, quantifies the local rotation of a element of fluid about its center of mass. [7]

Closely linked to vorticity is the scalar quantity Circulation. Circulation is defined over a closed loop, or contour is introduced into a flow field. It is defined as the surface integral (around a contour C) of the dot product between the velocity vector and a contour element ds as stated in Equation 1.9 (See Figure 1.4). [4]

$$\Gamma = \quad u \cdot ds \tag{1.9}$$

Circulation leads to an interesting consequence in the form of a theorem. A vortex tube is a fluid volume bounded laterally by “vortex lines” (parallel to the vorticity vector $\omega = \nabla \times u$) (Figure 1.4). [8]

Figure 1.4: A vortex tube with circulation Γ. [8]

It can be shown that by taking the time derivative of Equation 1.9 and using Euler's equation, gives Kelvin's Theorem.

$$\frac{d\Gamma}{dt} = 0 \tag{1.10}$$

An example of such a vortex tube would be the drain in the bath tub when a "whirlpool" forms over the sink. If a vortex tube results, a shearing flow must have been present initially. The presence of the sink allows the gravitational force to do work. It creates a three dimensional vortex tube. A somewhat similar process is responsible for larger vortex tubes known as tornados [4].

Vortex tubes become relevant to this problem when considering reasons for displacements in the water-air interface. This disturbance may be a feature in the turbulent boundary layer, namely a vortex tube in the air that approximates a 2-dimensional vortex at the interface.

1.2.6 Outline of Thesis

In the next section, a description of the experimental approach will be presented. Results of the experimentation will be given in Chapter 3 with discussion to follow in Chapter 4. Chapter 5 will contain a brief summary and some conclusions. Scripts used for analizing data will be included in the Appendices.

Chapter 2

Approach

2.1 Apparatus and Setup

Having observed these waves in the field, our experimental goal was to develop an approach that would allow reliable generation of the waves. We want to measure the characteristics of the waves and explore conditions under which they are formed. Once these goals were achieved we focused on establishing a method for generating the waves that was not only reliable but repeatable and consistent as well.

Repeatability means that we can continuously generate the phenomenon using a technique that is the same each time. While the apparatus developed is still limited in that they only allow a qualitative description of the forcing conditions, it has allowed us to quantify different aspects of the wave propagation, that will be discussed in Chapter 4.

With the experimental approach in mind the first task was to find an appropriate apparatus and image analysis techniques.

The first and most important piece of equipment was the digital camera (Model: SONY DCR TRV25). Digital image stabilization is one of the most important features of the camera as it ensures that the camera does not move during capture, thus preventing the change of the view field and altering the results. This does become an issue especially when capturing waves produced naturally by the wind. The camera is a Megapixel camera and has 10x optical and 120x digital zoom for optimally clear images. This choice of camera proved to be sufficient in tracking the properties of the phenomenon, however the standard frame rate of 30 fps did not seem to track all the details of the wave propagation. The waves moved too quickly to be easily tracked at such a low frame rate, at least for the particular experimental configuration as described above.

To capture a more detailed video of the wave propagation, a high speed camera system was also used. The MotionScope PCI Series is a PC peripheral that allows high speed image capture directly to the PC. Once the videos are captured, the images of the event reside on the RedLake MASD MotionScope PCI board in the PC until transferred over the computer's PC bus for display and analysis. The software used with the system is RedLake Imaging. Playback rates range from 1-1000 Hz. [9]

Figure 2.1: MotionScope PCI Series high speed camera and RedLake MASD MotionScope PCI board. [9]

Along with this camera setup, an automatic trigger is used to detect motion and capture the event with the camera. The triggering takes place when a given percentage of bright pixels change to dark pixels or vice versa on a monitor. Once the trigger is activated it detects a given wave event and tells the camera to record the event.

While the camera does allow a higher frame rate, there are trade-offs. As frame rate gets higher, the resolution of the camera decreases. In the case of the experimental lab setup, the reduction in the field of view is from an area of 1 m^2 to that of about 40 cm × 40 cm. A higher frame rate also requires more lighting. So with a given light source one loses brightness and contrast as higher frame rates are used.

A choice of two different types of tanks was made to contain the capillary waves. For the outdoor experiment a wooden box was constructed with approximate dimensions of 3 m by 1m with a 4-inch depth. To prevent reflections of waves off the sides of the tank caused by the blowing wind, sponge like strips were place around the upper inside of the tank to act as dampers. Dexion beams were fastened to the sides with guide wires for added support. The background color on the floor of the tank was chosen to be a light gray to help provide contrast for the shadows of the waves.

For the lab experiment, a Plexiglas tank was constructed with 1 m by 1 m dimensions with a depth of 4 cm. A Plexiglas tank allows for different types of lighting/background techniques to be used.

