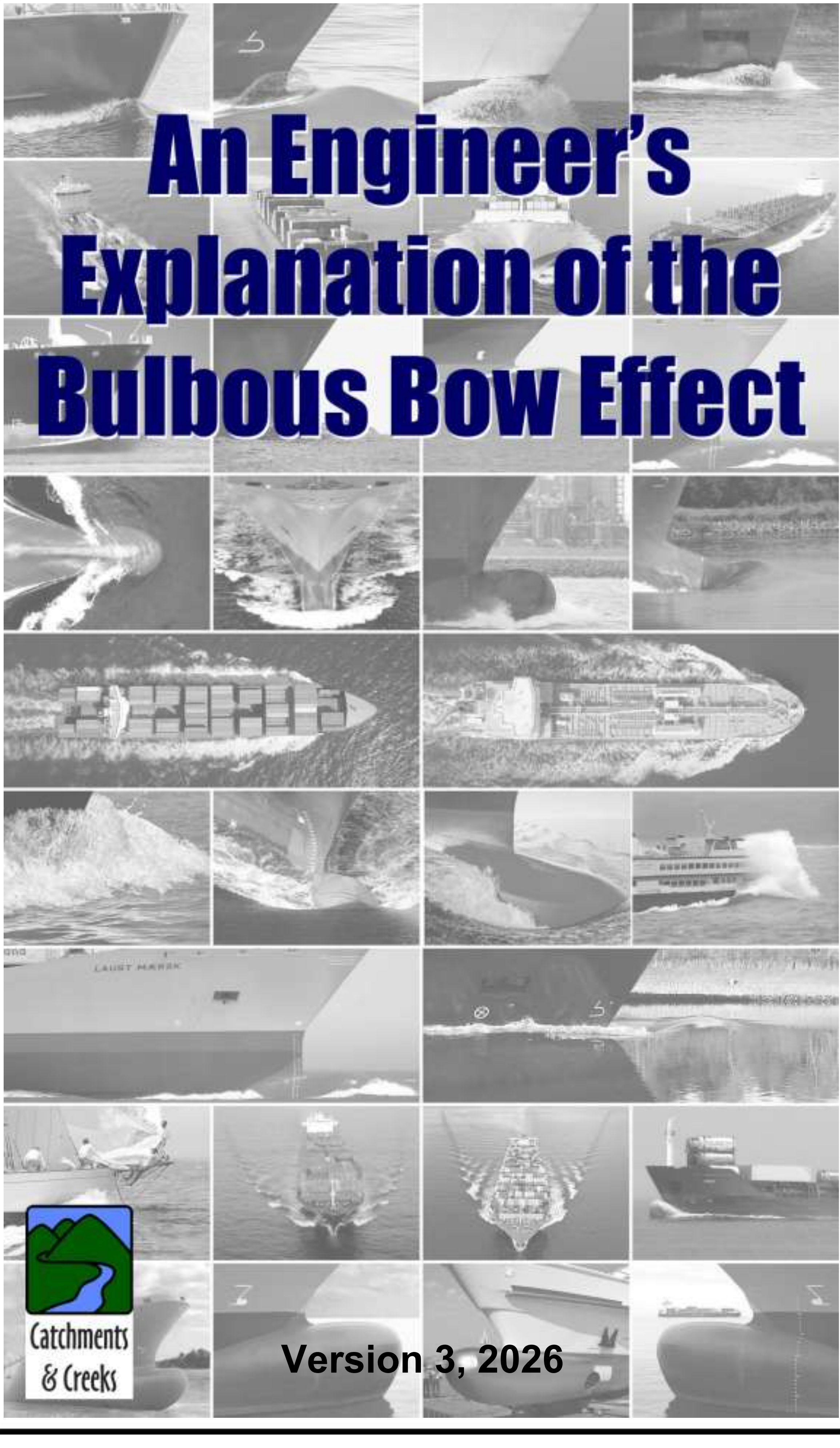
An Engineer's Explanation of the Bulbous Bow Effect



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Purpose of paper

The purpose of this paper is to put forward my explanation of the fluid mechanics involved in the operation of a bulbous bow as used in naval architecture. It is my position that the currently-accepted description of this hydraulic effect incorrectly associates the hydraulics with the actions of destructive wave interference.

I am not questioning the value of a bulbous bow. I am simply questioning the current description of how they work.

About the author

Grant Witheridge is a retired civil engineer with both Bachelor and Masters degrees from the University of NSW (UNSW). He has 40 years experience in the fields of hydraulics, creek engineering, stormwater management, and erosion & sediment control, during which time he has worked for a variety of federal, state and local governments, as well as private organisations.

Grant commenced his career at the UNSW Water Research Laboratory (1981) constructing and operating physical flood models of river floodplains.

Grant is the principal author of more than 50 engineering publications covering the topics of creek engineering, fish passage, stormwater management, aerodynamics, astrophysics, and erosion and sediment control. A common feature of all these publications is the science of fluid mechanics.

Contents

Preface

YouTube uses mathematics to predict what videos I am likely to be interested in watching. Watching YouTube is a bit like looking into a mirror. What is being presented to you is just a reflection of what you are projecting towards it. In this case, the image that I was 'projecting' was the videos that I had previously chosen to watch, and the 'reflected image' was a collection of videos that YouTube believed I would be interested in watching.

Unlike a mirror that projects as exact image, YouTube presents you with a reflection of your likely interests, which is based in-part on your past viewing, and partly on those YouTubers that have shown a similar past history.

One of the consequences of this AI-generated intelligence is that the regular watching of YouTube can reinforce in your brain that what you 'believe-to-be-true' is in fact the truth. You are constantly directed towards videos that tell you:

- what you are watching is of interest to other people
- the opinions expressed in the videos are likely to reflect your own opinions; and
- that your understanding of events, of history, of sport, and of the sciences, is in fact the correct understanding.

Wow!

So, what does all this intellectual bullsh.. have to do with 'bulbous bows' on ships?

Well, the other day YouTube decided that I would like to watch a video which described the hydraulic properties of bulbous bows. As a retired hydraulic engineer, I watched and listened to the presenter's explanation of the hydraulics, and I had to disagree with the person's point of view. This was a video the interested me, but it did not reflect my beliefs.

I have long taken an interest in the functioning of the bulbous bow on ships, but until I watched the video I had never heard the term 'bulbous bow'. I just knew that many ships were built with this lower protruding bow. I have even spoken about the purpose of such protruding bows to my hydraulics students, and even referenced to it in a court case.

I had done all of this without ever studying the hydraulic properties of bulbous bows, or reading any naval architecture books about the subject. So, have I been wrong all these years?

Logic would suggest that I am likely to be the one that has a false understanding of the bulbous bow. But I am not convinced that I am the one that is wrong (typical engineer!).

So, here I find myself writing a new document to explain my understanding of the bulbous bow.

Of course I realise that I could be completely wrong. The best that I can do is to leave it to the naval architects and naval engineers to determine if my explanations are justifiable.

Introduction

Before reading this document you need to know that I am not a trained naval architect. I know probably as much about naval architecture as your average naval architect knows about waterway and stormwater hydraulics.

This document represents just the opinion of one hydraulic engineer. However, as a retired hydraulic engineer (or water engineer if you prefer), my specialty was in fluid mechanics, which applies equally to water movement as it does to boat movement.

I believe that the currently-accepted description of the hydraulic properties of a bulbous bow is incorrect, or at least misleading. I also believe that the current description of the bulbous bow hydraulics has been repeated so many times that people have stopped questioning the stated hydraulics.

Introduction

My work place, but a borrowed car!

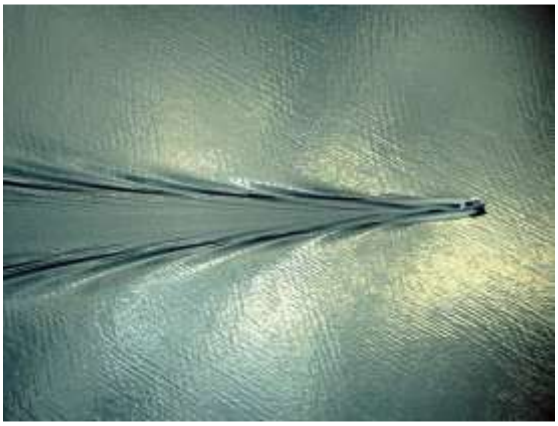
Who am I to have an opinion

- I graduated from the University of New South Wales as a civil engineer.
- I specialised in water engineering, and my first job was at the University's Water Research Laboratory.
- My work primarily involved operating physical models of river flooding—a job that, these days, is mostly performed by numerical models.
- In this laboratory we operated flume studies, which are similar to tow tanks.

Mt Druitt Water Works (water engineering)

My speciality

- While working for the University on a full time basis, I returned to my studies to complete a Masters Degree in fluid mechanics, which allowed me to also study aerodynamics at the School of Mechanical Engineering.
- Unfortunately I never studied naval architecture, but in hindsight, I wish I had.
- My expertise in fluid mechanics lies in three-dimensional flow conditions, creek engineering, and wave theory.



Bow wave

My interest in naval architecture

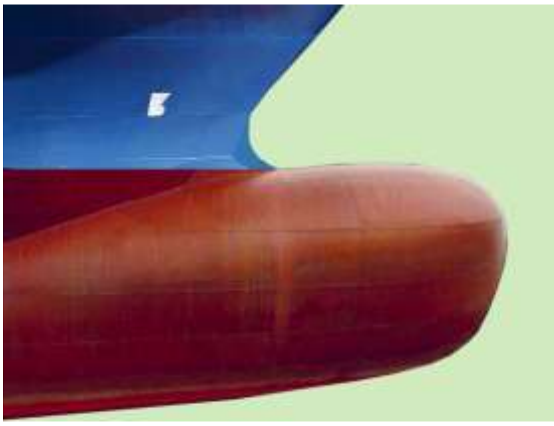
- I don't think there is a person in water engineering that does not show some interest in boats and boating.
- My brothers and uncles sail, but for me my interest has always been in understanding the movement of waves, including bow waves.
- I could sit on a boat and watch bow waves forming and dissipating, for what would seem to be an endless period of time.

YouTube

The purpose of this document

- I started preparing this document because I watched a Youtube video that reported to explain the fluid mechanics of a bulbous bow.
- I was disappointed to see that the video described the hydraulics in a manner that I could not agree with—no problem, I will just watch a video presented by a trained naval architect—Oh no, it was the same explanation, again and again.
- So, I wrote this paper with my explanation.

