Physics extended essay:

Mechanisms and effects of wave breaking lanelines

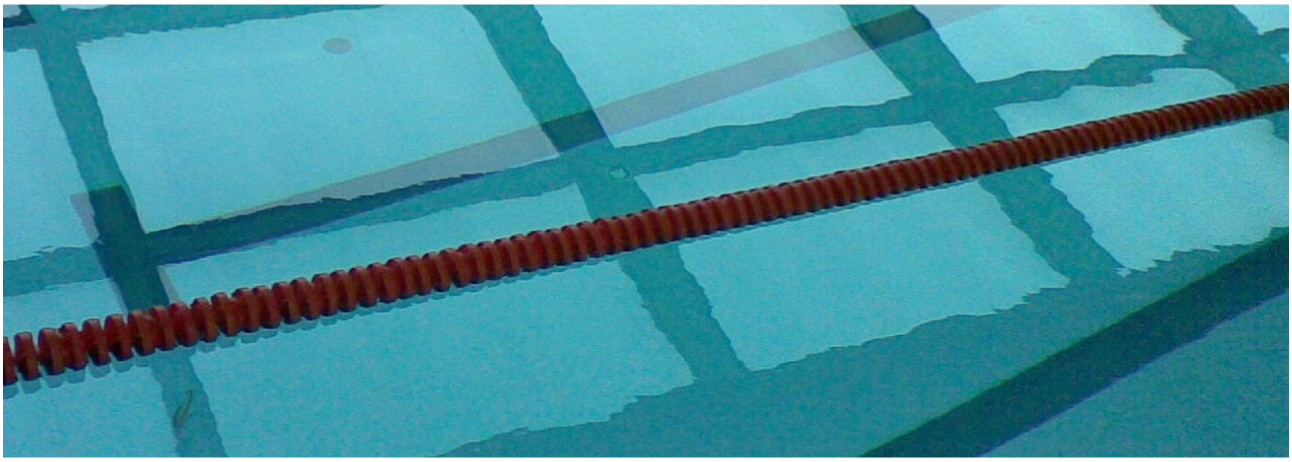

Illustration 1: A wave breaking laneline in a pool

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Abstract

In this essay, the mechanisms by which Wave breaking lanelines (WBLs) reduce energy transfer through water have been investigated. A theoretical discussion of wave theory and basic fluid dynamics is presented, literature is consulted, three experiments are conducted, and a conclusion is formed to answer the research question “In what way does a WBL limit energy transfer across a water surface?”

From theoretical models it was discovered that WBLs create turbulence by water passing through the holes of the perforated stiff plastic discs that make up a WBL. This effect was calculated to only happen at velocities of 0.75 ms^{-1}, but water waves often travel faster than this. The five radial vanes were also found to be responsible for a large amount of turbulence production. In connection with this it was discovered that these discs have a very high drag coefficient.

The effects of diffraction and interference were observed on a small scale, and these effects seem to contribute towards creating turbulence around the WBL. It was discovered that the water emerging from the holes sometimes interferes with itself, producing large circular waves, and sometimes turbulence, illustrating the difference between a flow representation and waves.

Unfortunately the effects discovered on a small scale could not be verified on a macroscopic scale, as the macroscopic experiment was conducted in a swimming pool, without adequate control of variables. But in this experiment, the WBL was observed rotating, hinting at the fact that to fully describe a WBL, we also need to consider mechanics in a broader scope than possible in this essay.

The final conclusion, formed on the basis of my theoretical considerations, available literature and the three experiments, is that the main wave dampening mechanism used by WBLs is creating turbulence, thus reducing energy transfer across the water surface.

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Introduction

The aim of this essay is to investigate the mechanisms by which a wave breaking laneline calms incident waves, primarily using wave theory and the concepts of fluid dynamics.

Wave breaking lanelines (WBLs) are used in swimming pools to reduce the effect swimmers feel from other swimmers on adjacent lanes, i.e. reduce the amount and intensity of large waves that may interfere significantly with their swimming. Modern WBLs are constructed from stiff plastic discs placed on a steel wire. This wire is affixed to each end of the pool, at one end with a spring, and at the other with a small winch to tighten it.

The shape of the plastic discs varies significantly between manufacturers, and several patents have been granted within the field. Illustration 2 below shows a single disc of the type I have studied.[1] WBLs have been designed with several mechanisms in mind to dissipate the energy of incoming waves, and in this essay I will primarily investigate the radial vanes and the web of holes, visible in the illustration.

Illustration 2: A single disc from the type of wave breaking laneline studied, from three angles. For physical data about the disc, please see Appendix 2: Data about a single disc.

It would be possible to describe and mathematically solve these problems with a high degree of accuracy, but this would mean resorting to generally insolvable Laplace or Navier-Stokes equations, which are beyond the scope of this essay. In fact, as Mandal & Chakrabarti (2000, p.109) note: ”Explicit solutions to water wave scattering problems are known in the literature only when the obstacle is in the form of a thin vertical plane barrier.” It will be appreciated that a WBL is more

1 It seems to be the same design as described in Walklet, 1973.

complex than this, and thus I will not attempt to model the entire situation using fluid dynamics.

Instead, I shall attempt to describe the motion of water around and through the WBL using concepts such as reflection, interference, turbulence and friction. I will test these predictions using experiments, and attempt to answer the research question "In what way does a WBL limit energy transfer across a water surface?"

Theory

In this section, I will present some relevant theoretical considerations, which I shall apply in the following experimental sections.

Linear waves in water have a direction and a speed, determined as with other waves by $v = f\lambda$. a single water particle in the path of the wave will, as shown in Illustration 3, move in a circle parallel to the direction of the wave, at the crest of the wave moving forward, and at the trough of the wave backwards. (Russell, 1999)

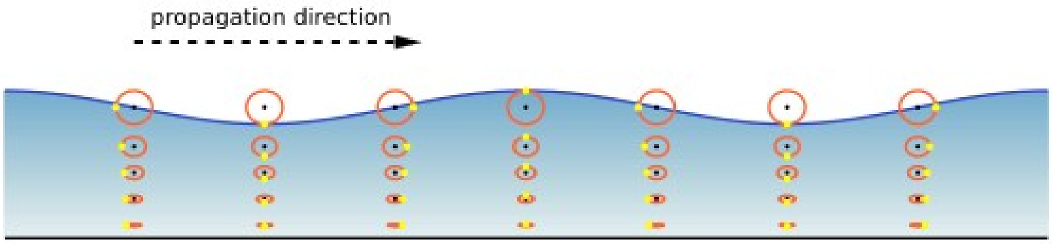

Illustration 3: A wave through water, showing anticlockwise movement of particles, (Kraaiennest, 2008)

Water waves may, like all other waves, be reflected and also interference with each other, constructively or destructively. Diffraction may also happen, but shadow regions of calm water will only occur when the obstructing object is large in relation to the wavelength (Giancoli, 1998, p.339).

As seen above, we can represent water movement as waves, but we can also represent it as a flow using fluid dynamics.

In a laminar flow of water, in contrast to a wave, particles move in the same direction as the flow. We can categorise whether the flow is in fact laminar or turbulent by its Reynold Number, which is defined[2] by $N_R = \frac{\rho v D}{\eta}$. If this unit-less Reynold number is greater than 3000 the flow

2 For explanation of symbols, please see Appendix 1: List of symbols and constants used.

can be considered turbulent (Ohanian, 1985, p.329). Turbulence is when water particles in a flow no longer travel in the same direction, instead forming eddies and swirls. Turbulence “drastically affects the transport efficiency of mass, momentum, and heat” (Hof, 2004).

It is important to note that turbulence is not a wave, but a collection of waves interfering with each may be modelled as a turbulent flow (Christensen & Deigaard, 2001).

From the principles of fluid dynamics, several powerful equations arise, Navier-Stokes and Laplace equations have already been mentioned in the introduction, but these will not be discussed in this essay. But the concept of drag is of use when considering what happens when water passes across an object. The equation for the force that drag exerts on an object is $F_{drag}=\frac{1}{2}C_d \rho v^2 A$ (e.g. in Benson, 2008). This equation contains the drag coefficient, C_d, which must usually be experimentally determined, and will usually be different for laminar and turbulent flows (Fitzpatrick, 2006). Low values for the drag coefficient imply that an object will require less work to be exerted on the part of the water flowing across it, while high values for the drag coefficient mean that the object poses a significant barrier to the effective passage of water.