When in the lab, the issue of generating wind arises. The simplest way to generate the aforementioned waves is to simply blow across the surface of the water. This proves to be quite effective. Ideally however, a mechanical process is preferred for generation of the waves. Such a process allows one to reproduce the results consistently. For that a piston was constructed. ABS piping acts as the outer tube of the piston and a metal cylinder was cut to fit just inside. Dropping the cylinder forces air down the vertical column and out through a small diameter vinyl hose. A small clamp, such as an alligator clamp, may be used to pinch the aperture of the hose ending to obtain the desired affect.

Although this technique does in fact produce the desired waves, they are of small amplitude. These waves dissipate very quickly, and are not good enough to produce useful videos. For that reason, a second technique was devised. Instead of ‘mechanically blowing’, this apparatus uses a waving motion of a solid object to generate wind.

The actual mechanism used is a ‘bungee-cord loaded’ lever. It was constructed of a hinged lever that was attached to a solid body by an elastic cord. To operate it the lever was pulled to some measured angle and released. The lever was situated so that it would swing over the surface of the water. This device generated the phenomenon in such a way that useful videos could be obtained.

Lighting also proved to be important for obtaining useful imagery. In the outdoor setting the best results were achieved with an overcast setting, where the light source was not as intense as direct sunlight, and the light field was diffuse.

In general, for lighting in the lab, diffuse and/or broad lighting is required. To achieve this, 120 W floodlights were used with lamps on flexible arms. For lighting from underneath a portable light box was used with four 24-inch, 20 W fluorescent light bulbs. This was made diffuse by placing a white sheet of paper over the surface of the light box.

Light needed for the MotionScope camera was necessarily much brighter. One high power outdoor flood light was used. It was positioned on a tripod that extended about 1 m above the tank and was directed onto the water surface at about 45 degrees.

With the apparatus at hand, there were several possible techniques to be used in the lab. Only one proved to be worth using, but the others are worth mentioning as they may prove to be useful in the future.

The lighting from underneath as it turned out, was not desirable. In this arrangement, the camera is above the tank looking directly into the light source or light box. However, one could use a different light source; say the defocused beam from a slide projector, below the tank pointed upward. Then some translucent sheets between the projector and the subject could be used to further diffuse the light. This could potentially provide excellent contrast. The first attempts with this method, however, resulted in less than adequate visibility.

A much more complicated method, known as a “reflection schlieren” system, seemed ideal but was too technically complicated for this preliminary study. It is best to describe the system in terms of Figure 2.2 below. Three diagrams of an optical system for schlieren photography of liquid surfaces can be seen in the figure. In each diagram the light source D projects a beam through the field lens H to the large mirror I which is positioned at 45 degrees above the liquid surface and slanted slightly sideways. Rays reflected from the liquid are directed to the small mirror E and thence to the camera lens which houses the knife edge or diaphragm assembly and come to a focus on the ground glass G. The lowest perspective view shows an idealized liquid surface with area A supposedly flat and B and C sloping towards (+) and away from (-) the camera. One half of the ray-bundle reflected from A is intercepted by the knife edge at F and the other half produces a grey image of A on the ground glass. Rays reflected from B miss the knife edge and form a bright image of B in the camera. Since most or all of the rays from C are intercepted, a dark image of C appears by default on the ground glass. [10]

The actual setup (Figure 2.3) that was used involved using a compact light source several feet above the tank and a white, featureless screen on the floor several feet below the tank. For this, one of the outdoor floodlights was placed about 1 meter above the tank and slightly off to the side as not to produce a reflection of the actual

Figure 2.2: Schlieren system. [10]

light bulb in the video. A few inches below the tank was a large sheet of blank white Bristol board. With this, it was possible to cast shadows of small surface features onto the screen with good contrast. It allowed observation of small amplitude ripples; exactly as required to view the surface waves. The camera was placed directly above and normal to, the water surface. Even though two such lights were available and could potentially increase the lighting for the camera, only one was used to ensure that only one shadow would be cast on the back drop.

2.2 Procedure for Test and Analysis

The protocol was standard for all variations of the experiments conducted. Once video was obtained from the regular DV camera, it was imported to an iMac. It was imported using the standard Macintosh video software, iMovie. It was in iMovie that the movie was edited to contain only the necessary frames.

It is also important to note that iMovie is where the digital effects can be used to enhance the videos. Adjusting the contrast and brightness often proved quite

Figure 2.3: Actual Setup.

effective in making the phenomenon more visible. Most cases involved just increasing the contrast to about $\frac{3}{4}$ maximum.

Once a given video was modified to the proper size and contrast it was exported into QuickTime format. The settings for exporting the movie are the default settings under Export. After the file has been exported it can then be opened in the VideoPoint software.

For the MotionScope, the videos exist in the RedLake MASD MotionScope PCI board in the RedLake imaging software before they are saved to the PC disk. Once a video is ready to be saved it can be compressed or remain uncompressed. In order to be used in VideoPoint, the videos must be compressed.