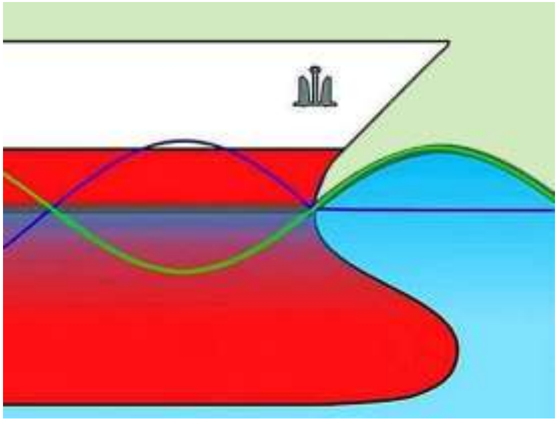
Bulbous bows



Bulbous bow

What is a bulbous bow

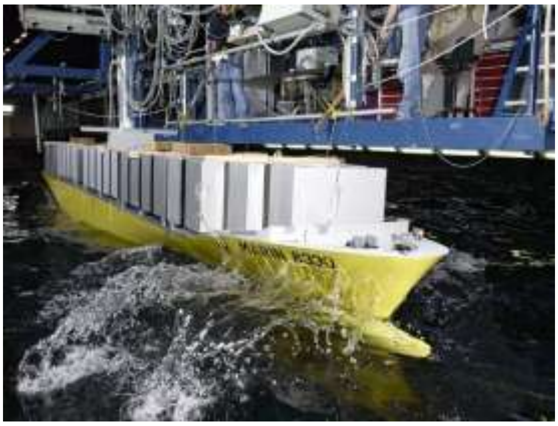
- Wikipedia (2025) states that *'a bulbous bow is a streamlined flaring or protruding bulb at the bow (or front) of a ship just below the waterline.'*
- These bulbous bows are primarily seen on large ships.
- Its primary purpose is to reduce drag, and thus save fuel and money.
- It is not a bumper bar used to push whales out of the way.



Commonly used diagram

The 'reported' fluid mechanics of bulbous bows

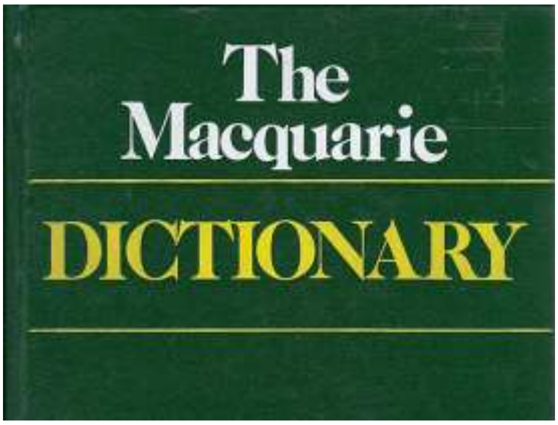
- It is reported that the effects of the bulbous bow are linked to the actions of destructive wave interference.
- It is said that the bulb is positioned such that the trough formed by the bulb aligns with the wave crest formed by the bow.
- The destructive interference of the combined crest wave and trough wave generates a lower net wave height.



Towing tank (Wikipedia)

Naval architecture

- Naval architecture involves the research, design, development, and evaluation of all aspects of a marine vehicle.
- I am not aware of the type of professionals that perform towing tank testing—but I assume they include naval architects, naval engineers, and hydraulic engineers.
- Each of these professions have their preferred terminology, which can cause confusion between the professions.

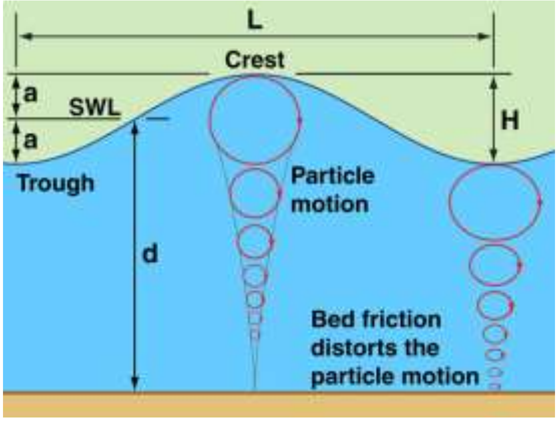


Terminology

Terminology

- I am sure that a lot of my concerns can be linked back to the different terminology used in water engineering and naval architecture.
- I primarily use water engineering terminology; however, I will try to utilise naval architecture terminology as much as possible throughout this paper.
- I have included a short glossary of terms at the end of the paper.

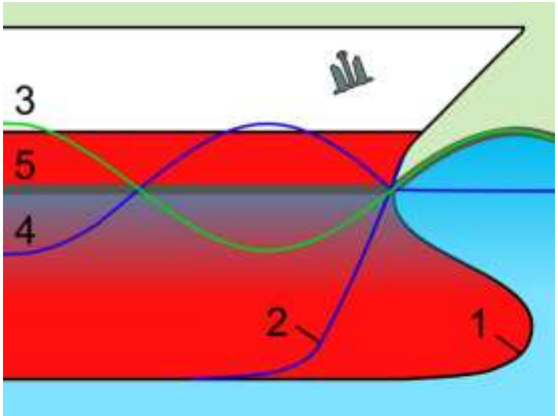
Layout of this document



Surface wave terminology

Review of fluid mechanics and wave mechanics

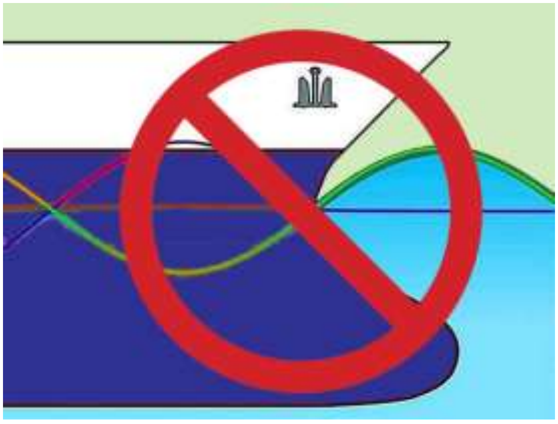
- I am completely aware that most of the naval architects reading this document will not require a refresher course in fluid mechanics and wave theory.
- However, for completeness, chapters 1 to 3 provide a review of fluid mechanics, wave mechanics, and the mechanics of bow waves.



Destructive wave interference

Chapter 4: The Currently-Accepted Theory of Bulbous Bow Hydraulics

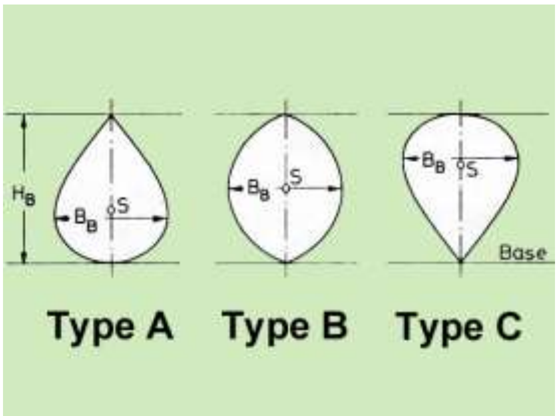
- Chapter 4 provides a summary of the currently-accepted theory of bulbous bows as provided on the Internet.



No destructive wave interference

Chapter 5: My Explanation of the Bulbous Bow Hydraulics

- Chapter 5 provides my explanation of how I believe a bulbous bow is able to reduce hull drag, and thus save fuel.



Bulb forms and parameters

Chapter 6: My Recommended Design Rules

- Chapter 6 provides my seven (7) recommendations for the design of bulbous bows.
- These recommendations must be treated with caution given my limited training in naval architecture.

1. Introduction to Fluid Mechanics

An introduction to <u>fluid mechanics</u>

The science of fluids in motion

Fluid mechanics

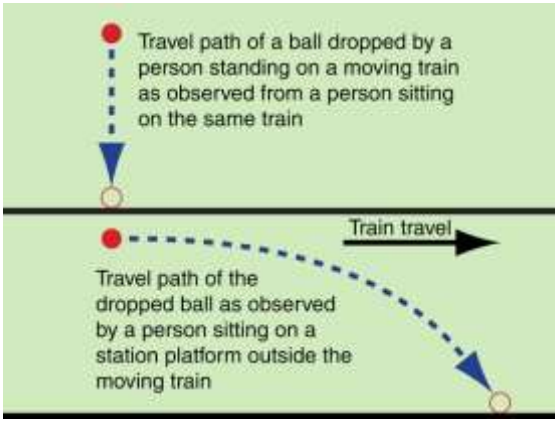
- A 'fluid' is *'a substance which is capable of flowing and offers no permanent resistance to changes in shape; a liquid or a gas.'* (Macquarie Dictionary, 2006)
- The science of fluid mechanics covers water engineering, aerodynamics, astrophysics, and naval architecture.

(The image, left, is a photo I took of Niagara Falls in 1995; an example of water in motion).

Wind tunnel testing of a Boeing 777

Point of reference

- According to the laws of motion, it does not matter if you study the dynamics of a boat moving through still water, or if you study the dynamics of water moving past a stationary vessel held in a test flume.
- The same forces will act on the boat if the water is moving and the boat is still, if the boat is moving and the water is still, or if both the boat and water are moving.
- The only issue that matters is the relative velocity difference.



Observing the dropping of a ball

Observers on a train and on a platform

- If a passenger sitting on a train watched someone on the same train drop a ball, then the passenger would observe the ball simply falling vertically to the floor.
- If a passenger sitting on a railway platform observed the same person (on the train) dropping the ball, then they would observe the ball moving along a curved path.
- The two observers would see two different forms of motion, but in each case the same laws of physics apply.

Hull testing (Wilipedia)

Hull design and testing

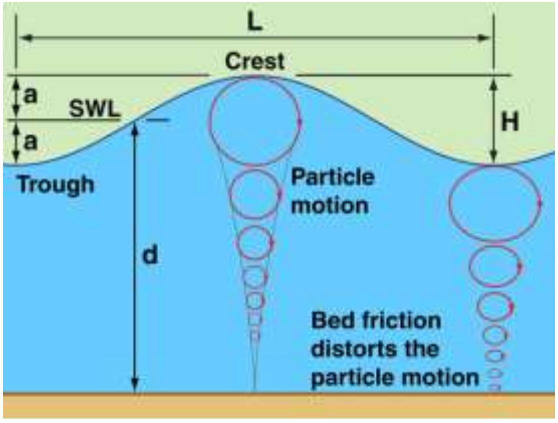
- The hydraulics of hull design and testing can involve:
  - studying a model boat being driven by a gantry through still water in a towing tank
  - studying a stationary boat held in flowing water (a flume).
- In naval architecture it is more common for the former case because it is desirable to have a wide tank that avoids wave reflection issues.