Investigation

Theoretical model: Description of mechanisms

Consider a wavefront incident on a WBL. According to Rademacher (1986, p.5) waves usually ”approach at an angle of 45° (…) however it is to be appreciated that this is a simple approximation of the highly complex physical interrelation between numerous proximate and irregular wave forms.” This angle of 45° results from the angle of the bow wave of a swimmer swimming parallel to the WBL. We may, as stated in theory, also choose to model this as a turbulent flow. Each simplification has advantages.

This wavefront, when it hits the series of discs, will be partially reflected by the baffles, as shown in Illustration 4. Meanwhile, a large part of the wave will pass through the gaps in the outer baffle, and be incident with the vanes and web. The reflected water from the baffles will likely interfere with other waves and produce more turbulence, but the water that either passes through the web or hits the baffles is more interesting.

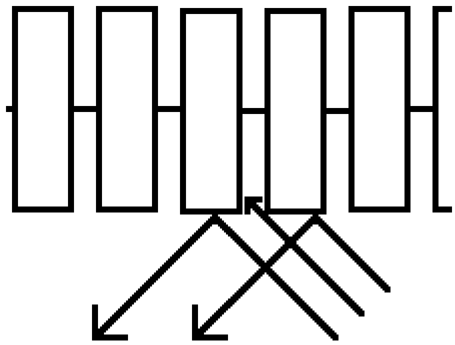

Illustration 4: Three rays incident on a WBL.

Water passing through the web will encounter friction due to the large surface area, and rapidly become turbulent due to the small diameter of the holes. When emerging on the other side of the holes, our two different representations give different predictions. We might assume it to be simple turbulence, but if we assume it is a wave, then by Huygens' principle[3], we might also assume that each hole will produce a elementary circular wave. Each of these two possible outcomes has been investigated respectively in experiment #1 and #2.

Rademacher (1986, p.5) further claims the holes function to “aerate” the water, but this is not directly within the scope of the current essay. It is more important to remember that turbulence, as cited above, reduces the transport efficiency of energy. Thus a WBL that produces large amounts of turbulence locally will be an effective WBL.

Recalling that water particles both in a flow or a wave move, they will collide with vanes. This collision, by the laws of mechanics, will some of the kinetic energy to the disc. As seen in a waterwheel, the disc will rotate.

But in the process of rotation, the regularly spaced vanes will impact with the water surface, and to continue rotating, the vanes must overcome surface tension. Rotation will also eventually stop due to friction with the water, and the steel wire on which the disc is placed. This means that very rapidly most of this rotational energy will get transformed to heat. Even though an experiment to investigate this was considered outside the scope of this essay, some observations on this effect are noted in experiment #4.

3 Stated in Giancoli (1998, p.724) as ”every point on a wave front can be considered as a source of tiny wavelets that spread out in the forward direction at the speed of the wave itself. The new wave front is the envelope of all the wavelets - that is, the tangent to all of them.”

Some water might, if we considered it a flow, get directed under the WBL, flowing around the obstruction in its path, and by friction with the baffle wave energy will be transformed to heat. This effect seems to be present in experiment #1, with the taped disc.

From this theoretical description we see how a WBL will "break up" (Walklet, 1973) incoming waves. Water passing through the WBL will inevitably lose energy, either as friction or due to collisions, destructive interference and turbulence. Constructive interference, although to a lesser extent, also takes place, this is investigated in experiment #2.

As stated in the introduction, it is feasible to model the entire situation by mathematical methods, and many effects may also be predicted from theoretical principles, as I have done above, but below I have tested some of these mechanisms as well. I have designed and conducted three experiments, and the methods and results from each are presented below.

Experiment #1: Drag

Experiment #1 was designed to investigate the effect of the holes on the terminal velocity of a single disc.

It is assumed that a higher terminal velocity means that less turbulence, and thus less frictional drag is exerted on the disc, expressed by the drag coefficient. It will be realised that if the disc passing through water encounters a large amount of friction, then the opposite, with the disc stationary, and water moving, will also be very frictional.

Two discs were used. One was taped up so that the holes were covered. The other was left as is. A bathtub was filled to a water level of 50 cm, and a string was tied to the plug at the bottom. The discs proved to be buoyant, so two small weights were placed on either side of each disc to give it a slight negative buoyancy. The first disc was released from just underneath the surface, making sure no air was trapped under the tape covering the holes. The time for it to drop to the bottom along the string was measured, and this was repeated 5 times. The other disc, untaped, was also dropped in a identical way 5 times. The obtained data is presented in Table 1.

Taped (seconds)	**Untaped (seconds)**
8.59	6.12
8.53	6.37
9.06	6.40
7.43	7.03

7.18	6.56
Average (std.dev.): 8.16 (0.72)	*Average (std.dev.): 6.45 (0.30)*

Table 1: Results from experiment #1, comparing taped holes and untaped holes.

As can be seen, the untaped disc fell considerably faster, and thus we can reasonably conclude that its terminal velocity is faster, remembering that after the addition of weights they were only slightly negatively buoyant. This experiment unfortunately does not prove that the holes produced turbulence, and thus drag.

Rather, by taping up the holes, we increased the area significantly, and this gave the disc a significantly higher water resistance, as we see from the formula $F_{drag}=\frac{1}{2}C_d \rho v^2 A$. If we assume that the disc reached terminal velocity instantly (a reasonable assumption since the terminal velocity in both cases is rather low), it is possible to equate the forces on the disc, as shown below in a free body diagram, with gravity acting downwards, and buoyancy[4] and water resistance (drag) acting upwards, giving a net force of zero, which in this case means travelling at terminal velocity.

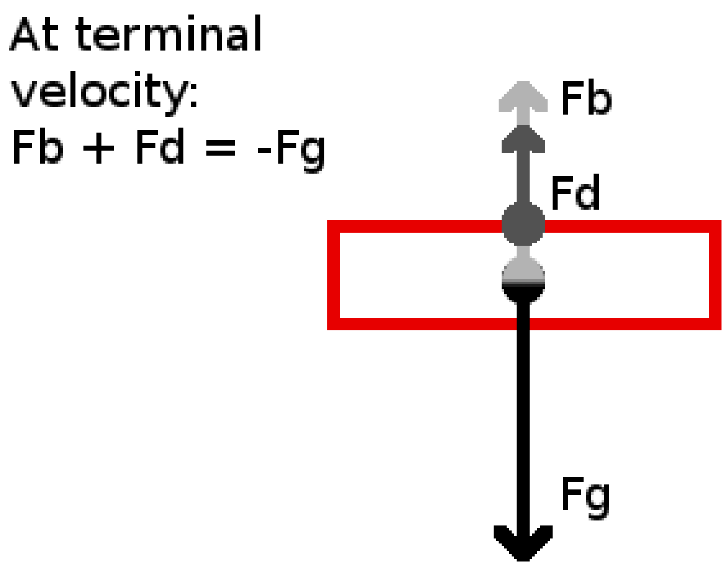

Illustration 5: Diagram showing forces acting on disc as it sinks through water, with points of application.

Using measured data about the disc (provided in Error: Reference source not found) we can calculate the drag coefficient of these discs, which will help to understand the shape of the discs, and how they interact with incoming water. The weight and volume of the tape is assumed to be

4 A force that is exerted on all objects immersed in a fluid. It is directed upwards and is equal in magnitude to the weight of the fluid displaced (Sears, 1987, p311).

negligible, thus the first three calculations below apply for both discs:

$$F_{gravity} = m\,g = 0.00633\,kg * 9.82\,m\,s^{-2} = \underline{0.621\,N}$$

$$F_{buoyancy} = V_{object}\,\rho_{water}\,g = 5*10^{-5}\,m^3 * 998.21\,kg\,m^{-3} * 9.82\,m\,s^{-2} = \underline{0.490\,N}$$

$$F_{drag} = F_{gravity} - F_{buoyancy} = 0.621\,N - 0.490\,N = \underline{0.131\,N}$$

For the taped disc: $C_d = \frac{2\,F_{drag}}{\rho\,v^2\,A} = \frac{2*0.131\,N}{998.21\,kg\,m^{-3}*(\frac{0.5\,m}{8.16\,s})^2 * 8.9*10^{-4}\,m^2} = \underline{7.8}$

For the untaped disc: $C_d = \frac{2\,F_{drag}}{\rho\,v^2\,A} = \frac{2*0.131\,N}{998.21\,kg\,m^{-3}*(\frac{0.5\,m}{6.45\,s})^2 * 8.3*10^{-4}\,m^2} = \underline{5.3}$

Here we see that the drag coefficient of the taped disc is higher, in accordance with its terminal velocity being slower. This tells us that the holes seem to help the water pass through the disc with low resistance.