When the videos from either camera are in VideoPoint it is possible to produce displacement, velocity, and acceleration graphs for any object in the video to be analyzed. (As an important side note, there must be an Object of Known Length, abbreviated as OKL, in the video.) The program requires you to track the object on each frame on the video, adding a scaling factor based on the object of known length, and setting an origin. With these steps completed, it simply remains to select New

Graph to obtain data.

In addition to using VideoPoint, some analysis was also done in Matlab. If the data is extracted from the Sony DV, VideoPoint can be used to obtain the coordinates and times of the object that is being tracked. Data from the highspeed camera must use the RedLake Imaging software that is used with the camera to obtain the coordinates of the given points. In either case, the data is exported from the software and saved as a data file. The file can then be modified so that it contains only columns of data (i.e. a column each for x, y and t) with a space or some other delimiter. From this point the data can than be imported as matrices into Matlab for analysis.

Matlab can be used in a number of ways to analize the data. Velocities and acceleration can be calculated in Matlab as an alternative to using the other video software. With the highspeed camera system in particular the software allows one to obtain coordinates for multiple points on a given frame. This feature permits the generation of plot that represents the basic outline or profile of the phenomenon, which can prove to very useful.

With a procedure in place, a test of the main method of analysis is always ideal. One should make sure that the results one obtains are valid, especially in such a technical system being used here. To do so here, a determination of the acceleration due to gravity was calculated using the same technique.

The camera system was used to capture an object in free fall. After doing the video analysis with VideoPoint a value of 9.80 m/s^2 was achieved. This was a clear indication that following the same procedure for finding velocities of water waves would also be valid.

In order to find out exactly what VideoPoint did to calculate velocities and to test its reliability, velocities were calculated independently from VideoPoint. The time intervals and displacements were taken from VideoPoint. Before conducting the test however, the validity of these extracted displacements was first confirmed. In order to test the scaling and translation from pixels to distances, a video was captured with two objects of known distance visible. Then the procedure was followed using one of the objects. If the procedure produced accurate displacements, the Distance function in the program should produce an accurate interpolation for the length of the second OKL. This was in fact the case.

To test the velocity calculation the times and displacements were put in spread sheet form and saved in Notepad as an ascii data file. As an ascii file the data could be imported into Matlab. A short script named Velocity was written to calculate velocities (and accelerations) and plotted them versus time (The script can be found in Appendix A). Velocities calculated in Matlab are simply done by getting the difference in consecutive displacements and dividing by the time difference.

The result is that the VideoPoint graphs are smoother. It turns out that VideoPoint uses a 4-point algorithm that smoothes out the changes in velocity. What is more, the algorithm does not accurately reflect the changes between each of the points. That is where the Matlab script becomes useful.

Another technique for analysis that was used was Particle Imaging Velocimetry or PIV. PIV is a method that tracks particles and calculates velocity and vorticity fields. In order to do this, a Matlab script known as Partim [11] is used. It of course requires two consecutive pictures from the video, at least one of which has a scale. The program requires input of the length of the OKL and a the number of pixels that it encompasses which can be found using a program like Paint that gives you pixel coordinates.

Usually when using PIV there are physical particles that are inserted into the water. Instead of doing so here, the images of the phenomenon where digitally enhanced using other functions in Matlab. The enhancement is a topographical one, which generates a black and white picture with the brighter being higher and the darker ones being lower. The program can then track these contrasts as particles.

A new script was written incorporating this enhancement and PIV, and is called Impiv. It can be found in Appendix B.

One experiment involved the generation of typical capillary waves. To do so a small object was dropped from a height above the surface. The object chosen was a small droplet of water. It was small enough and disappeared afterwards, thus not being an obstruction to the ripples. The height at which it was dropped was based on attaining approximately the same amplitude as the waves being studied.

Chapter 3

Results

3.1 Initial Results

Through digital enhancement of the wave (done using a filter in Matlab) it is evident that there is a distinct structure to the phenomenon. Although we have observed many different wave patterns, they generally fit that seen in Figure 3.1. Because this particular event was captured while occurring naturally outside, the frames required enhancing in order for the structure to be visible. When generated in the lab, the structure of the wave was more easily visible, requiring little or no enhancement (Figure 3.2).

In the first frame, it can be seen that there is an elevated stem-like structure at the beginning that is trailed by a V-shaped wake. In the next frame, the stem is replaced by a point. This also holds true for the next 2 frames. In the last frame, the leading point can be seen as having a depression or dimple.

Figure 3.1: Enhanced pictures of phenomenon occurring in nature. 1, 2, 3 and 4 are video frames that are in sequence that occur 0.033 s apart.(Darker regions indicate depressions and higher brighter regions are elevated) Frame 4 is the same as the unedited picture in Figure 1.3. Here the v-shaped wake is more visible.