An introduction to wave motion

Surfing standing waves

The movement of fluids

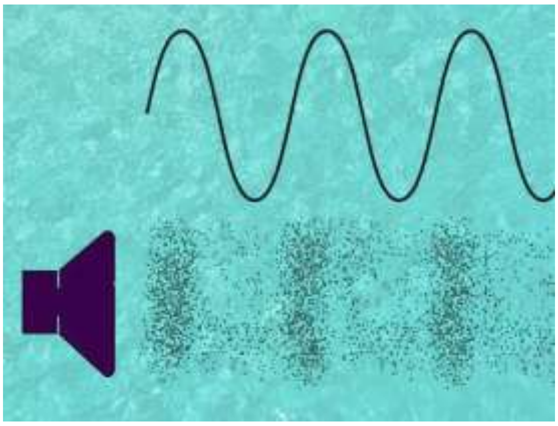
- Fluids are either moved by the force of gravity, of through the actions of pressure.
- Gravity works on every molecule of water evenly, so there is no time delay in the actions of gravity.
- Pressure forces, however, move through a fluid at the speed of causality.
- The speed of causality depends on whether the pressure message is being moved by a surface wave, or by an internal compression wave (e.g. sound).



Surface wave terminology

Surface waves

- Water is usually considered to be an incompressible fluid.
- This means that a change in water pressure is normally associated with a change in the effective water depth.
- Movement of a surface wave corresponds with the internal movement of a pressure wave.
- The speed of a wave (or wave celerity 'C') can be determined by its wave length (L) and period (T); thus: $C = L/T = (gT)/(2B)$.



Sound waves in water

Compression waves

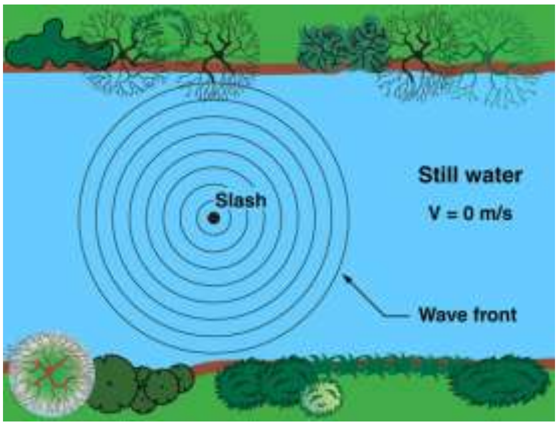
- Even though water is considered to be incompressible, it should be acknowledged that all matter is compressible to some degree, otherwise we would not have black holes.
- The movement of sound waves through water relies on the minor compression of water in order to carry these longitudinal compression waves.

A plunging bow wave with forward splash

Energy movement vs particle movement

- As is the case for any fluid, water can experience both energy movement and particle movement.
- Energy movement can involve pulsating particle movement, but there is no permanent displacement of the water molecules.
- Waves can move either as energy waves (e.g. sound and ocean waves), or as particle waves (e.g. a broken surf wave).
- Bow waves can move as both energy waves and/or as particle waves.

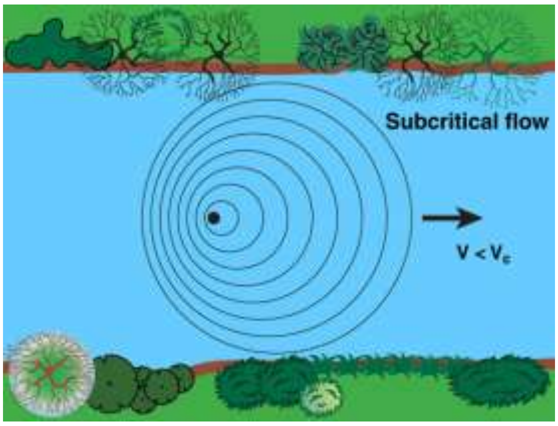
Critical, subcritical and supercritical flow velocity



A stone thrown into still water

The movement of surface waves

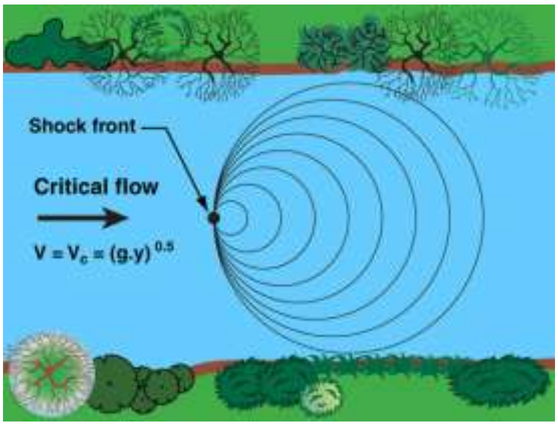
- A classical surface wave observed moving across still water is an energy wave, which means that only the 'energy' of the wave moves—the water surface may move up and down, but it does not permanently move horizontally.
- The driving force for these waves is gravity.
- The wave's energy is transferred across the pond through the actions of water pressure.



A stone thrown into moving water

The movement of waves in flowing water

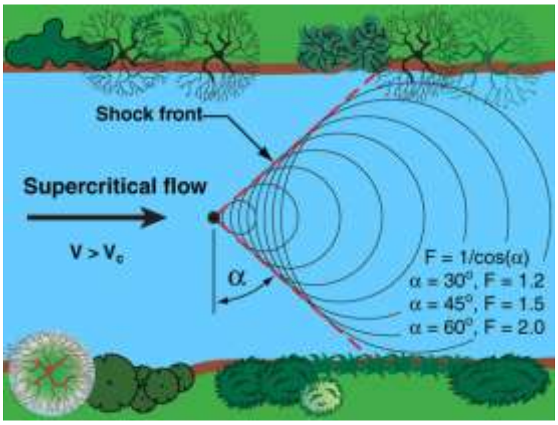
- If the same wave energy is released into a flowing river, then the wave movement will result from both:
  - the movement of the water pressure
  - the movement of the water current.
- If a stone is thrown into a flowing river, then the resulting circular waves will slowly be carried along the river.
- If the speed of the pressure wave is greater that the water velocity, then the wave can move upstream.



River flowing at its critical velocity

Critical velocity

- If the water velocity is equal to the speed of the pressure wave, then the wave cannot move upstream.
- When a stone is thrown into water, it causes the splash point to first fall, then rise, then fall, then rise, etc.
- This action continues to form new waves until friction calms the water surface.
- However, each 'new' wave fails to move upstream, and so a standing wave (or shock wave) is formed at the splash point.

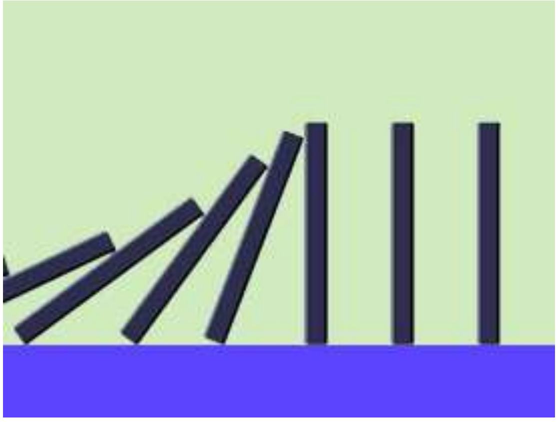


Supercritical flow conditions

Supercritical flow

- If the water velocity is less than the wave speed, then it is called subcritical.
- If the water velocity is equal to the wave speed, then it is called critical velocity.
- If the water velocity is greater than the wave speed, it is called supercritical.
- When a disturbance occurs in supercritical flow, the resulting wave action will form an angular shock wave, which is directly related to the movement of bow waves.

Critical velocity and the speed of causality



The domino effect

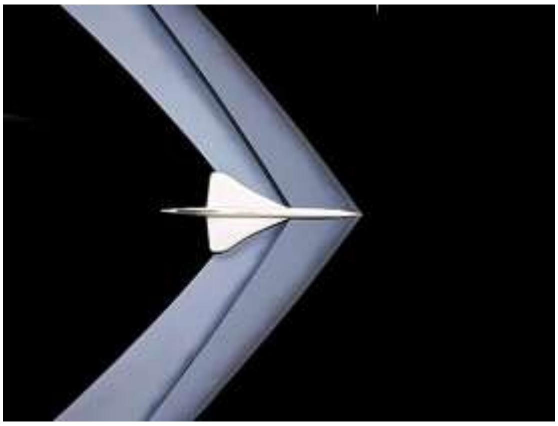
The speed of causality

- The speed of causality is the natural speed of the primary driving force.
- In air, the primary force is the speed of a pressure wave (i.e. a sound wave).
- In space, the speed of causality defines the speed of light.
- At an air–water interface, the primary force is gravity, which controls the speed of a pressure wave passing through the water.

Speed detection

The speed of causality of space

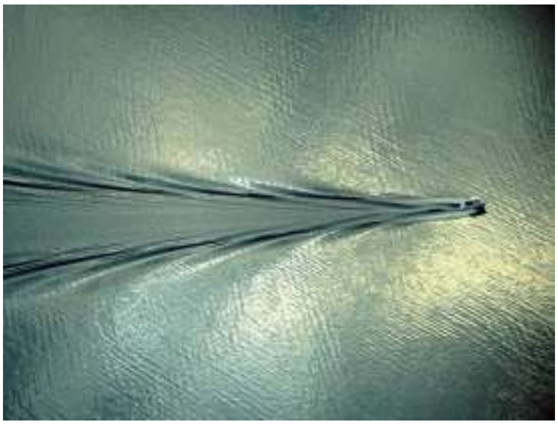
- The speed of light is the speed of causality of the media through which the light travels, which in space is 'aether' (a cloud of non-concentrated quantum forces).
- This means that the speed of light is not a constant, but actually depends on (i) the velocity of the media (e.g. Earth's atmosphere is moving through space), and (ii) the density of the media.