As to why the untaped disc with its theoretically turbulence producing holes fell faster, we can estimate the velocity at which the disc must travel for these holes to actually create turbulence.

By using the equation for the Reynold's number, we see that turbulence should theoretically set in with the untaped disc at velocities above $\frac{\eta\,N_R}{\rho\,D} = \frac{3000*1.03*10^{-3}\,Pa\,s}{998.21\,kg\,m^{-3}*0.004\,m} = v = 0.75\,m\,s^{-1}$, so in this experiment, due to the low velocities, we were unable to observe turbulence form. The taped disc thus fell slower due to the large surface area.

It is worth noting that waves in a swimming pool will likely travel at greater velocities than 0.75 ms^{-1}, so in this situation, the holes will produce turbulence, thus dissipating the wave energy.

But if the web accounts for the difference between a drag coefficient of 5.3 and 7.8, what sets a WBL disc apart from a flat plate, that has a drag coefficient in the range of 1.28 (Benson, 2008)? The obvious conclusion is that the vanes and baffle contribute to a very large extent to produce this frictional drag.

Experiment #2: Wave patterns

Experiment #2 was designed primarily to investigate the wave patterns produced when a wave is incident at a right angle on three discs placed close to each other.

Three discs were placed on a coarse string, and placed half-submerged in a basin of a depth of about 30 cm. The string was held tight, and a series of broad wavefronts were produced at one end of the basin. The basin was filmed from several angles using a digital camera, and the brightness and contrast of the film were subsequently modified to allow observation of the wave patterns formed.

Experiment #2 did not produce quantitative data, but a still image from the video reproduced in Appendix 3: Still images from the video in experiment #2. It is not possible to include the recorded videos from this experiment, instead Illustration 6 shows the wave patterns observed on the films.

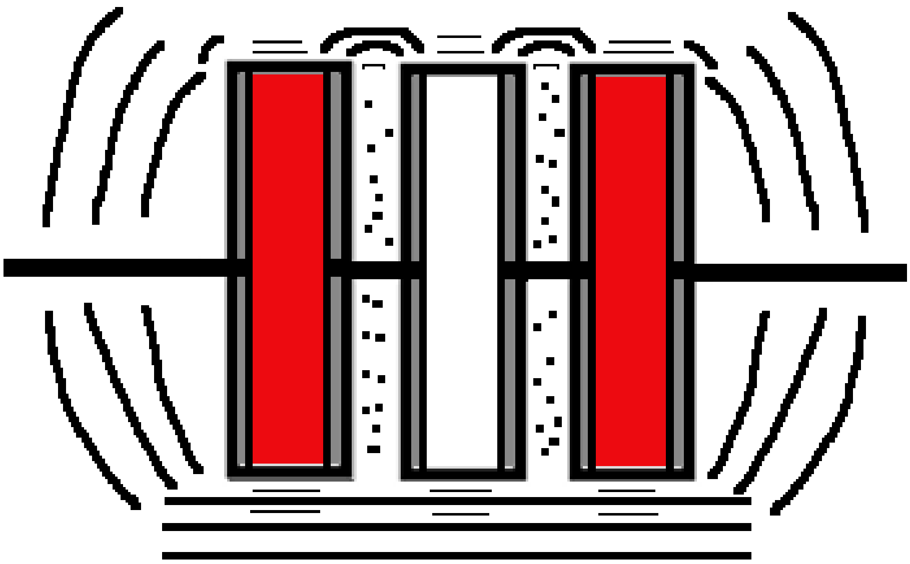

Illustration 6: Waves shown approaching from bottom of drawing, incident with a section of WBL, produced this pattern.

It is worth noting the circular waves that emanate from the side of the outer discs. This seems to indicate that the circular wavelets from the web combine to form these regular wave patterns, as Huygen's principle and the principles of diffraction state. The dots in between the discs indicate that it is impossible to resolve what is happening, but we may assume that the circular waves being produced by the web on the outer sides of this arrangement are also produced in between the discs, and then interfering to create turbulence.

The small circular waves produced on the far side of the WBL either result from waves passing through between the discs, or the impact of the vanes with water, as the discs are rotating back and forth.

So even though this experiment cannot tell us anything quantitative, it still seems to confirm that the shape of the discs is crucial for their effect, and they create large amounts of interference, sometimes even turbulence, reducing the energy of the wave passing through.

Experiment #3: In situ wave dampening

Having now examined some aspects of the WBLs at a small scale, and their possible mechanisms that produce the wave dampening, I turn now to my main experiment of this essay, which was conducted in a swimming pool, on a larger scale. Experiment #3 was an in situ experiment, designed to compare the real world effects of WBLs with open water. As such, not all variables could be controlled adequately, but data can still be analysed.

Two Go!Motion sensors (ultrasonic distance measuring devices, produced by Vernier) were affixed to a wooden plank 1.85 m from each other. The wooden plank was placed on a diving board centred over a WBL in a swimming pool, thus placing the sensors 1 metre above the water surface. The sensors were connected to a laptop computer running Logger Lite. (Vernier Software and Technology, 2008) Illustration 7 shows an image of the apparatus in situ, and Illustration 8 shows the set-up at water level.