3.2 Lab Experiments and Velocity Plots

Most of the results presented here come from waves generated using the bungee-cord loaded lever. Different trials were taken with both water and mineral oil as the fluid medium. (Fluid properties are listed in Table 4.1) For each trial, the lever arm was pulled back to some known angle and released. Two different angles were chosen for analysis. For water; one at 142 degrees and one at 170 degrees, for mineral oil; two at 142 degrees and one at 170 degrees.

Two sample images from a mineral oil trial (Figure 3.2) show that many different ripple patterns are present on the water with quite distinct wake patterns formed at the leading edge of a general area of surface roughness. The figure illustrates the geometry and position of the tracked wave (bright v-shaped wave) at two different times for a mineral water trial at 142 degrees. Other trials looked broadly similar to this one.

Figure 3.2: Two frames from a mineral oil trial at 142 degrees. The tracked wave is seen as the only bright v-shaped wave at t = 0.0 ms and the bigger one at t = 104.0 ms. An edge of roughness is outlined by the black curve.

3.2.1 Digitization

Just how the geometries of these waves change with time is not obvious from the extracted frames. For that reason, a digitization of the event was done and plotted in Matlab (See script in Appendix C for digitization script). By determining the coordinates of a number of points on the wave, the outline of the wave was traced out using RedLake Imaging software. The digitization was plotted for several times, from initiation to about 100 ms, along the path of a given event.

Figure 3.3 shows the digitization for the same evolving wave-front in the mineral oil as seen in Figure 3.2. The first and last frames that are digitized, corresponding to t = 0.0 ms and t = 104 ms, are the same frames in Figure 3.2.

Digitization of a 142 degree trial in water is given in Figure 3.3. Both figures illustrate the geometries and the associated times in milliseconds.

The digitization shows, for the most part, that the waves tracked have wake fields that stay roughly parallel with time. In other words, the ‘leg’ of the wake field in the digitization at t = 0.0 ms is roughly parallel with those at successive times.

Figure 3.3: Digitization of a 142 deg Mineral Oil trial.

Figure 3.4: Digitization of a 142 deg water trial.

Furthermore, the point source or leading edge follows a relatively straight line path. Both these aspects support calculations that will be made of wake and point source velocities.

3.2.2 Velocity Plots

The repeatability of the wind generation technique becomes important when comparing velocity measurements of waves generated in both mineral oil and water. Through use of the bungee-cord loaded lever released from some known angle, waves could be generated in the exact same way on each of the two surfaces and their average velocities could be calculated. The patterns formed do change with each trial but the intensity and overall character of the forcing is relatively the same.

Velocities obtained for each fluid were found using videos taken of the phenomenon generated by pulling the lever at 142 degrees and 170 degrees. Displacements and times of the leading point source were found using VideoPoint and plots of displacement versus time were made in Matlab.

Figures 3.5 through 3.8 are plots for water trials. They include wake and point velocities for both angles.

Figure 3.5: Plot of displacement versus time of the point source for a Water trial at 142 degrees. The linear fit gives an average velocity of 1.64 m/s

Figure 3.6: Plot of displacement versus time of a wake for a Water trial at 142 degrees. The linear fit gives an average velocity of 0.271 m/s

The plots include error bars estimated by the uncertainty in clicking on a given pixel when tracking an object in VideoPoint. Using an uncertainty, δpixels, of ±5 pixels gives an uncertainty of $\pm 2 \times 10^{-3}$m by using the equation,

$$\delta d = \frac{\delta \text{pixels}}{\text{resolution}} \tag{3.1}$$

where the resolution is a result of the VideoPoint calibration and has a value of 25.5 pixels/cm.

Each plot of displacement versus time also includes a fit. VideoPoint has the option of fitting the data to an equation, in particular a linear fit. A linear fit in this case will give the slope of a line which represents the average velocities. As can be seen in most of the figures (e.g. Figure 3.5), there is some small variation in the data points about the fit line, thus the actual slope represents the mean of these values.

The graphs look generally the same for the mineral oil events. The plots, along with the fits, for all these trials are presented in Figures 3.9 to 3.14.

Figure 3.7: Plot of displacement versus time of the point source for a Water trial at 170 degrees. The fit gives an average velocity of 3.44 m/s

Figure 3.8: Plot of displacement versus time of a wake for a Water trial at 170 degrees. Fitting gives an average velocity of 0.441 m/s

Figure 3.9: Plot of displacement versus time of the point source for a Mineral Oil trial at 142 degrees. The fit gives an average velocity of 0.940 m/s

Figure 3.10: Plot of displacement versus time of a wake for a Mineral Oil trial at 142 degrees. A fit gives an average velocity of 0.230 m/s

Figure 3.11: Plot of displacement versus time of the point source for a second Mineral Oil trial at 142 degrees. The fit gives an average velocity of 0.521 m/s

Figure 3.12: Plot of displacement versus time of a wake for a second Mineral Oil trial at 142 degrees. A fit gives an average velocity of 0.276 m/s

Figure 3.13: Plot of displacement versus time of the point source for a Mineral Oil trial at 170 degrees. The fit gives an average velocity of 1.78 m/s

Figure 3.14: Plot of displacement versus time of a wake for a Mineral Oil trial at 170 degrees. Fitting gives an average velocity of 0.451 m/s

Table 3.1: Table of point source velocities.