Sound-based shock wave

The speed of causality of air

- If an aircraft accelerates through the sound barrier (i.e. the speed of causality of air), a shock wave is formed.
- This shock wave travels with the plane because it is constantly being generated by the plane.
- The shock wave will trail behind the plane in a V-shape if the plane is travelling faster than the shock (sound) wave, and the angle of this shock wave becomes more acute as the plane's speed increases.

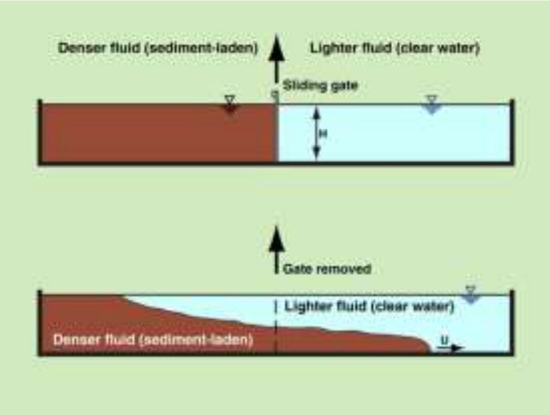


Water motion linked to critical velocity

The speed of causality of air–water

- The critical velocity of a fluid is the speed that an energy 'message', or a pressure wave (the same thing), can move through the fluid.
- The term 'critical velocity' is very similar to the term 'speed of causality'.
- The difference in how the terms are used is that a physical object can move through a fluid at speeds greater than the fluid's critical velocity, but a pressure wave cannot move faster than the speed of causality for that media.

The importance of water temperature and viscosity



Lock exchange test showing internal wave

Water viscosity

- The viscosity of water influences the reaction time of water to an energy message.
- Water viscosity affects the speed that a water surface can react to changes in water pressure, as well as the speed of these water pressure messages, as in the case of internal waves.
- The viscosity of water is primarily governed by the water temperature, but in freshwater, sediment concentration can also play a role.

Strong wave action at Shetland Islands

The effects of water viscosity on waves

- In coastal engineering, the viscosity of the water is often ignored because its effects on large waves can be minimal.

Dancing tropical waters

Tropical waters

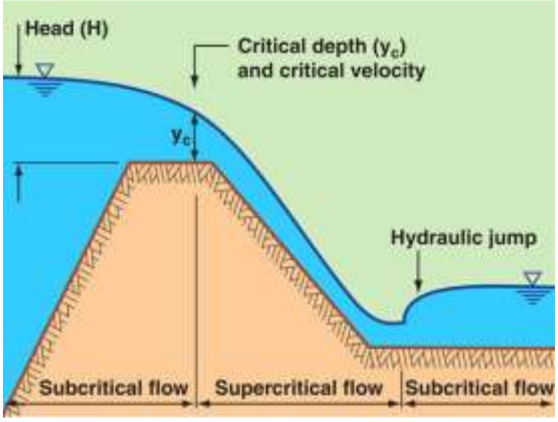
- In warm tropical waters, the water surface can appear to 'dance' in a noticeably faster way than it does in frigid waters (but not always).
- Experienced observers should be able to notice a difference in the movement of tropical waters compared to arctic waters.

The cold waters of the Shetland Islands

Frigid waters

- Arctic water can be just as choppy as tropical water, as shown in the image above, but the effects of viscosity can often be seen in the 'sharpness' of the wave crest.
- Even though the effect can be small, if the design of a bulbous bow is as sensitive to boat speed as is suggested by some authors, then temperature effects should be included in CFD (Computation Fluid Dynamic) modelling.

Subcritical and supercritical water flow



Flow conditions on a dam spillway

Subcritical flow in an urban creek (Qld)

Supercritical flow down a mountain stream

Critical flow at the crest of a dam spillway

Introduction

- Most people are aware that there are two types of air flow, subsonic and supersonic, which relates to the speed of sound.
- The speed of sound is important because it is the speed of a pressure wave in air.
- Well, there are also two types of water flow, subcritical and supercritical, which relates to the speed of a surface wave.
- The speed of a surface wave is important because it is the speed that pressure waves can move through water.

Subcritical flow condition

- During subcritical flow, the elevation of the water (the flood level) is governed by the flow conditions that exist downstream of the point of observation.
- This means that as floodwaters approach a coastline, the height of the flood will eventually become influenced by the tide conditions into which the waterway is flowing.

Supercritical flow condition

- Most people would have observed supercritical flow by simply watching stormwater flowing down a roadway.
- Only on very flat roads will stormwater be moving at subcritical velocities.
- In waterways, supercritical flow normally exists only in the steep upper reaches.
- During supercritical flow, the elevation of the water, and its flow velocity, will be governed by the flow conditions that exist upstream of the point of observation.

Critical flow condition

- Critical flow is a third flow condition that exists at the point where stream flows convert from subcritical to supercritical.
- In theory this condition also exists when flows convert from supercritical to subcritical, but this particular condition is so unstable it is difficult to detect.
- Critical flow may be important to hydraulic engineers, but it does not play a major role in creek engineering, or naval architecture.

Subcritical flow travelling down a roadside gutter (kerb & channel)

Roadside kerb drainage

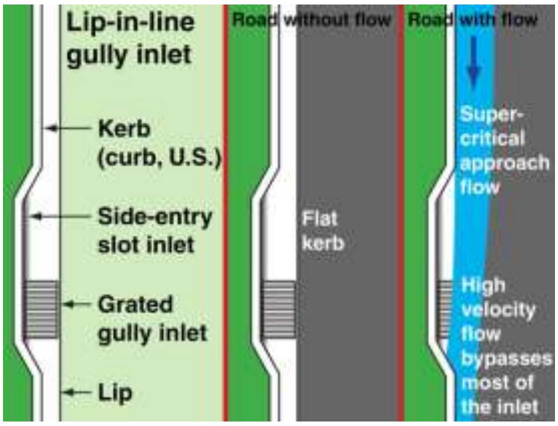
Roadside gully inlet

- The purpose of a gully inlet is to take water flow off the roadway at regular intervals in order to ensure:
  - pedestrians can safely cross a road while it is raining; and
  - driving conditions remain safe.
- So, somehow, the roadside kerb flow must be encouraged to turn 90-degrees over a very short distance in order to enter the gully inlet.

Supercritical kerb flow

Evidence of supercritical kerb flow

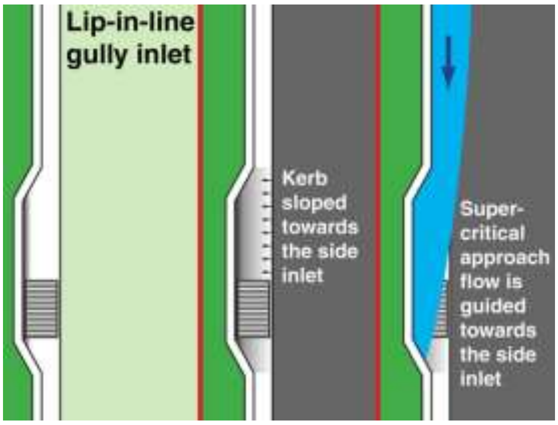
- Hydraulic messages move through water as pressure waves, which can normally be observed by a rise and fall in the water surface (i.e. as waves).
- When the flow passes down a kerb, and hits an irregular surface (e.g. a rough kerb stone), a shock wave is produced, which can be observed as 'lines' or wave crests on the surface of the water.
- Because the flow velocity is near-constant, these shock waves are usually parallel.



Flow with a 'flat' channel base

Kerb flow moving towards a gully inlet

- If the flow passing down a road is supercritical, then its movement is not controlled by downstream channel conditions, and it will resist any change of direction.
- If the 'base' of the channel (i.e. the kerb & channel) is sloped like the upstream section of channel, then the supercritical channel flow will simply travel past the gully inlet (i.e. no water will want to turn 90-degrees and enter the gully inlet).



Flow condition if the channel bed is tilted

Kerb flow moving towards a tilted gully inlet

- If the 'base' of the channel upstream of the gully is aggressively sloped inwards towards the gully, then the supercritical channel flow will begin to move towards the gully before the water even arrives at the gully.
- So, the slope of the channel's base (upstream of the gully) is used to send a message to the supercritical flow telling it that it needs to start moving towards the gully.

Energy conservation in fluid mechanics

Bow splash

Introduction

- Just like in politics, there are no free lunches in fluid mechanics—the more work you do on the water, the more energy you will consume.
- For ships, this energy consumption is linked to the ship's drag.
- There are at least four components of a ship's drag:
  - form drag (or pressure drag)
  - friction
  - turbulence
  - splash.

Turbulent water (jet wash from jet motor)

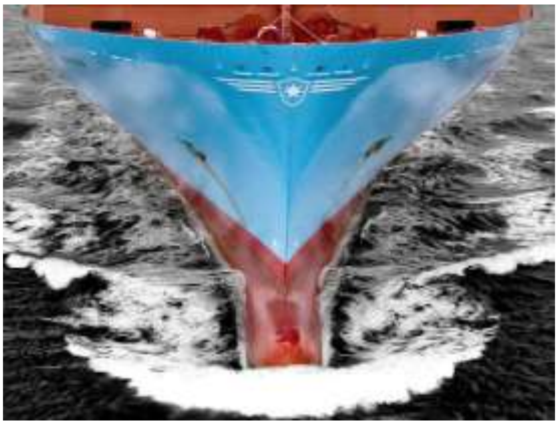
The energy consumption involved in creating turbulence

- It requires more energy to create turbulent water than to create smooth-flowing water.
- Boats can create a smooth-water bow wave, or a turbulent-water bow wave.
- This type of turbulence is most commonly associated with a boat travelling through choppy seas, but turbulence can also be generated by a bow that forces the passing water to rapidly change velocity.

Water supply dam outlet structure

The energy consumption involved in creating splash

- It requires more energy to create splash than to create smooth-flowing water.
- Some pipe outlets use the effects of water spray (splash) as a means of dissipating the outflow energy.
- Unfortunately, towing tanks do not reproduce the true effects of splash and turbulence because model scales are based on viscosity issues, not surface tension.