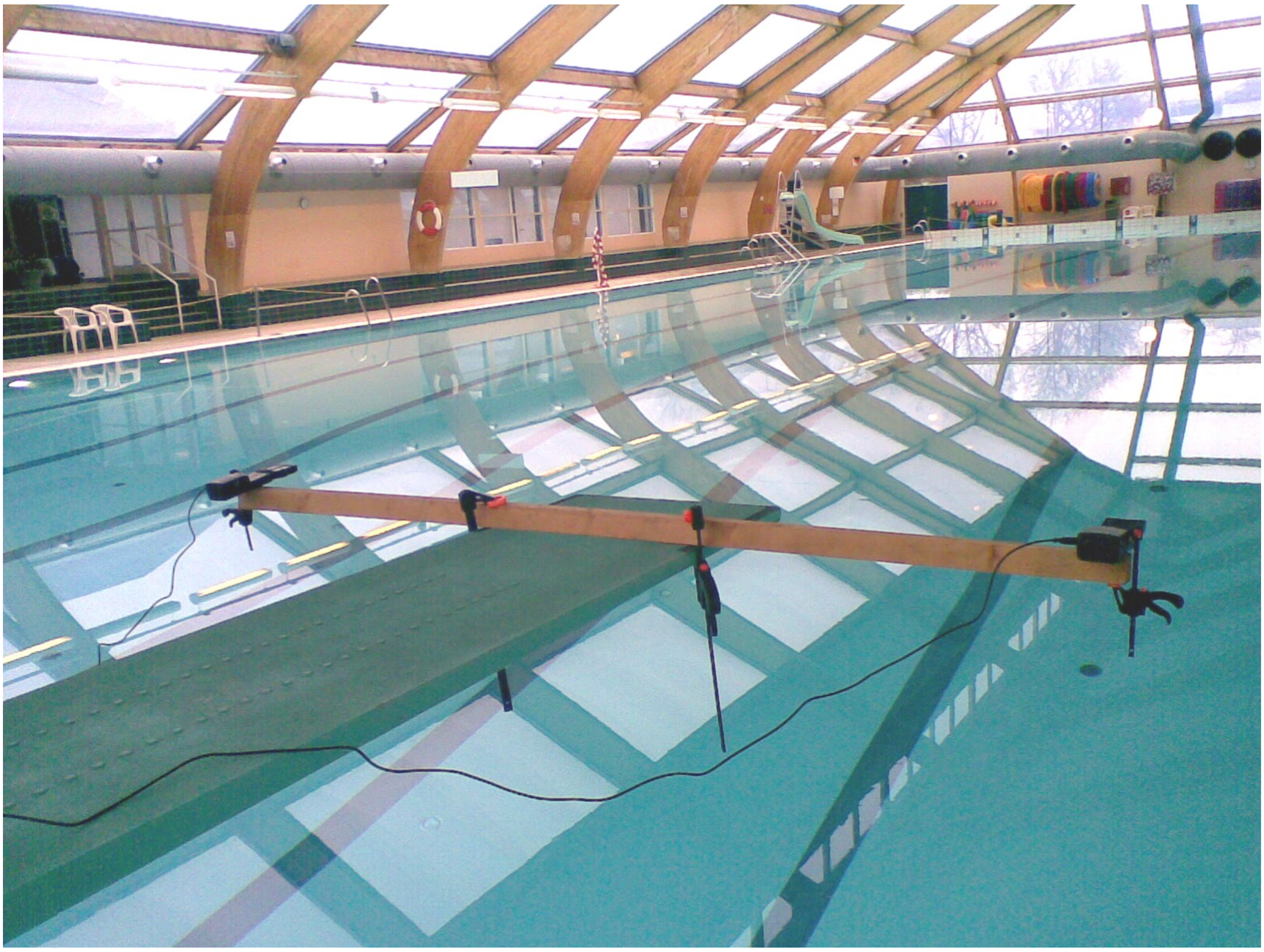

Illustration 7: The apparatus, showing the two sensors at opposite ends of the plank, pointing down towards the water surface one metre below.

The placement of each sensor was a compromise between placing them close enough to give similar results for the amplitude of a passing wave (as it decreases over distance), and far enough apart so as not to interfere with each other.

A wave was generated 4 metres away, on the edge of the pool (see Illustration 8), by pushing a semi-rigid swimming float out into the water and pulling it back again at a regular rhythm. The resultant wave was observed to travel in a straight line to the apparatus around the WBL 5 metres away, but some reflection from the edge of the pool could not be avoided, even though the apparatus was cantilevered as far out above the water from the edge of the pool as possible.

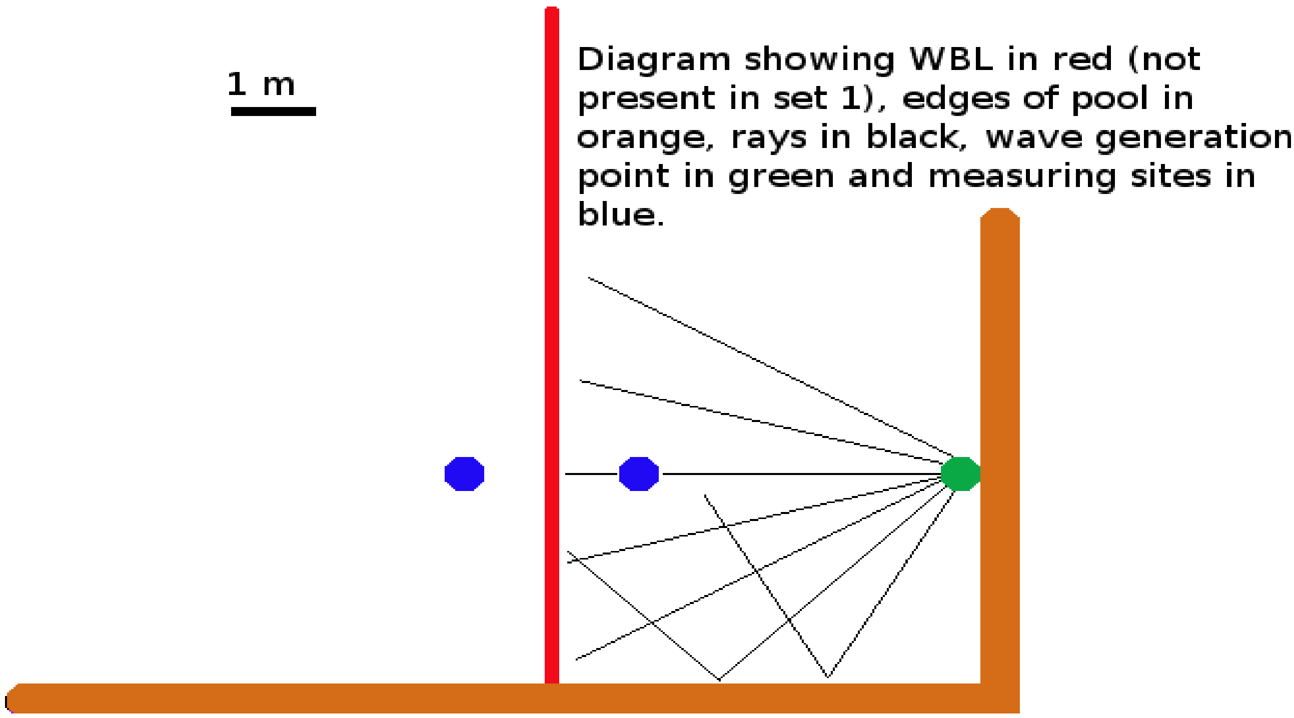

Illustration 8: Diagram (approximate scale) showing significant features of experiment #3 at water level.

Two sets of data have been chosen for further analysis. In set 1, no WBL was present between the measuring points, in set 2, a WBL was present. Between set 1 and 2, the only independent variable is the presence of a WBL. Before presenting the data from this experiment, I would like to comment on the restrictions and limitations of it. Most of these arise from this experiment being conducted in a swimming pool, and thus several variables not being as controlled as we might wish.

As noted above, waves reflect off all edges of the pool, and it was unfortunately not possible to eliminate this effect. Instead, by keeping the apparatus and wave source stationary, this effect should be constant. Even so, the waves generated by people in the water up to 5 minutes before the experiment were still bouncing off the edges, and this is probably why set 1, conducted first, is more noisy than set 2, conducted afterwards.

As the waves needed to be of a certain amplitude to still be recognisable at the measuring points, a resulting lack of consistency in their frequency and wavelength could not be avoided. And with reference to figure 7 in Kiefer, 1990, (reproduced below as Illustration 9) and my considerations in experiment #2, WBLs have varying effect across different wavelengths, so a large deviation in observed dampening may show up as random errors.