The results of the velocity calculations for point sources and wakes are summarized in Tables 3.1 and 3.2. The leading edge moves faster than the wake speed in every case. These leading edge speeds are noticeably higher over water, than over the light mineral oil.

At this point it is worthwhile noting that the tank was only filled halfway with mineral oil to 2 cm while the water was filled to the full 4 cm. Thus the height of the fluid, relative to the forcing, did differ between the two cases.

The wake field speeds are roughly the same in both fluids. For a given angle the speed differs by at most 0.04 m/s between fluids. Wake speed does increase however by about a factor of two as the angle is increased from 142 degrees to 170 degrees.

3.2.3 Wake Angle

The angle that the wake opens up from the leading point is known as the wake angle. A measurement of such a parameter may provide important information about why the velocities between trials compare as they do (as seen in Table 3.1 and Table 3.2).

Plots of wake angle versus time for the water trial at 142 degrees in Figure 3.15,

Table 3.2: Table of wake field velocities.

and for two mineral oil trials at 142 degrees in Figures 3.16 and 3.17 (wake angles for the other 170 degree trials were too difficult to produce meaningful results) all include a linear fit of the data. The slope here represents the rate at which the wake angle changes with time. As with the point velocities, this number represents an average value.

For the 142 degree water trial, the slope has a value of 84 degrees per second. This number gives an indication of how the velocity of the point source changes in comparison to the wake field velocity. Here this number is only meaningful when compared with rates of angle change for the other trials. The rate of change found for the other two mineral oil cases was 130 and 246 degrees per second.

These numbers indicate that the wake angle changed more slowly for in water than in mineral oil. The second mineral oil event however, has a rate that is much higher (by a factor of 3) than the event in water. It is noteworthy is that two runs in mineral oil, both at the same angle produce quite different results.

These two otherwise similar events, that actually track an almost identical path across the tank, must therefore be at different stages in their evolution. It is apparent

Figure 3.15: Plot of wake angle versus time for a Water trial at 142 degrees (trial 02). The average change of wake angle is 84 degrees per second.

Figure 3.16: Plot of wake angle versus time for a Mineral Oil trial at 142 degrees (trial 02). The average change of wake angle is 130 degrees per second.

Figure 3.17: Plot of wake angle versus time for a Mineral Oil trial at 142 degrees (trial 04). The average change of wake angle is 245 degrees per second.

from the video, and from Figure 3.17 that the second trial (trial 04) run wake angle "open up" very quickly. Thus the velocity of the point source must necessarily be decreasing with respect to the wake field.

A close look at Figure 3.11 shows that the slope, or equivalently the average velocity, undergoes a change at around 0.22 seconds. The slope appears to be somewhat higher before this point than after. Thus this wave may be slowing down or dissipating.

3.2.4 Barrier Test

To investigate the properties of the air above the water a special experiment was conducted using a barrier placed across the middle of the tank. The experiment, the results of which are depicted in Figure 3.18, revealed that the water disturbance in question has enough room to get past a barrier but the air disturbance does not necessarily go past.

Figure 3.18: Barrier Test. The Penny indicates the half of the tank that has a barrier 2 cm from the surface as opposed to the other half at about 10 cm. The red arrow indicates the wave that does not pass the barrier while the blue one signifies a wave passing the barrier.

Placing the a barrier across the middle of the wave tank with one half about 2 cm from the fluid surface and the other about 10 cm from the surface, was the basis for setup of the Barrier Test. The idea is that the 2 cm gap on the “blocked” side of the barrier is enough to allow the wave, which has an amplitude less than 2 cm, to pass.

A wave event was generated where at least two clearly visible waves approached impinged each side of the barrier. The resulting movie showed that only the one on the “unblocked side” passed. The other wave took a sharp turn as it approached the barrier, and traveled down parallel to the barrier.

3.2.5 Phenomenology

Not all of the events seemed to undergo simple propagation. Various events seemed, at least under this visualization technique used, to propagate in a discontinuous fashion. Such an event seemed to “skip” along the fluid. Figure 3.19 shows the resulting eddies forming as the disturbance moves across the tank.

Another phenomenon exhibited by some of the waves was a spinning motion. In Figure 3.20 a small disturbance can be seen traveling a short, nearly perfect circular path at the leading point of the wave. A full video of this event seems to show that a number of these events occur during the propagation of the wave being tracked. It is difficult to say how many or how often this occurs for events of this nature as some of the circular paths may be very small and or traversed very quickly.