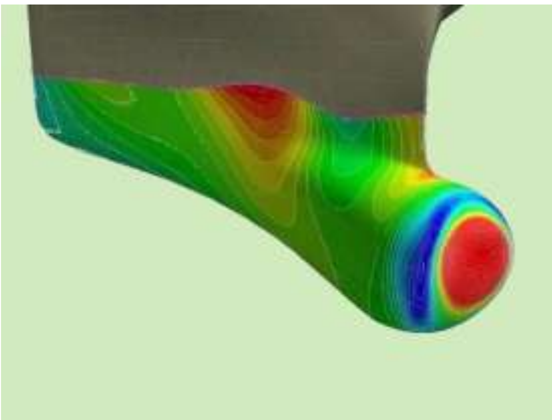


Bow wave

The energy consumption involved in creating waves

- It requires energy to create any form of bow wave.
- Waves are formed by the actions of pressure, and the application of a pressure differential requires a force, and a force applied over a period of time involves 'work' and 'energy'.
- However, boat drag can be minimised by reducing both the wave height, and the turbulence associated with the waves.

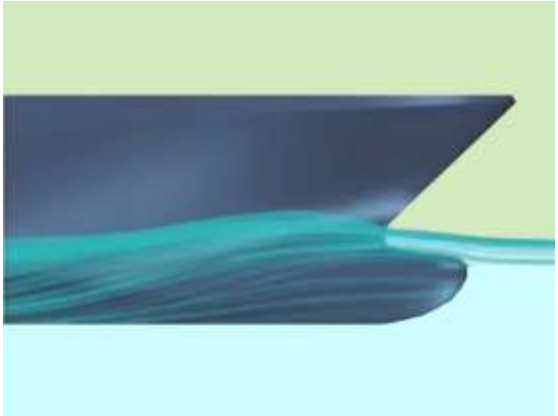
Computational Fluid Dynamic (CFD) modelling



CFD modelling

Introduction

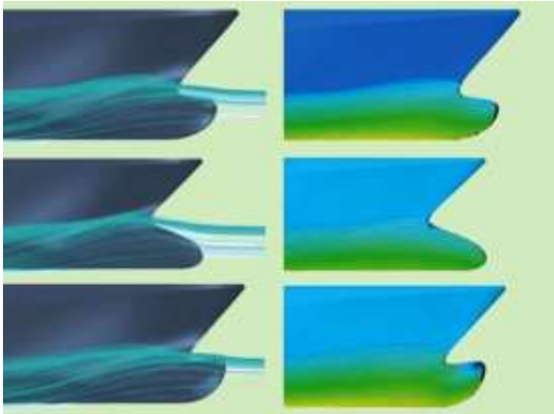
- Computational Fluid Dynamic (CFD) modelling can tell us many things, but it cannot tell us 'why' something works.
- Over my career I have met many people who believe that CFD modelling is error-free; that it is a form of modelling that can be trusted.
- However, people forget that everything that goes into a CFD model was 'invented' or introduced by a human, and humans are not perfect.



CFD modelling

The use of hydrostatics in CFD modelling

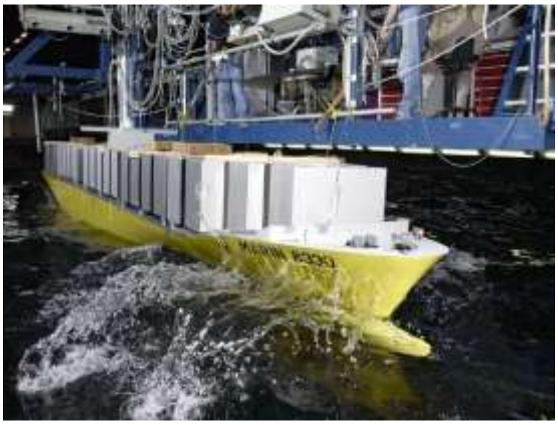
- Most of the hydraulic equations that are used in CFD modelling are based on the 'laws of hydrostatics'.
- These 'laws' relate to the properties of water when it is at rest (hence the term: hydrostatics).
- Unfortunately, the laws of hydrostatics begin to break down when the flow conditions become unsteady and turbulent, so errors can creep into the modelling.



CFD modelling

Incorporating temperature and viscosity corrections in CFD modelling

- Water viscosity can play a major role in the movement of water, the degree of turbulence, and the level of friction.
- A major factor affecting water viscosity is the water temperature.
- Therefore, a boat's drag can vary as it moves through different water temperatures.
- CFD modelling needs to account for these temperature differences.



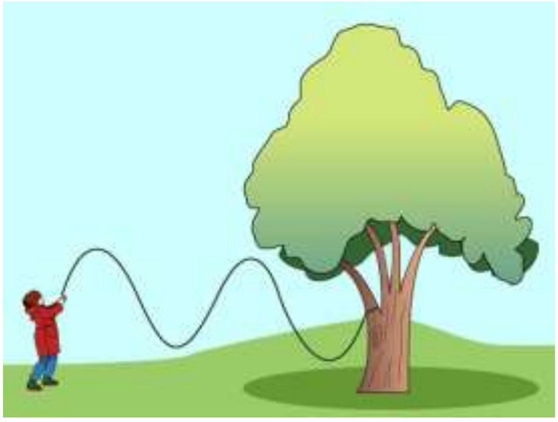
Towing tank (Wikipedia)

CFD modelling of storm conditions

- During storm events, the bow can generate significant amounts of splash.
- The energy consumption of 'splash' will also vary with water temperature.
- However, if properly calibrated, CFD modelling should be able to analyse storm conditions better than a tow tank.

2. Wave Mechanics

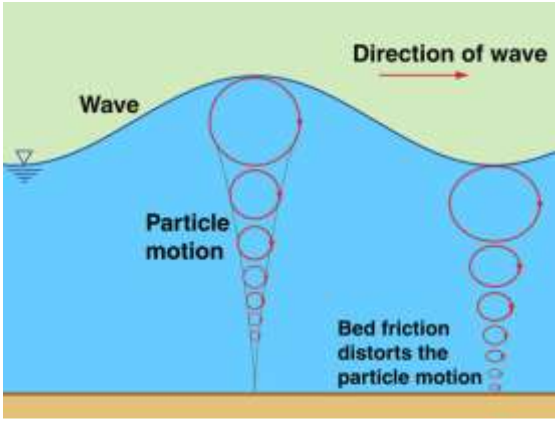
Introduction



Transverse waves

Types of waves

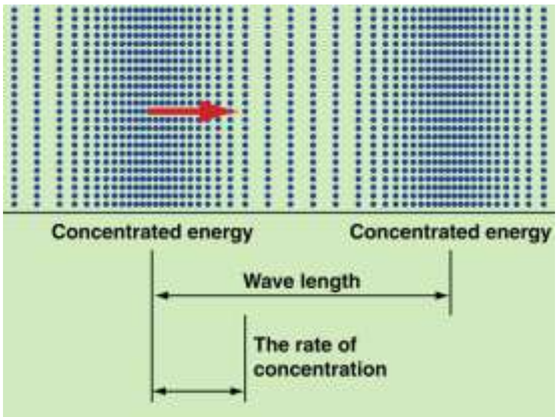
- Waves can be either travelling waves or standing waters.
- Standing waves are waves that appear stationary to an observer, even though they may be moving relative to the media.
- Waves can also be classified as either energy waves, particle waves, longitudinal waves and transverse waves.
- Waves can travel as a single wave, or as a set (group) of waves.



Wave mechanics

The structure of waves

- Waves normally involve a disturbance within a given media, or along the interface between two different forms of media (e.g. air and water).
- Energy waves involve a flow of energy, with the media not moving with the wave.
- Particle waves involve a flow of media (e.g. water) along with the flow of energy.
- The physics involved in the 'meeting' of two opposing waves depends on the structure of the waves.



Energy compression waves

Energy waves

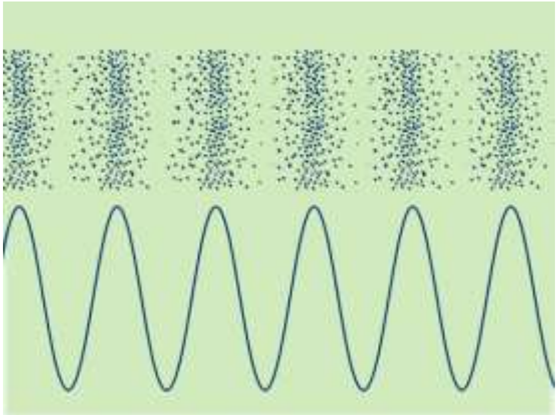
- Both energy waves and particle waves are examples of pressure waves.
- An energy wave transports only energy, i.e. there is no permanent movement of the water.
- Examples of energy waves includes:
  - gravitational and ocean waves
  - electromagnetic waves and light.
- **Only** energy waves can experience constructive or destructive interference.

Surfing a coastal (broken) wave

Particle waves

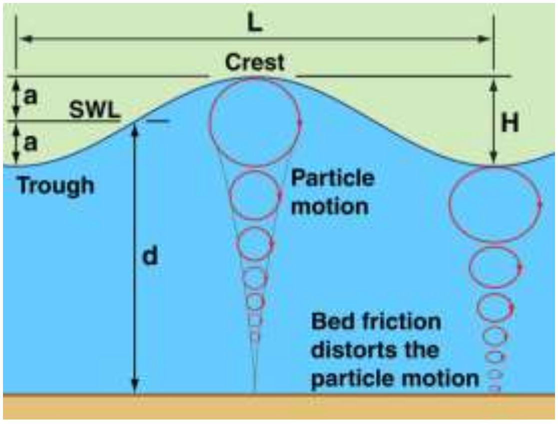
- A particle wave transports energy and matter.
- Examples of particle waves includes:
  - coastal (broken) waves
  - tsunami waves travelling over land
  - weather fronts.
- Particle waves cannot experience constructive or destructive interference.
- Once a coastal wave has broken, it cannot pass through another broken wave.

Critical velocity and its relationship with wave action

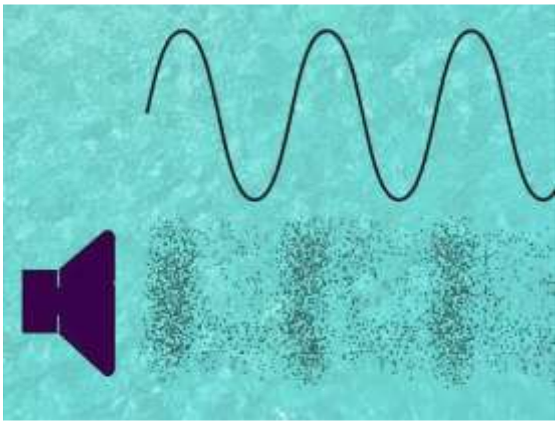


The speed of sound (compression wave)

Surface waves



Surface wave terminology



Sound waves in water

Introduction

- As discussed in the previous chapter, the critical velocity of a fluid refers to the speed of a force or pressure wave.
- In water engineering, the term 'critical velocity' is commonly used.
- In aerodynamics, the equivalent term is the 'speed of sound'.
- In astrophysics, the equivalent term is the 'speed of causality', which determines the speed of light.