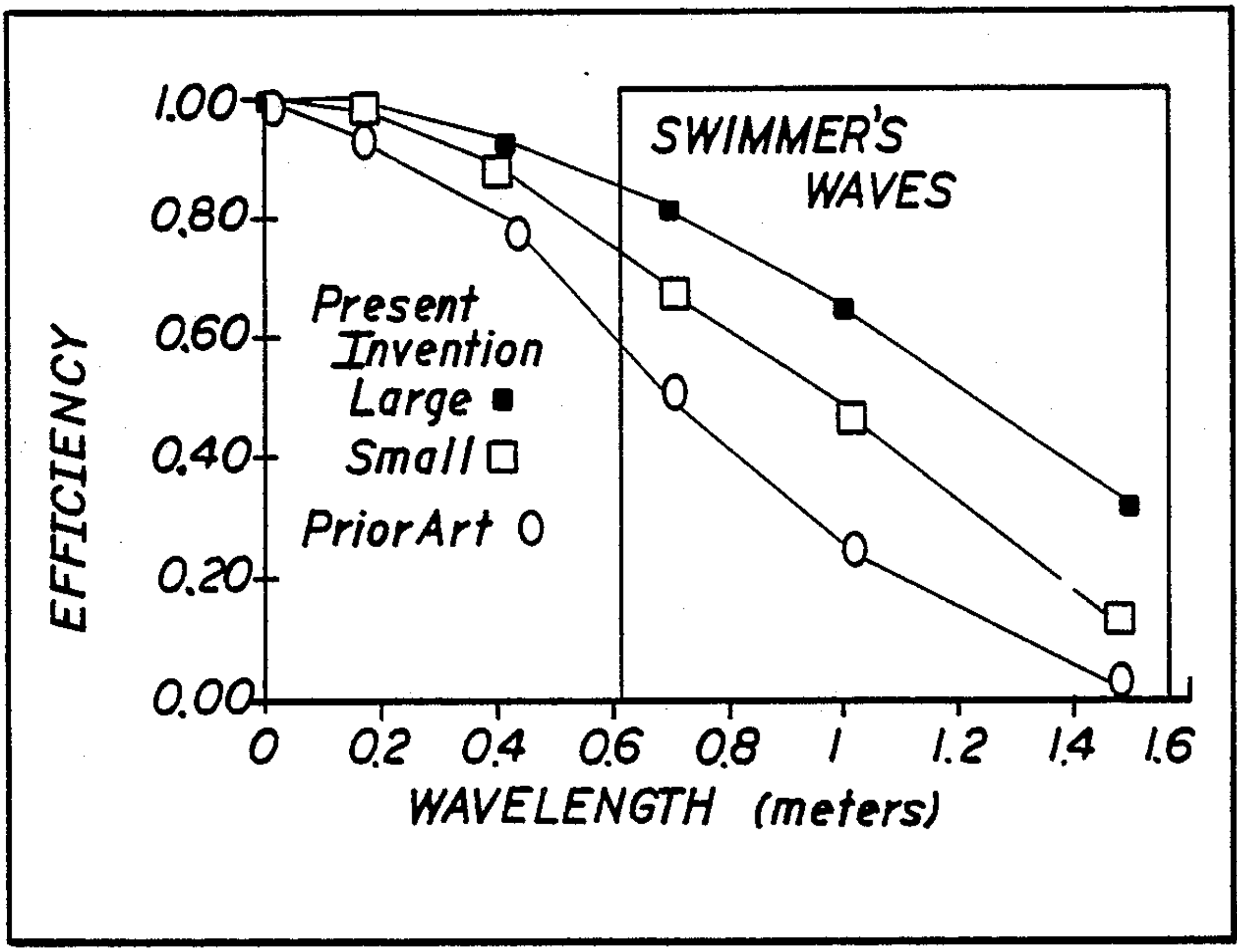

Illustration 9: "Efficiency" of WBLs at different wavelengths. (Kiefer, 1990)

The Go!Motion sensors do not in fact measure a single point, as that would be impractical for most mechanics experiments for which they are designed, instead they report the placement of the closest object in “a cone-shaped area about 15 to 20° off the axis of the centerline beam.” (Vernier Software and Technology, 2007, p.2) For this experiment, this means that the measurement points are in fact circles of approximate radius $1\,m * \sin\frac{\pi}{12} = 0.3\,m$. This means that waves of significantly less than this wavelength cannot be resolved from each other.

Minor concerns include the currents arising from the rinsing and circulation processes in a swimming pool, which may show up on some results, and slight flex in the diving board on which the apparatus was mounted.

Experiment #3 as noted, was in situ. Illustration 10 shows a part of the graph produced from set 1, with a series of waves passing the two sensors, the waves have passed across open water. All these graphs are taken from Logger Lite, and they show displacement of the water surface from the sensor, sampled at 25 Hz. Thus, points which have a greater y-value are troughs of waves, and points closest to the sensor (lowest values) are crests.

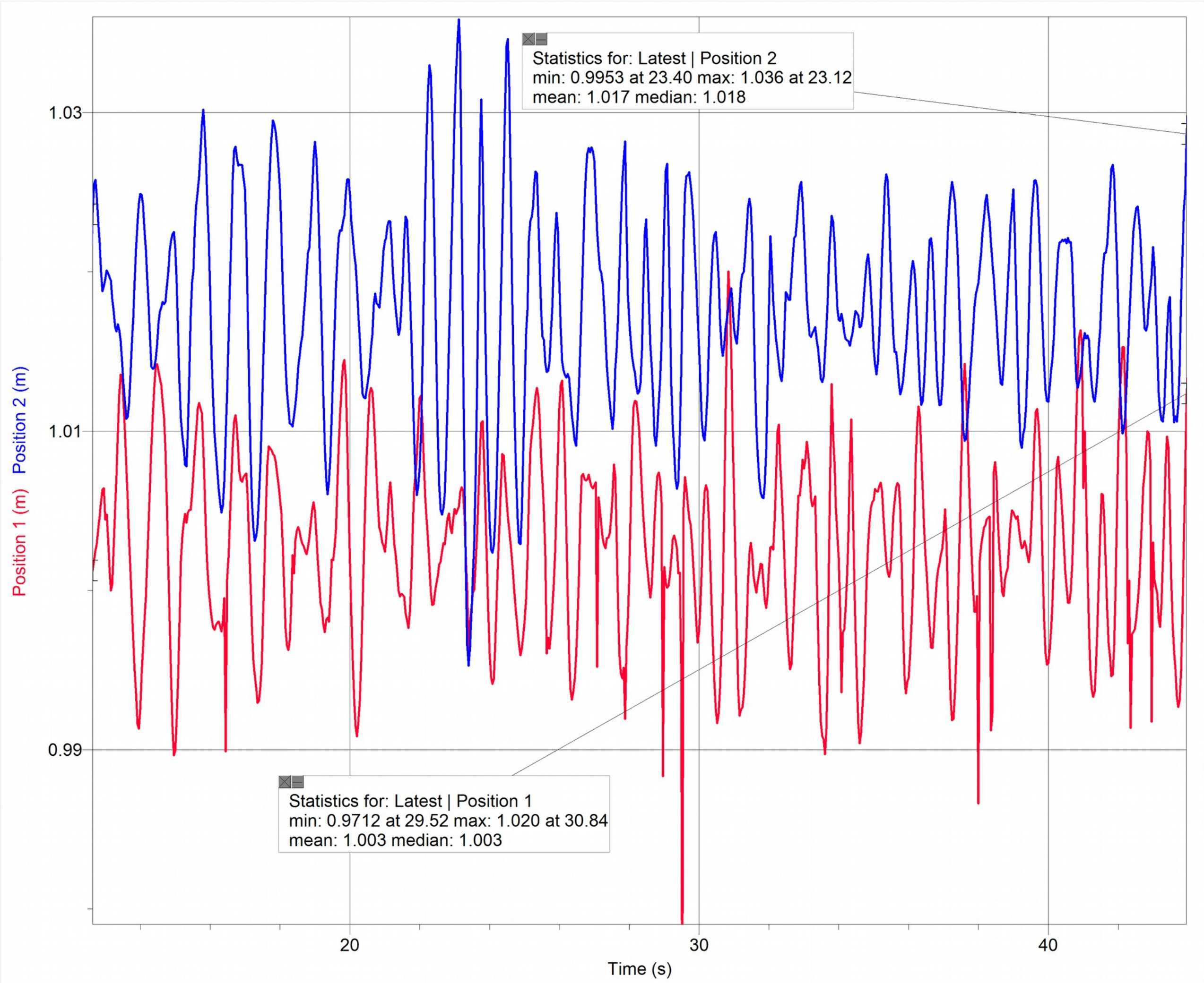

Illustration 10: Series of waves travelling across open water, from set 1.

As I mentioned earlier, large amounts of noise are present in this graph, especially when compared to Illustration 11, taken from set 2. This is most likely due to waves still present from swimmers no longer in the water, as the swimming pool was only empty for a very short time period.

Alternatively, and perhaps more interestingly, we might see the difference between these two graphs as evidence of WBLs calming the water, but unfortunately that conclusion is impossible to prove from this experiment, as the generated wave patterns are quite different.