These small disturbances that travel the circular patterns seem to be a number of smaller waves that seem to “finger” in a circular motion. This is best realized in the first from of Figure 3.20. In this frame 3 fingers of disturbed fluid can be seen curling around the point source.

Figure 3.19: Frames from a 500 fps movie capturing the phenomenon as it exhibits a ‘skipping motion’ as it forms numerous circular eddies (red arrow). A second event can be seen as indicated by the blue arrow.

Figure 3.20: Frames from movie capturing the phenomenon as it exhibits a ‘spinning motion’ as it forms numerous circular eddies (red arrow).

Chapter 4

Discussion

4.1 Forced or Free Wave

It is very important to classify this phenomenon as either a forced or free wave. In general as any wave that is being propelled, by the wind for instance, is classified as a forced wave. On the other hand free waves are waves in which the forcing mechanism stops and the momentum that the wave has accumulated allows it to move on its own. [5]

Capillary waves, once generated by wind, quickly flatten out after the wind stops blowing. The rate of dissipation depends greatly on the molecular viscosity of the fluid. Thus if a capillary wave retains its amplitude for a relatively long period of time than it can be assumed that the wave is forced. [12]

The event that is described in Figures 3.11 and 3.12 (a wave in mineral oil with a 142 degree forcing term) illustrates that these waves are in fact forced. At around 0.22 seconds the point speed of the wave decreases. It is at this time that the wave begins to dissipate and it is likely that the wave transitions to a different state. Thus the wave must have been forced. More arguments for this are presented in Section 4.3.

4.2 Velocities

4.2.1 Kelvin Wake Theory

From the velocities presented in Tables 3.1 and 3.2 it is possible to discuss some of the conditions that define how fast the phenomenon propagates.

One of the most obvious things to conclude is that the point source speed is always greater than that of wake field. In search for some relationship between velocities of the point source and wakes, the Kelvin ship wake model is presented.

Assuming they are dispersive, ship waves in deep water, where the length of the moving object is not comparable to the depth of the fluid, have a simple relationship between the object speed V, and the wake speed c,

$$c = 0.816V. \tag{4.1}$$

This Kelvin wave theory also requires that the wake angle be 35°. [12]

Using this relation for water trials in Table 3.1 for point source velocities, should give the corresponding values in Table 3.2 if Kelvin's wake theory holds true for our special waves. It is obvious that this is not the case as the first value of 1.64 m/s, when substituted into Equation 4.1 gives a wake speed of 1.34 m/s as opposed to the observed value of 0.271 m/s. The ratio of the point speed to wake speed for water trials actually ranges from 6 to 8 while the that for mineral oil is between 3 and 4. Observed angles, seen in Figures 3.15 and 3.16, are smaller than the 35° required for this regime.

4.2.2 Dispersion Relation and Wake Speeds

Because all the wake field velocities are between 0.232 m/s and 0.451 m/s something can be said about where these waves lie on the dispersion curve (Figure 4.1) in reference to the minimum speed of a capillary wave. (See page 7). The values for each parameter for water and mineral oil used in plotting the dispersion curve are listed in Table 4.1.

In order for the wave to have a speed of about 0.45 m/s it could either be to the right or left of the minimum capillary phase speed at 1.73 cm on the dispersion curve. Left of this wavelength is the pure capillary wave domain and to the right is the capillary-gravity wave domain. To achieve phase speeds of 0.45 m/s in the capillary-gravity wave domain a wavelength greater than 50 cm is required. This is an unrealistic value. An estimate of the observed wavelength can be done by looking at Figure 3.2. The length of the bright portion of one ‘leg’ of the wake, indicating the distance between troughs, has a value much less than 20 cm and is actually about 1 cm.

Table 4.1: Table of fluid properties for water and mineral oil. [13]

To achieve these speeds on the pure capillary wave domain requires a wavelength of 1 cm or less. Thus the observed waves are pure capillary waves and thus Equation 1.7 can be used as the dispersion relation.

The fact that the wake speeds of both fluids were approximately the same reinforces the fact that the waves must be pure capillary waves. A plot of the dispersion relation in Figure 4.1 shows that when the wavelength is less than 1.73 cm (in the pure capillary wave regime) the phase speed at a given wavelength differs by at most 0.15 m/s between fluids. However, at wavelengths greater than 1.73 cm, (near the speeds observed) the phase speeds between the two fluids become increasingly different.

Figure 4.1: Plot of phase speed versus wavelength for both water and mineral oil using Equaiton 1.7

Knowing that the waves are pure capillary waves allows the calculation of the actual wavelengths of the waves based on their measured phase speeds and Equation 1.7. As seen in Table 4.2 these wavelengths seem reasonable in comparison with the estimated 1 cm wavelength for the mineral oil trial illustrated in Figure 3.2.