The critical velocity of water

- Open channel flow is a special form of fluid mechanics because it involves an interface between two different fluids, usually air and water.
- This means water flow has two critical velocities:
  - the velocity of a surface wave; and
  - the velocity of a compression wave, such as the speed of sound in water.

Surface waves

- In most circumstances, water can be treated as an incompressible fluid.
- This means that a change in water pressure is normally associated with a change in the effective water depth.
- The speed of a wave in shallow water is given by:

$$C = (gT/2\pi).\tanh(2\pi d/L)$$

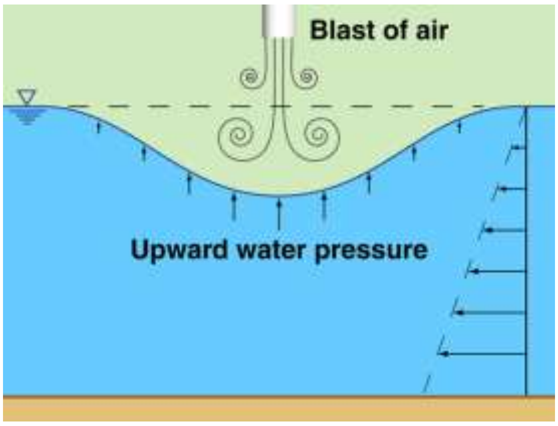
- The speed of a wave in deep water:

$$C = (gT/2\pi)$$

Sound waves

- Even though water is generally considered to be incompressible, it should be noted that all matter is compressible to some degree.
- The movement of sound waves through water relies on the minor compression of the water in order to carry the longitudinal compression waves of sound.
- It is because the driving force of a sound wave is different from a surface wave, that it has a unique speed of causality.

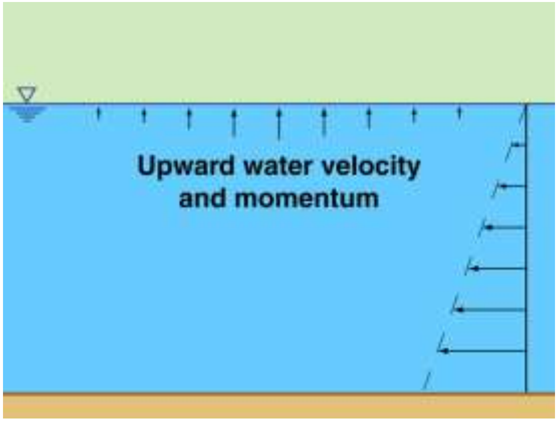
Wave dynamics



Effects of a vertical blast of air

Standing waves

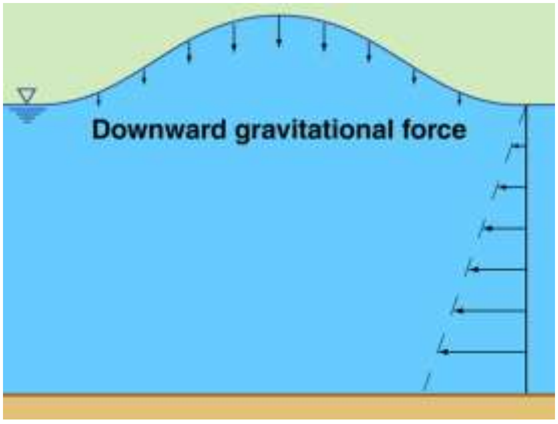
- A standing wave experiences primarily vertical movement, with no permanent horizontal movement (i.e. the wave appears to the observer to be stationary).
- If a blast of air were to be directed vertically downwards onto a body of still water, then the water surface below the jet of air would form a depression, in other words, a 'trough'.



Rising water level

Rising water level

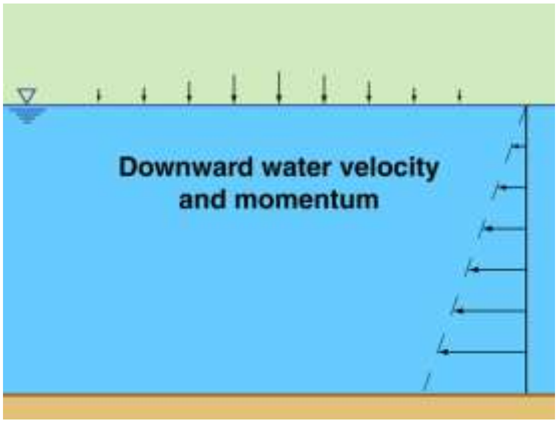
- Once the blast of air was stopped, the water surface would desire to return to its normal water level.
- The speed of this rising phase is a function of:
  - the wave amplitude (a), and the
  - the water viscosity.
- By the time the water has reached its normal water level, the rising water would have obtained an upward velocity and corresponding momentum.



Crest of the standing wave

Crest of the standing wave

- The momentum lifts the water surface above the normal water level, while its upward velocity begins to decline until a wave crest is formed.
- The water surface then begins to fall.
- Once again, the water surface accelerates to a maximum downward velocity, gaining momentum as it falls.
- The speed of this falling water surface is governed by the wave amplitude and the water viscosity.



Ongoing downward movement

The cycle repeats

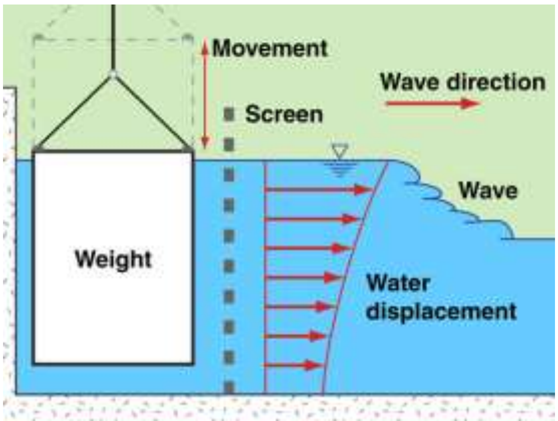
- The water surface rises and falls repeatedly forming a classic standing wave pattern.
- However, because the water pressures radiate out in all directions, this central standing wave will generate additional circular waves that radiate outwards across the water surface.
- This action is repeated every time an object, such as a water drop, falls into a pond of water.

Generating different types of moving waves

Wave generation water park

Wave generation

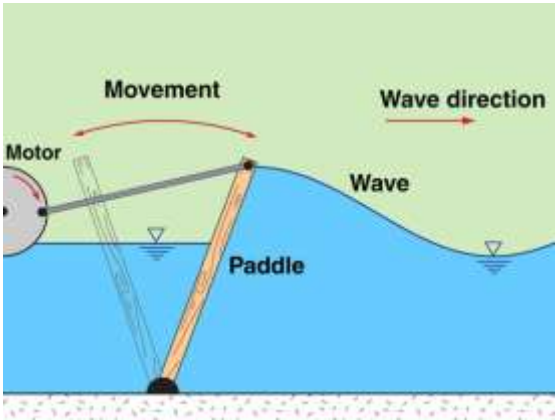
- Waves can be generated by various actions, including:
  - the action of wind
  - the movement of objects across the water
  - wave paddles.
- At water parks, wave generators can be used to form a variety of waves depending on how the wave is intended to be used.



Positive displacement wave

Positive displacement wave

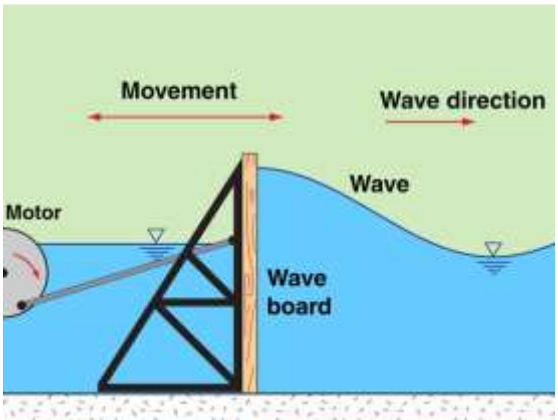
- Rapidly lowering a large weight into the water will typically generate a positive displacement wave, which is a type of particle wave.
- Being a particle wave, a portion of the water moves with the wave.
- This type of wave can be used to body surf, or catch with a surf board.



Wave paddle

Wave paddle

- A wave paddle is usually hinged at the base of the water tank, which means there is minimal paddle movement and water displacement at the base of the tank.
- This system typically generates energy waves.
- Wave paddles are used when it is desirable for bathers at an artificial beach to simply move up and down with the wave action, and not be constantly carried towards the beach.



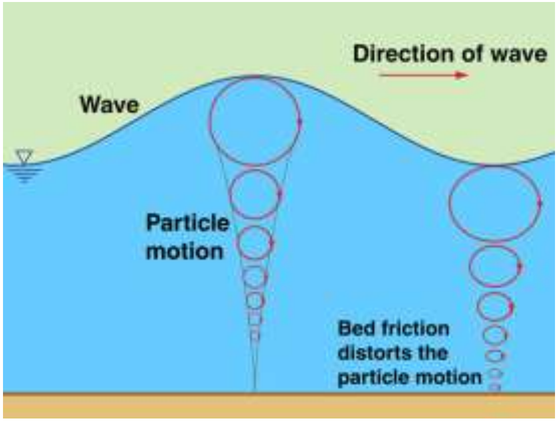
Cyclic displacement wave

Cyclic displacement waves

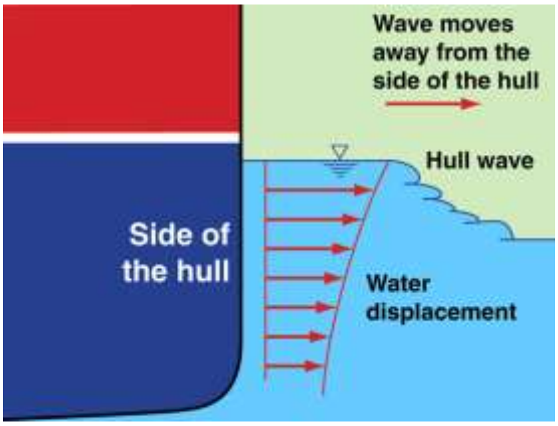
- Vertical wave boards can generate a variety of waves depending on the speed of the driving motor.
- At slow speeds, this system will generate energy waves.
- However, if the forward motion of the wave board exceeds the speed of the resulting gravity wave, then a positive displacement wave will be formed.
- In many ways, this system simulates the generation of hull waves.