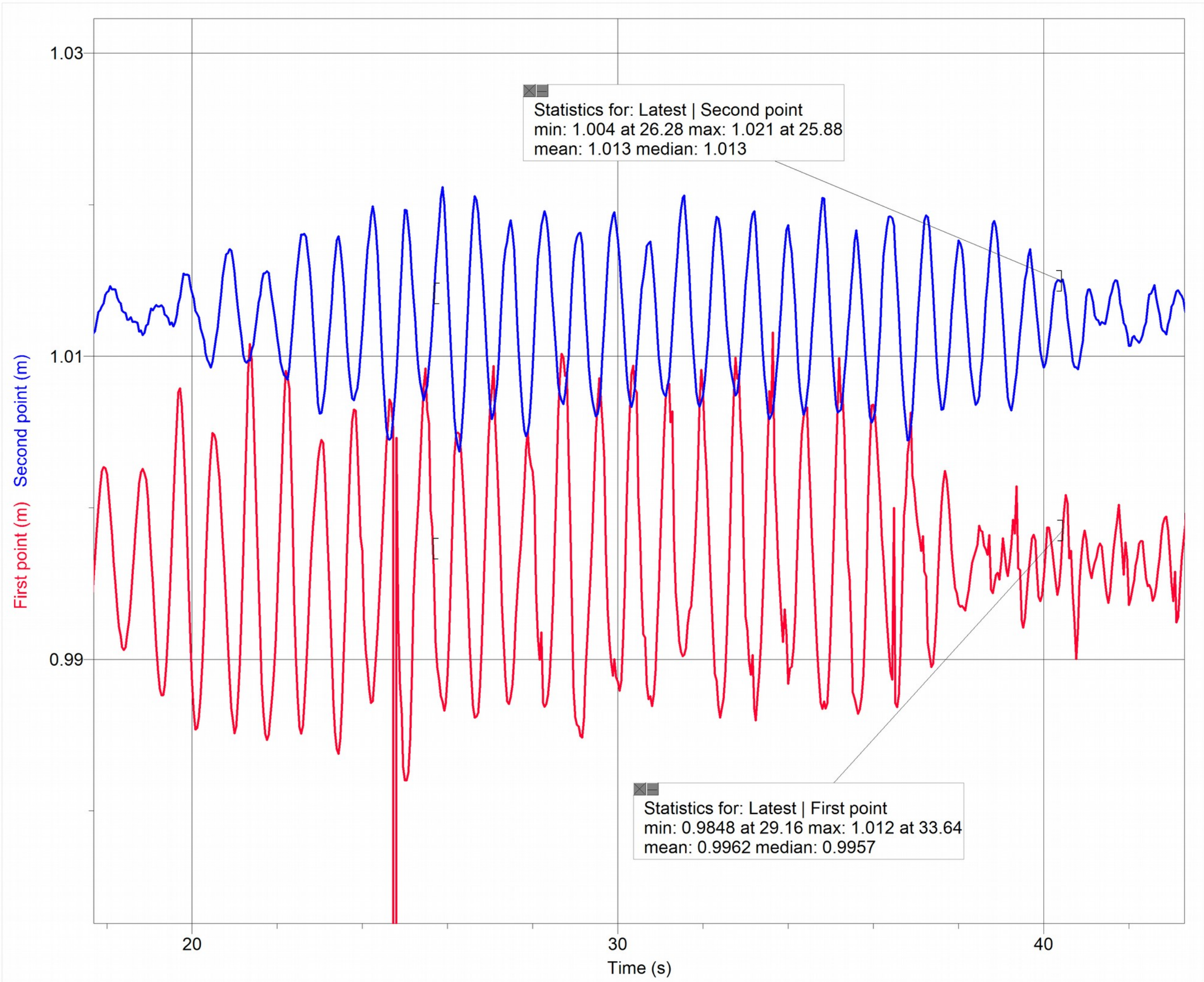

Illustration 11: Series of waves travelling across a WBL, from set 2.

The graph above in Illustration 11 shows data from set 2. The spike on the red curve at 25 seconds is a random error produced by these particular sensors. Note how the pattern of waves is similar at the two points, but smaller and occurring later in time on the blue curve, as we see in the statistics boxes in Illustration 11.

To attempt a qualitative comparison between set 1 (without WBL) and set 2 (with WBL), I have closely examined the output graphs from Logger Lite in search of pairs of points that come from the same wave. It will be recognised that a wave registered on one sensor will some time later, after having travelled along the 1.85 m line between the sensors register on the second sensor. This time period for a trough of a wave to travel is dependent on the speed of the wave, which varies according to the wavelength and frequency. Unfortunately in this experiment, I do not have exact values for the frequency and wavelength of the generated waves, but I do have an estimate for the time it took for a wave to pass between the sensors, as approximately 1-2 seconds, which I observed and timed in the pool. Using this information,the graphs were searched for pairs of points where it is clear that the shape of the waves are similar.

In set 1, I have chosen 6 distinctive waves marked out and zoomed in on in Illustration 12, and compare the amplitude of the same wave at the two different points. In set 2, I shall choose the first 6 waves from the series above, and compared them in the same way, as seen in Illustration 13. Please note that the numbering of the sensors has, for unknown reasons, swapped.

It will be noted that I have chosen to compare troughs, this is because, due to the nature of the sensors reporting the displacement to the closest object, measuring the height of the crests will be inaccurate, as droplets might register, or two waves might not resolve, due to the large radius of the measuring area.

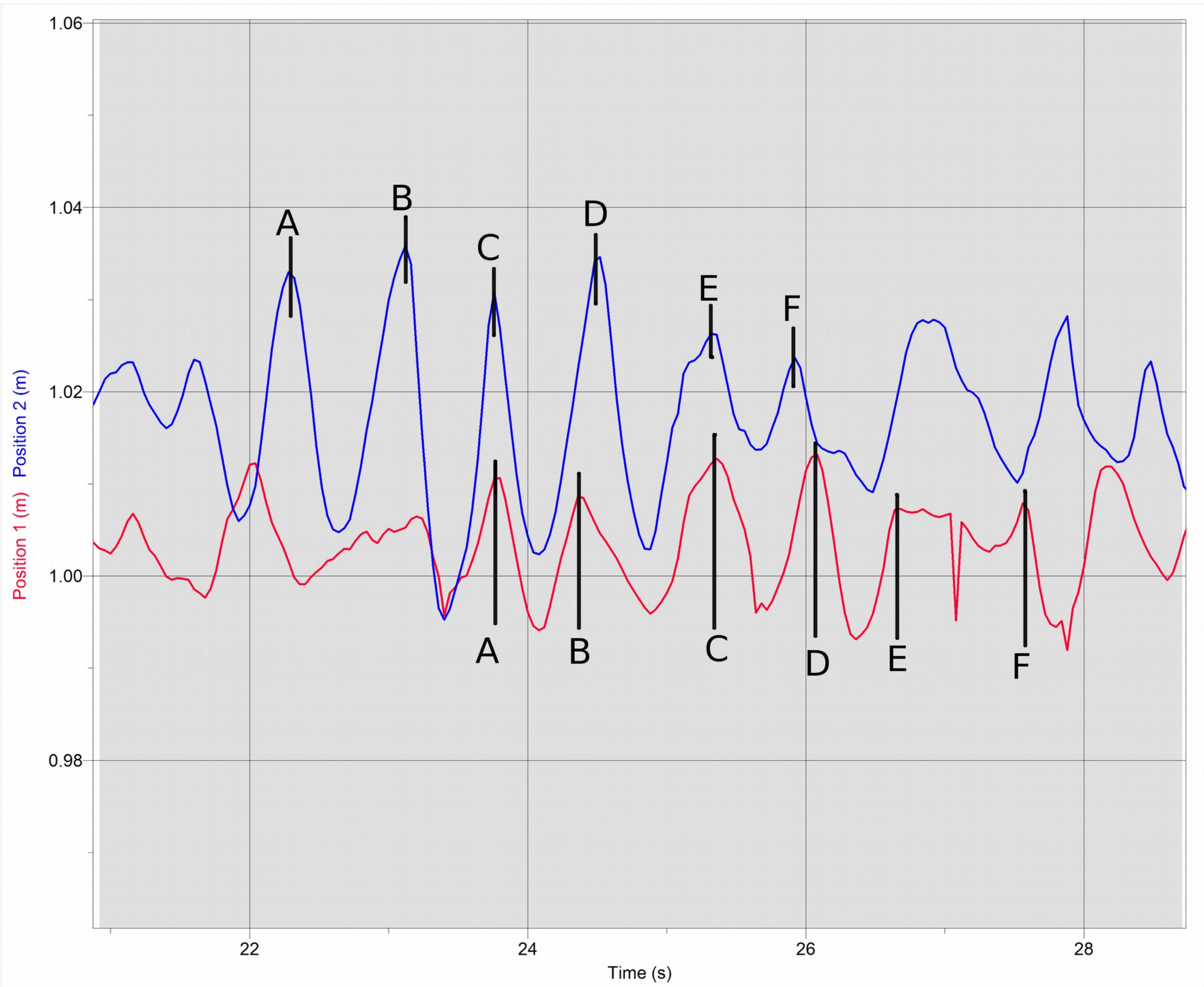

Illustration 12: Six waves passing over open water, from set 1.