Because the wake speeds are close to the same in two fluids of differing surface tension with equal forcing angles, their wavelengths must differ according to Equation 1.7 . Thus each time a given angle of forcing is used, different wavelengths may

Table 4.2: Wavelengths calculated using Equation 1.7 for water and mineral oil.

result.

Figure 4.1 also shows that the phase speed in water is greater than or approximately equal to that in mineral oil for the same wavelength. This is in agreement with experimental results in Tables 3.1 and 3.2.

It is possible that the waves cannot be described by the dispersion relation of Equation 1.6 at all. For that reason there is need for further experiments aimed at testing just that.

4.2.3 Viscosity, Forcing and Point Source Speed

Traveling pressure gradients characteristic of vortex tubes, act as a shear stress on the surface of water. Thus a localized group of particles at the surface move but not without the effects the effective friction coefficient known as viscosity. [4]

Being analogous to friction and friction coefficients, viscosity is proportional to the drag induced by a fluid. Thus the lower the viscosity the less drag induced by a fluid on an object moving through its surface. Because water has a lower viscosity the dissipation of kinetic energy of a moving pressure structure in the air will be less than that for mineral oil. The velocities of the point source should be higher in the water than in the oil if the dissipation is significantly higher in the mineral oil. Table 3.1 does list the observed point source velocities as being higher in water than in oil. While this provides a possible explanation for the different point source characteristics, the agreement between the wake speeds (Table 3.2) suggests that the point source velocities differ because of slightly differing forcing conditions.

The forcing of the air by the swinging lever at various angles seems to have the expected affects on the point source speed. In general the greater the forcing angle, the greater the point source speed. For both fluids the speed approximately doubled when the angle of the lever increased from 142° to 170°. A simple explanation follows from the fact that the larger the angle the lever moves through, the faster the air moves. Thus at higher angles the lever imparts a greater momentum to the air, and then the air can impart a greater momentum to the water. The differences in point source speeds between water and mineral oil could be because the surface level of the mineral oil was 2 cm lower (thus 2 cm farther from the forcing lever) than that of water.

This however does not tell us exactly how the air imparts its momentum to the water.

4.3 Barrier Test

The way which the air interacts with the water was investigated through the Barrier test. This test is designed to test the hypothesis that these waves may be generated by a localized pressure gradient traveling over the surface of the barrier. If this pressure gradient is the result of a vortex tube in the air, then the “Barrier Test” would help confirm that. This seems to be the case.

In Figure 3.18, the wave on the blocked half of the tank is seen making a sharp turn to move down along the left side of the barrier. A vortex tube, if the circulation is in the right direction, would also move down the side of the wall as predicted by the method of images. The method of images implies that a vortex tube approaching a wall will feel the wall as if there was a mirror image of that vortex tube (of equal strength and opposite circulation) on the other side of the wall. [4]

At the same time, the wave on unblocked side of the barrier propagates past the barrier. A vortex tube approaching this side of the barrier, with enough room underneath it as not to destroy the tube, would pass underneath it while being only slightly disturbed.

Both these scenarios agree with the vortex tube theory but the question that still remains is whether the circulation of a vortex tube, generated by the mechanism used would be in the right direction to travel down the side as it did in the figure. A vortex tube generated from the lever would be shed off the lever's edge, while the direction of circulation would depend on whether the lever traveled from right to left or left to right. For the case in the figure, the lever would have had to moved from left to right. Information of the levers movement however, was not recorded during the experiment. Future tests of this nature should include the direction of the lever movement.

From this barrier test, statements made in Section 4.1 can be further reinforced. It is obvious from the Barrier test that the waves are forced by the air. These waves that are not freely propagating waves which are forced only initially and then move free of the wind's forcing. By moving down the side of the barrier, the wave in the figure has illustrated the continuous affect that the forcing term has on the wave's propagation.

4.4 Phenomenology

The eddies formed in the event shown in Figure 3.19 may always happen, but are not usually visible, in all occurrences of the phenomenon. During this trial, the eddies that form as the disturbance “skips” across the surface seem to form a v-shape similar to that characteristic of the typical wave-phenomenon. These typical waves could also form eddies in the same way but at a higher frequency. If the frequency of the eddy formation was high enough, only the v-shaped pattern would be visible.

Another event seen in the same figure, but illustrated with a blue arrow, resembles a wave resulting from a small traveling sphere with a v-shaped wake field [14].

The spinning motion seen in another event (Figure 3.20) could be a result of vorticity being transferred form a vortex tube in the air to the water. Small vortex tubes circling a large vortex tube as it traverses its path over the water could give the net result as seen in the figure.

4.5 Naturally Occurring Phenomenon

Most of the phenomenological waves witnessed in the field were the direct result of a large gust of wind. Strong winds without gusting did not result in the waves discussed here.