Generating particle waves

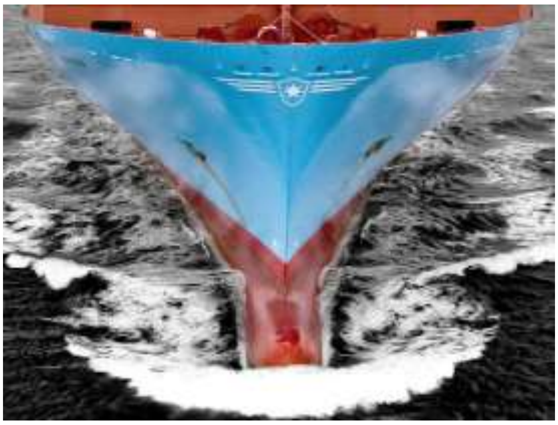
Particle wave



An energy wave



Bow wave pushed away from the hull



Bow waves

Introduction

- A wave does not have to be either an energy wave, or a particle wave, but can be a combination of both types of waves.
- Bow waves are usually a combination of particles waves and energy waves.
- A pressure wave is just another term used to describe an energy wave.
- In naval architecture it is important to understand the conditions that allow the formation of all three types of waves.

The properties of energy waves

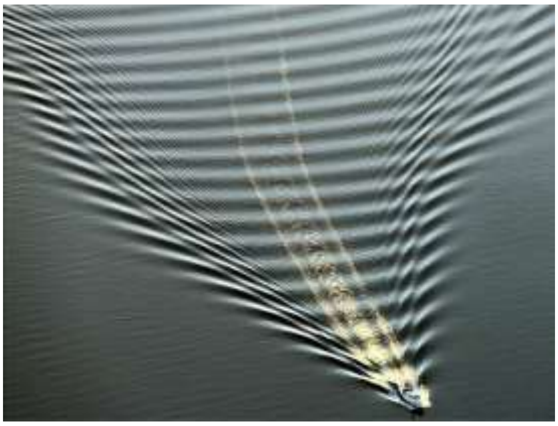
- A critical factor in the formation of waves is the speed of causality.
- The driving force of an energy wave in open water is gravity and the speed that water pressures can be transferred through the water.
- In these conditions, the speed of the pressure wave becomes the speed of causality.
- The maximum speed of an energy wave is its speed of causality.

The formation of particle waves

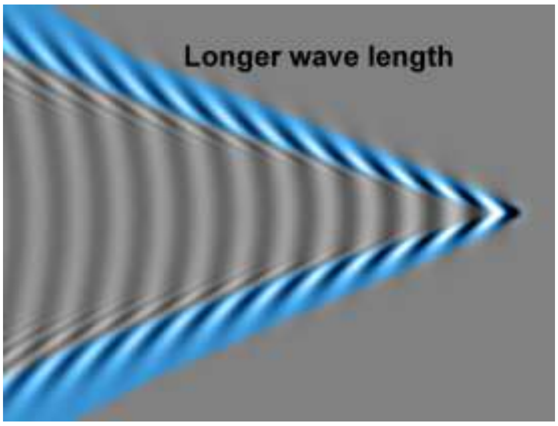
- When water flows along a channel, the driving force is usually gravity, and the flow represents a particle flow, independent of the speed of the water.
- When water is pushed in a manner that forms a wave, then technically a particle wave is formed.
- However, if this forward movement is immediately followed by an equivalent reversal of movement, such as when waves are formed by a wave paddle, then no net horizontal movement occurs, and the wave is considered to be just an energy wave.
- Further complicating this issue is the speed of the action (i.e. the speed of the wave paddle or boat).
- If the water is forced to move at a speed that exceeds the speed of the resulting pressure wave, then a part of the wave will accelerate past the lower pressure wave causing a spilling wave to be formed.
- Large boats travelling at their normal cruising speed typically form combined energy and particle waves.

3. Bow Waves

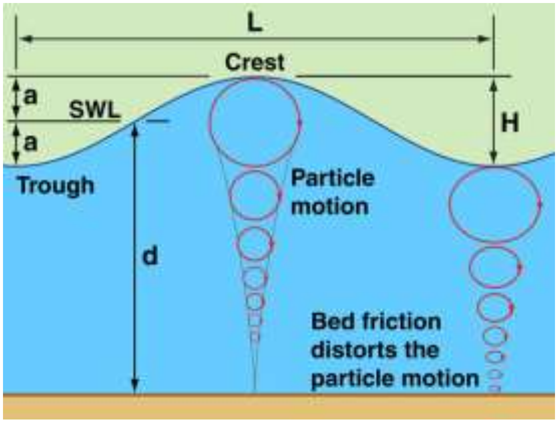
Introduction



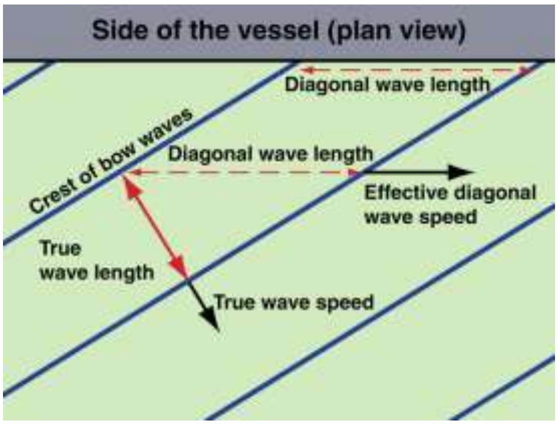
Complex bow wave



Longer wave length hull waves (blue)



Wave length



True and diagonal wave length

Bow waves

- A bow wave is the wave that forms at the bow of a ship as a consequence of its movement through the water.
- Initially, the spread of this bow wave will define the outer limits of a ship's wake.
- However, if long waves are generated by the vessel's hull, then these longer and faster waves will eventually overtake the bow wave, and form a wider wake angle.

Controlling factors

- The size of the bow wave is a function of:
  - the speed of the vessel
  - its draft
  - existing surface waves
  - water depth, and
  - the shape of the bow.
- The 'size' of a bow wave is defined by its wave height (amplitude) and its length.
- The region shown in 'blue' highlights the waves with a longer wave length.

Wave length

- Some commentators discuss the wave length in terms of the wave's profile as projected onto the hull of the vessel; however, this is NOT the true wave length.
- The true wave length is measured along the direction of travel.
- It is necessary to view the bow wave in 'plan view' in order to determine the wave direction, and the 'true' wave length.
- The speed of a bow wave, as measured in the direction of the wave, is a product of its wave length.

A fact of geometry

- Projecting a wave onto the hull of the vessel is equivalent to cutting a diagonal through a wave pattern.
- Such a diagonal would present a longer wave length.
- The 'effective' wave speed in the direction of this diagonal would be proportional to this longer diagonal wave length.
- Consequently, describing the wave speed in terms of the wave length as projected onto the hull of a vessel is still 'technically' correct.

Energy conservation

Bernoulli principle:

$$V^2/2g + P/\rho g + Z = \text{constant}$$

Kinetic energy + Potential energy = Total energy

where:

V = relative speed difference

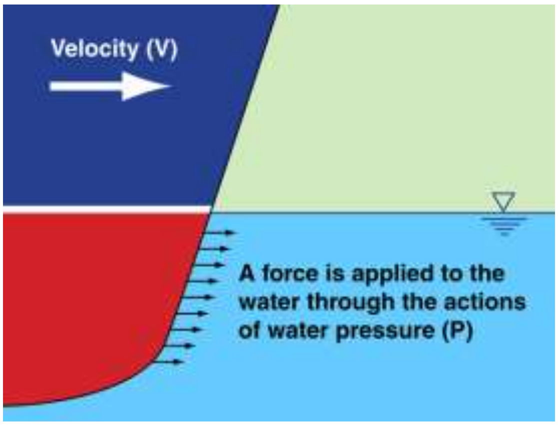
g = acceleration due to gravity

P = hydraulic pressure

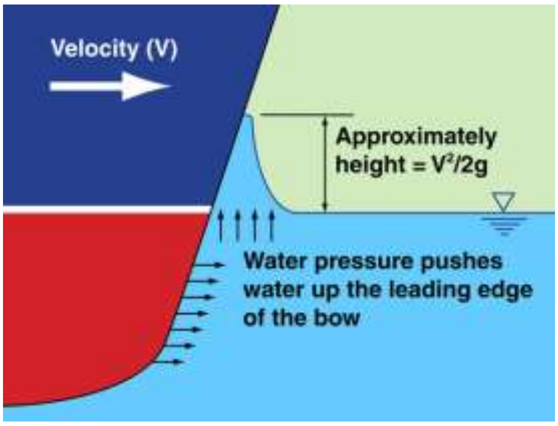
ρ = water density

Z = datum elevation

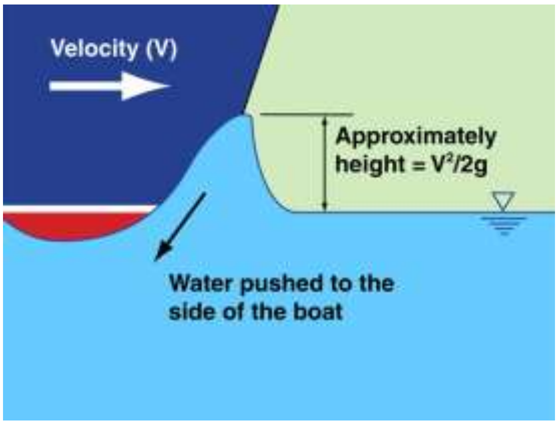
Bernoulli equation



Water pressure at the bow



A rising 'column' of water



Water deflected to the side of the vessel

Introduction

- The Bernoulli equation tells us that the total energy (H), expressed as a 'head' of water, is a sum of the kinetic energy ($V^2/2g$) plus the potential energy ($P/\rho g$) plus the datum height (Z).

where:

V = the closing velocity of vessel to water

g = acceleration due to gravity

P = water pressure

ρ = water density

Z = datum height.

Energy transfer at the bow of a vessel

- The Bernoulli equation tells us that the response of the water at the bow of a boat will depend on the resulting change in velocity and direction of the water.
- Any change in velocity and direction of the water must be generated by the water pressure exerted on the water.
- It is important to remember that water pressures act in all directions, not just in the direction of the vessel.