To calculate the dampening, first an average displacement for the red and blue graphs is found, and then the difference in the depth of the troughs from this average is compared across the two graphs. Full calculations may be seen in Appendix 4: Full calculations from experiment #3 but results are presented in Table 2 and Table 3.

Trough name	Time elapsed travelling (s)	Relative size after travelling (% of initial size)
A	1.52	53.3
B	1.24	33.3
C	1.60	76.9
D	1.52	58.2
E	1.32	50.0
F	1.64	83.3
Average (std.dev)	1.47 (0.14)	59.3 (18.4)

Table 2: Quantitative results from set 1, showing dissipation of wave energy over open water.

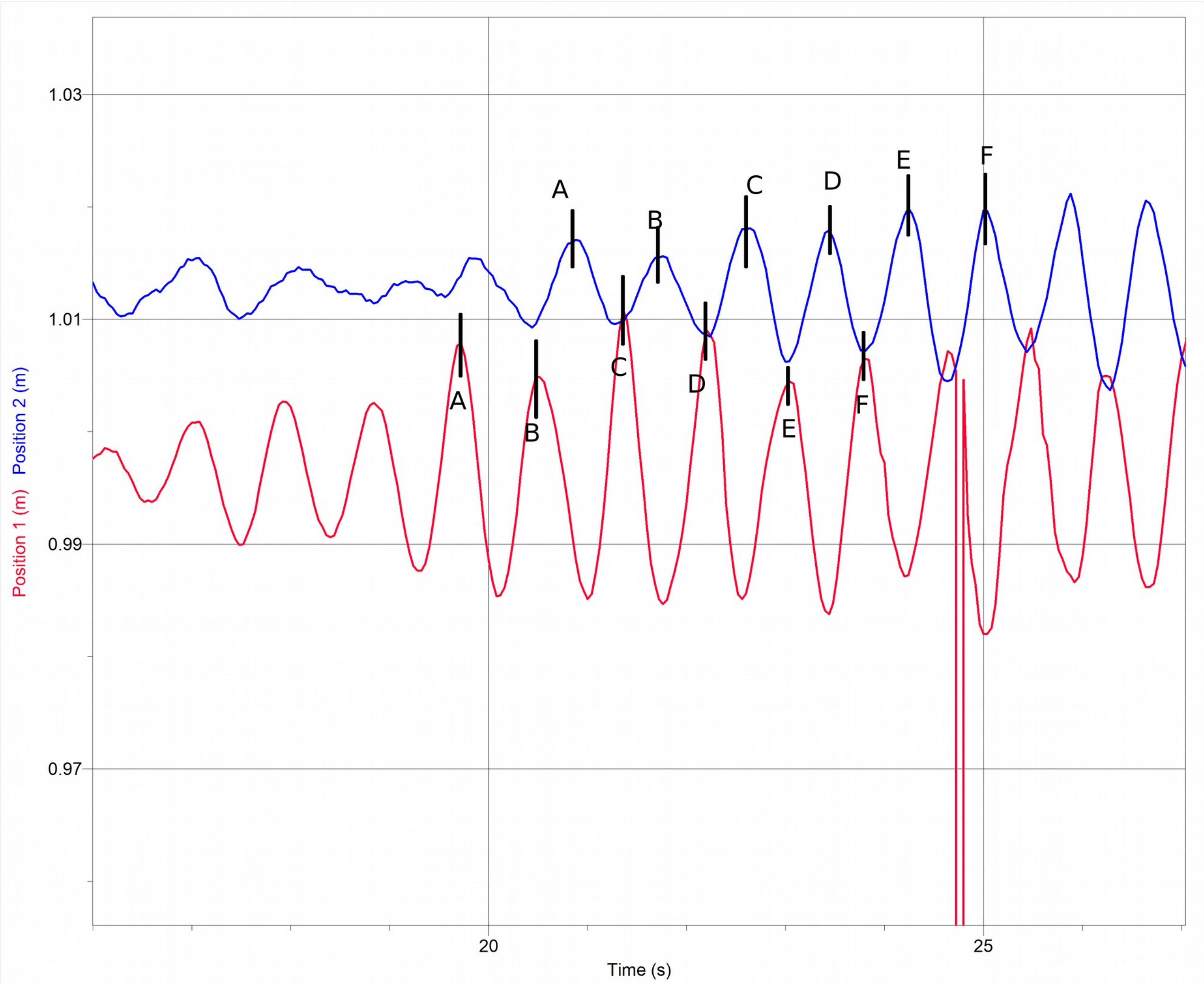

Illustration 13: Six waves passing across a WBL, from set 2.

Trough name	**Time elapsed travelling (s)**	**Relative size after travelling (% of initial size)**
A	1.16	33.6
B	1.28	33.7
C	1.28	33.6
D	1.2	38.8
E	1.24	88.6
F	1.24	70.7
Average (std.dev)	1.23 (0.05)	49.8 (23.9)

Table 3: Quantitative results from set 2, showing dissipation of wave energy across a WBL.

Due to the high uncertainties presented above, we cannot conclude anything statistically significant, as the uncertainty range of the two values overlap considerably.

From this experiment, other mechanisms which I have commented on in the Introduction and Theory were also observed. Besides reflection, the spinning of the discs was seen, and a minor experiment was conducted to measure how much a disc spins by marking a point on its circumference. It was discovered that even with waves much greater in amplitude than the height of the WBL, the maximum rotation was 6/5 revolutions, but most revolutions were 1/5 or 2/5. Re-examining the shape of the discs shows that they have a natural balance within the water, with one vane pointing up, thus the rotation of the disc is a discrete quantity, with multiples of 1/5 possible.

Conclusion

In this essay I have investigated the mechanisms which make a WBL restrict energy transfer across it. I have not seen turbulence created by the holes, but this was due to the low velocities of the disc in this experiment. An experiment with a higher terminal velocity, by adding more weights, could be conducted, to verify the presence of turbulence from the holes at high speeds.

I have conducted an experiment that shows the shape of the WBLs will cause large amounts of friction with incoming water, due to both the vanes, the baffle, and the web, significantly slowing a flow around it. I have observed constructive interference creating regular circular waves, which I have speculated interfere with each other to produce turbulence, contributing strongly to the effect of the WBL.

I have attempted to verify the effect of a WBL on a macroscopic scale, but was unable to prove anything statistically significant. This experiment, on reflection, needed more diverse data, such as high quality imaging of the water surface from many angles, for easier interpretation of the graphs.

It is still unclear what influence the rotation of the discs has, whether this is a significant factor in reducing energy transfer.

The overall conclusion of this essay is that wave breaking lanelines employ several different mechanisms to limit energy transfer, several of which I have verified, but further investigation is needed to quantify these effects to an adequate extent.

Bibliography

Benson, T., 2008,
Shape effects on drag [online],
Available at: http://www.grc.nasa.gov/WWW/K-12/airplane/shaped.html.
[Accessed 20th December 2009]

Christensen, E. D. & Deigaard, R., 2001.
Large eddy simulation of breaking waves.
Coastal Engineering, 42 (1), pp.53-86.

Fitzpatrick, R.,
Air drag [online],
Available at: http://farside.ph.utexas.edu/teaching/329/lectures/node42.html.
[Accessed 20th December 2009]

Giancoli, D, 1998,
Physics, 5th ed.,
Upper Saddle River (NJ): Prentice Hall.

Hof, B. et al, 2004,
Experimental Observation of Nonlinear Travelling Waves in Turbulent Pipe Flow.
Science, 305 (5690), pp.1594-1598.

Kiefer, J. D., 23rd January 1990,
Wave suppression means,
US patent #4,894,873.

“Kraaiennest” (online alias), 2008,
Orbital wave motion [electronic scalable vector graphic],
Available at: http://commons.wikimedia.org/wiki/File:Orbital_wave_motion.svg
[Accessed 10th November 2009]

Mandal, B. N. & Chakrabarti, A., 2000,
Water wave scattering by barriers,
Southampton: WIT press.

Ohanian, H., 1985,
Physics,
New York: W. W. Norton & Company.

Rademacher, T., 14th October 1986,
Aquatic turbulence suppression device,
US patent #4,616,369.