During the time of lab experimentation observations were made of gusting winds in the field (during winter). Strong winds can be seen to blow particles of snow in a curved streamline. When a gust of wind blows however, a vortex tube forms on occasion. Thus a gust of wind required to produce the phenomenon in the field may also coincide with the formation of a small cyclone.

4.6 Further Experimentation

Many of the details of the propagation of this phenomenon remain to be discovered. We have shown that the point source propagates as a forced wave and that the wake field appears to propagate as free, capillary waves. Unfortunately it was not possible to precisely control the wind forcing nor was it possible to measure it directly. Further understanding of the wave will require a more controlled experiment and direct measurement of the air speed and pressure.

These future experiments should measure accurately and precisely the depth of the fluids used, with comparison trials in equal depths of two fluids being preferable. Ideally one of the depths, if even in only one fluid, should be greater than the 4 cm depth used here. Currently, it is unclear if the size of the point source or effective disturbance is comparable to the 4 cm depth and whether or not that will affect the dispersion of waves.

Also, some of the velocities achieved for trials were over a very short time, generally about 0.1 seconds. For all trials, when the wave was filmed it exited the field of view shortly after it developed. Extending the experimental domain would permit study of the evolution of the waves over a longer period of their existence. The approximate 40 × 40 cm^2 view of the tank only allows for a portion a of waves lifetime to be tracked. Ideally, to capture the wave in full, one would like to track the wave form as it develops, measure its velocity once it is fully developed, and track its dissipation once it becomes a free wave.

Barrier tests as conducted thus far prove to be very informative as to what is going on above the water-air interface. It is useful to obtain more videos similar to that of Figure 3.18. Varying the height on both the blocked and unblocked side of the barrier would also give useful results. Varying the height of the unblocked side by increasing the distance from the water surface should allow for larger, and larger amplitude waves to penetrate the barrier if they are a result of varying sized vortex tubes. However measurement of the amplitudes of the forced wave was not possible in this experiment

Possibly the most effective way to sample the activity in the air above the water is to use smoke to visualize the motion of the air. Even though the technique was described in Chapter 2, results were not clear enough to present here. Some vortex motion was seen on video but the visualization was not of a quality that would allow further image analysis. A better way to capture motion is necessary in order to present results. Otherwise a second visualization technique is required.

Similarly to these unused results, the PIV experiments also described in Chapter 2 proved to be inadequate. The problem with the PIV technique is that the expected vorticity may be on a scale too small to be detected. However, PIV may prove to be useful in some of the more recent videos acquired of the spinning action visible in Figure 3.20. At present, no attempt has been made to use PIV on such videos.

As far as the technical setup goes, at least two improvements on apparatus or technique would be ideal in further investigation of the wave. Both are concerned with reproducibility and the validity of comparison between trials. The first improvement would require the production of a more reliable wind generation device. This new device would allow a more precise determination of the level of forcing, instead of the current measurement of angle of the lever. A second improvement, would allow measurement of wind speed. Ideally, wind speeds could be measured, through use of a sonic anemometer, to ensure that the trials being compare in different fluids have the same forcing term. This would also allow direct investigation of correlations between wind speeds and wave speeds.

Chapter 5

Summary and Conclusions

Three very fundamental but important characteristics of the phenomenon can be extracted from experimentation, that allow for classification of wave type. First, the wave is almost certainly a pure capillary wave. Velocities predicted by pure capillary wave dispersion relations for water and the light mineral oil agree with those observed. The wavelengths determined from the dispersion relation appear to agree roughly with the observed length scales of the waves. Second, the point source of the wave field appears to be a forced wave. A number of experiments, including the barrier test, exhibit this forcing nature in the phenomenon's motion well after it has developed. Third, the wake field appears to propagate as a free, capillary wave.

Results also strongly suggest that the forcing term is a pressure disturbance in the air above the water as indicated by the Barrier test. The experiments indicate that the pressure gradient is due to a traveling vortex tube.

There is clearly a need for further experimentation and analysis. For this reason there is need for further experimentation. It would be useful to find a way to approximate the wavelength, and then do extensive trials to determine whether the velocity numbers correspond those calculated using the dispersion relation. Further work also needs to be done with the goal to obtain a wider range of velocities, under a more reliable forcing process and to better visualize the effects of the disturbance in the air above the water. More quantitative measurements of the air speed and pressure and the amplitude of the water-air interface displacement would enable more quantitative analysis of the propagating wave characteristics.

Appendix A

Velocity Matlab Script

A matlab script was used for velocity calculations or to make a displacement plot.

Appendix B

Particle Image Velocimetry Matlab Script

Particle Image Velocimetry requires a number of scripts in Matlab. A script, IMPIV, was written to enhance frames of video before going to the Main program PartIm_Batch. This newly written script enhances the frames to make tracking the desired object possible, in some cases, without the use of a tracer in the fluid.

The program is listed here.

Appendix C

Point Digitization Matlab Script

Frames of moveis were taken in to Matlab and digitized using the below program.

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