Russell, D., 1999,
Longitudinal and Transverse Wave Motion [online],
Available at: http://paws.kettering.edu/~drussell/Demos/waves/wavemotion.html.
[Accessed 9th November 2009]

Sears, F., Murmansk, M. & Young H., 1987,
University Physics, 7th ed.,
Reading (MA): Addison-Wesley.

Vernier Software and Technology, 2007,
Go!Motion user manual [online],
Available at: http://www2.vernier.com/booklets/go-mot.pdf.
[Accessed 18th December 2009]

Walklet, M., 4th September 1973,
Turbulence suppression apparatus for a body of water,
US patent #3,755,829.

Vernier Software and Technology, 2008,
Logger Lite, version 1.4, net book edition,
Available at http://www.vernier.com/netbooks/

Appendices

Appendix 1: List of symbols and constants used

Symbol	**Quantity**	**Value, if constant through essay**
A	Cross sectional area	
C_d	Drag coefficient	
D	Diameter	
F	Force	
f	Frequency	
g	Acceleration due to gravity	9.82 m s^{-2}
m	Mass	
V	Volume	
v	Velocity	
η	Viscosity (in this essay exclusively) of water	0.00103 Pa s (Pascal*second)
ρ	Density (in this essay exclusively) of water	998.21 kg m^{-3}
λ	Wavelength	

Appendix 2: Data about a single disc

A single plastic disc of the type shown in Illustration 2 possessed the following characteristics:

Quantity	**Value**
Mass	45±2 g
Diameter of disc	107±0.5 mm
Diameter of central hole	8±0.5 mm
Diameter of small holes in web	4±0.5 mm
Cross sectional area disregarding holes	8.9±0.2 cm^2
Actual cross sectional area	8.3±0.5 cm^2
Volume	45±5 cm^3
Density (it floats semi-submerged)	1±0.16 kg/m^3

Adding the weights used in Experiment #1, the mass increased to 63.3±0.1 g (this measurement was done on a more accurate pair of scales than the other mass measurement) and the volume was then 50±8 cm^2 (this proved very difficult to measure, the uncertainty stated in this value is the standard deviation of 7 measurements done using Archimedes' principle.)

Appendix 3: Still images from the video in experiment #2

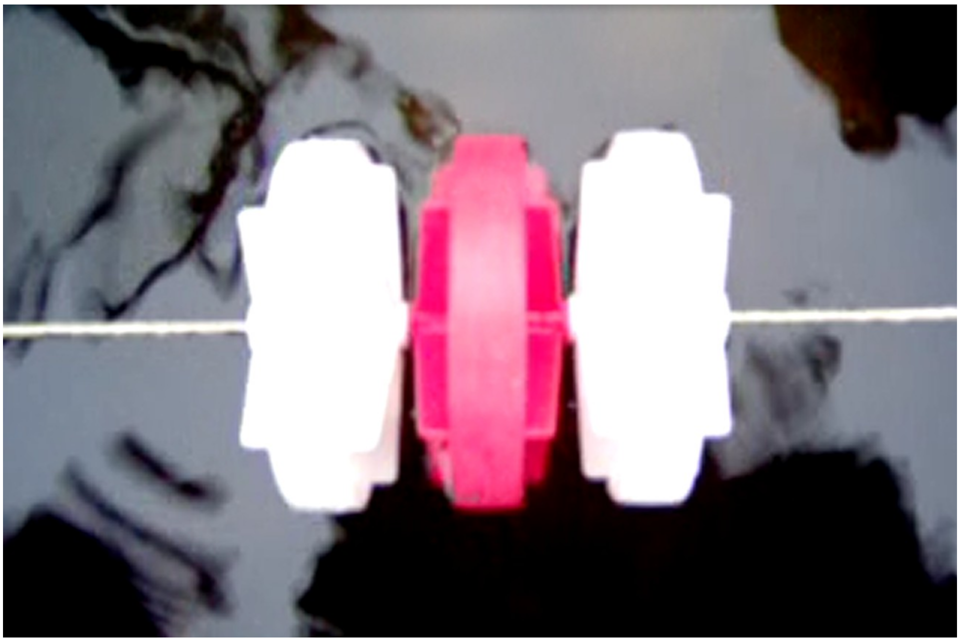

Illustration 14: One frame of the recorded video, showing circular waves on the left side.

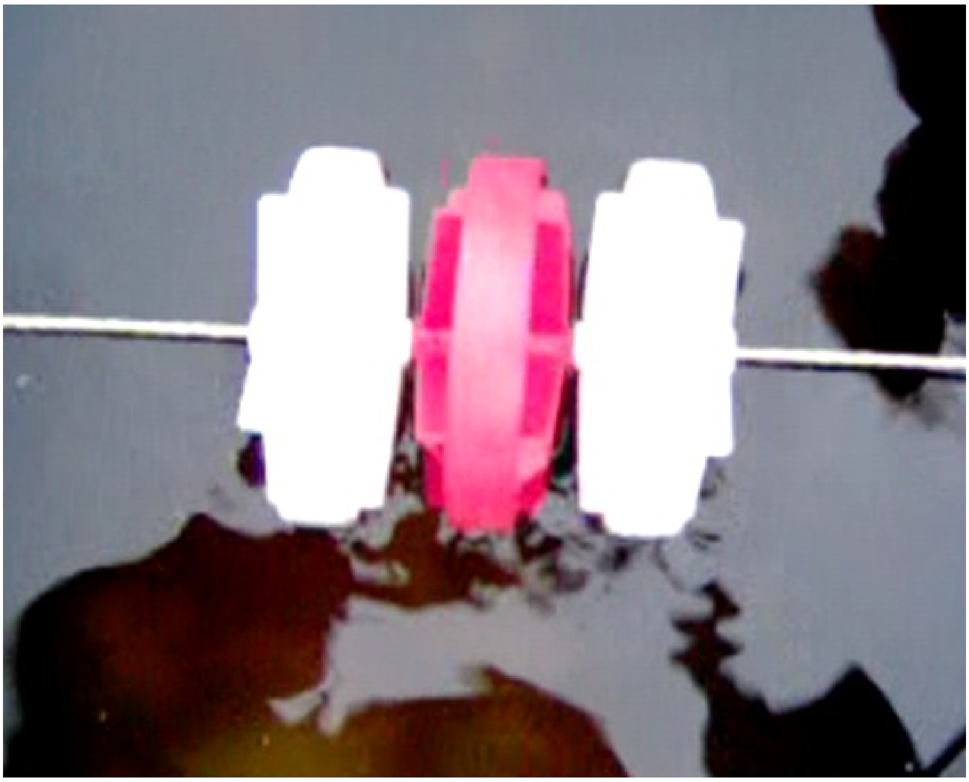

Illustration 15: Another frame of the recorded video, showing regions of turbulence.

Appendix 4: Full calculations from experiment #3

The displacement of the troughs was measured from the graphs shown. This is shown in Table 4 for both set 1 and set two. The final row shows the average displacement of the relevant graph, obtained directly from Logger Lite.

Displacement (m)	**Set 1, blue graph**	**Set 1, red graph**	**Set 2, red graph**	**Set 2, blue graph**
A	1.008	1.017	1.033	1.011
B	1.005	1.016	1.036	1.009
C	1.011	1.018	1.031	1.013
D	1.009	1.018	1.035	1.013
E	1.004	1.020	1.026	1.007
F	1.006	1.020	1.024	1.008
Mean	0.996	1.013	1.018	1.003

Table 4: Displacement of troughs.

The mean displacement is subtracted from each value to give an approximate amplitude for the wave, shown in table Table 5.

Amplitude (m)	**Set 1, blue graph**	**Set 1, red graph**	**Set 2, red graph**	**Set 2, blue graph**
A	0.012	0.004	0.015	0.008
B	0.009	0.003	0.018	0.006
C	0.015	0.005	0.013	0.010
D	0.013	0.005	0.017	0.010
E	0.008	0.007	0.008	0.004
F	0.010	0.007	0.006	0.005

Table 5: Approximate amplitude of troughs.

The amplitude of the wave in the second position is observed is then divided by the amplitude the first position, so that a percentage amplitude after travelling the 1.85 metres between the sensors is obtained, as shown in Table 2 and Table 3.