Water <u>unable</u> to deflect to the side of the vessel

- The elevated water pressure that forms in front of the bow will cause water to rise up the bow to a height that approximates the kinetic energy (i.e. velocity head) of the vessel.
- In other words, this localised elevation in the water surface is equivalent to that required to balance the underlying water pressure.

$H = V^2/2g = P/\rho g$ (approximate)

Water deflected to the side of the vessel

- The elevated water surface that forms at the bow will be subjected to the force of gravity.
- As a result of gravity, the flow of water that is pushed up the bow, will eventually fall back towards the normal water surface, either:
  - forward of the vessel in the form of a spilling bow wave; or
  - to the side of the vessel.
- As the water falls, it gains momentum, which it uses to form a wave-trough.

Types of bow waves

Complex bow wave

Combined spilling and energy waves

- Based on my limited observations, the most common bow wave is a combination of a spilling wave and an energy wave.
- Most vessels are likely to be travelling faster than the speed of causality of a pressure wave, which means some of the deflected water will want to 'spill' over the energy wave.
- The energy wave results from the elevated water pressure at the bow.

Complex bow wave

Complex bow wave

Smooth energy wave

Energy waves

- Energy waves are a type of pressure wave.
- The flow of 'energy' moves as a pressure wave.
- Energy waves are formed by the transfer of energy from the vessel to the water, and from the water converting this energy from the kinetic energy of velocity, to the potential energy of water elevation, and then back again.

Smooth energy wave

Smooth energy wave

Types of bow waves

Plunging wave

Plunging waves

- A plunging wave is formed when:
  - the rising column of water at the bow is deflected down the sides of the vessel, and
  - this deflected water is then hit by the 'expanding' sides of the hull, which gives the water lateral momentum, which causes the water to spill away from the vessel.
- The spilling water plunges into the 'still' water forming turbulence.

Plunging wave

Plunging wave

Spilling wave

Spilling waves

- A spilling bow wave can be formed by two processes:
  - the rising water column at the bow is pushed forward by the bow at a velocity that exceeds the speed of causality of the pressure wave
  - the rising water column at the bow is pushed forward by the rake of the bow.
- This turbulent 'white water' is trying to overtake the underlying pressure wave.

Spilling wave

Spilling wave

Types of bow waves

Wave splash

Splash

- Splash occurs when the impact of the vessel on the water is so great that the released energy is able to 'fracture' (or atomise) the rising water column causing spray.
- The more the water atomises (turns into splash), the more energy is required.
- Splash is most commonly associated with unsteady flow conditions, meaning that the behaviour of the vessel varies with time, and/or the water surface is unsteady (i.e. waves exist on the water surface).

Wave splash

Wave splash

Turbulent surface water

Turbulent surface water

- When the rising column of water falls back down to 'normal' sea level, it builds momentum, which causes the water to form a trough immediately behind (downstream of) the crest of the bow wave.
- If the shape of the bow is irregular, then the bow can induce turbulence within the expanding and contracting water flow.
- This turbulent water can spill into the trough formed behind the bow wave crest.

Turbulent surface water

Turbulent surface water

Equivalent 'bow' waves generated by cars

Energy wave

Energy wave

- Cars driving through shallow water can generate the same types of waves that the bow of a ship can generate.
- If the vehicle is moving slower than the critical velocity of the water (i.e. its speed of causality), then a simple energy wave will be developed.
- In ideal conditions, a trough will form adjacent the doors such that the inflow of water into the cabin is minimised.

Plunging wave

Plunging wave

- A plunging wave is formed when the upper section of the vehicle hits, and then projects the water outward at a velocity that exceeds the speed of a pressure wave (i.e. the critical velocity of the water).
- The vehicle needs to be moving faster than the critical velocity of the water.

Spilling wave

Spilling wave

- If the vehicle is moving faster than the critical velocity of the water, then its movement through the water will generate both:
  - an energy wave
  - a spilling wave that projects water over the energy wave at a velocity that exceeds the speed of the underlying pressure wave.
- The spilling wave is either projected forward, or to the side of the vehicle.

Splash

Splash

- Splash is formed by either:
  - a high energy input (i.e. a fast moving vehicle)
  - unsteady flow conditions, typically generated by the rolling tyres.
- The vehicle needs to be moving much faster than the critical velocity of the water.
- The degree of splash can be affected by the tread pattern on the tyres.
- Note: rolling tyres represent a form of unsteady motion.

The importance of boat speed on the formation of bow waves


Turbulent shock wave

Introduction

- I do not want to repeat myself over and over again, but I need to make it perfectly clear how important the boat speed is to the formation of the different types of bow waves.
- Even the waves produced by cars and trucks driving across flooded causeways is governed by the speed of the vehicles.
- If the 'disturbance' is moving faster than the reaction speed of the water, then the disturbance will create turbulence.


Mr Angry

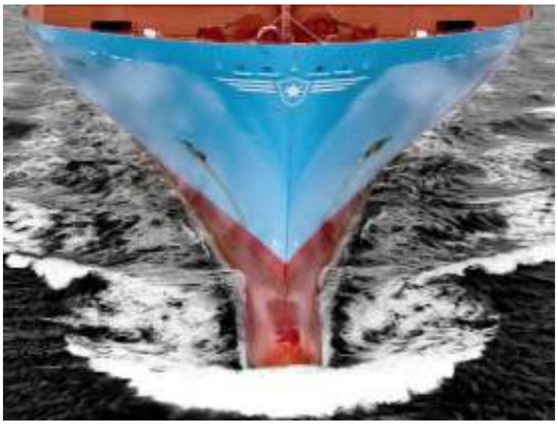
The reaction speed of water

- Some of you would have experienced the trauma of getting a teenager up and moving early in the morning—the end result usually involves 'turbulence'.
- Forcing your will onto others usually does not go smoothly.
- The same situation exists for water—water has its desired reaction speed, which is directly linked to the speed of causality of the water body—move faster than this speed, and you create turbulence.


Turbulent flow conditions

Boat speed

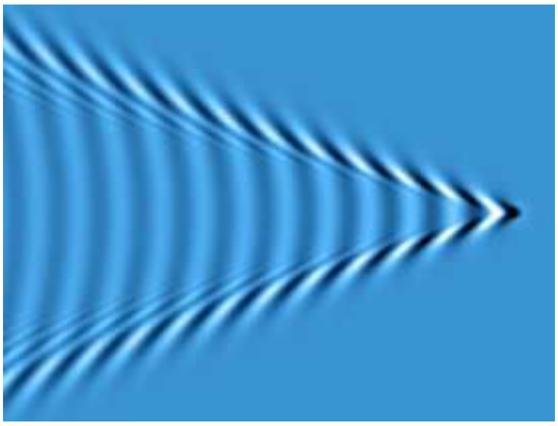
- Every time I mention 'boat speed', I am really referring to the velocity difference between the vessel and the water, whether the water is still, or moving.
- If the vessel is moving slowly into port, and it is travelling slower than the speed of causality of the water (i.e. the reaction speed, or critical velocity), then the water surface is usually smooth.
- If the vessel is moving faster than the speed of causality, then turbulence and shock waves will be produced.


Spilling bow wave

Types of bow waves

- The following types of bow waves were introduced on the previous pages:
  - energy waves (pressure waves), which dominate at low speeds
  - spilling waves, where water is pushed forward faster than the water's reaction speed
  - plunging waves, where the water is pushed sideways faster than the water's reaction speed.

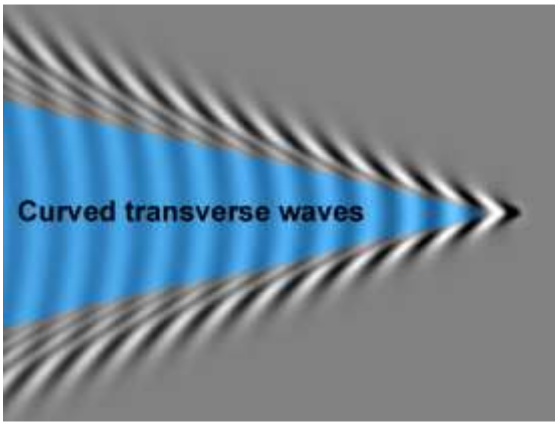
Kelvin wake pattern



Kelvin wake pattern

Introduction

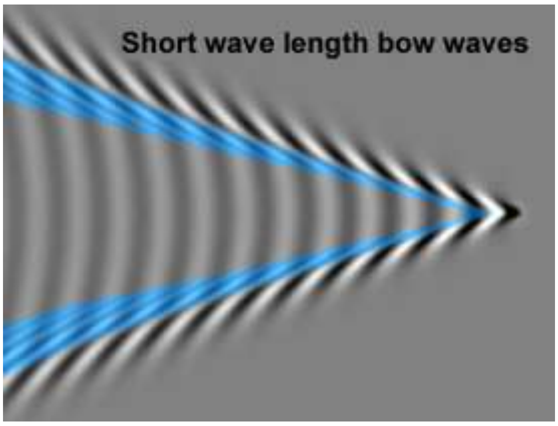
- The Kelvin wake pattern is a term used to describe the combined wake of a vessel, incorporating waves generated by the:
  - bulbous bow
  - bow
  - hull, and the
  - vessel's stern.
- (The blue highlight identifies the part of the wave pattern that is currently being discussed.)



Curved transverse waves

The Kelvin wake pattern

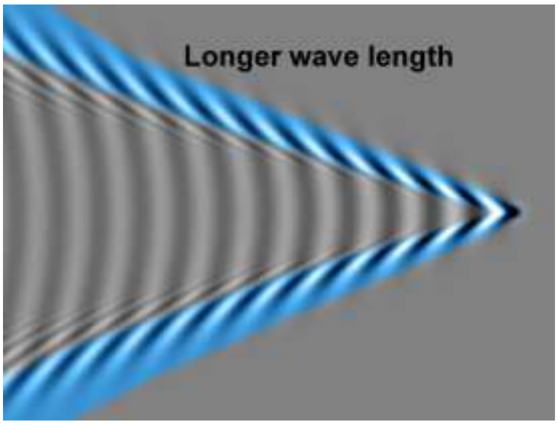
- Wikipedia (2025) states that the Kelvin wake *'pattern consists of two wake lines that form the arms of a chevron, V, with the source of the wake at the vertex of the V.'*
- Each wake line is offset from the path of the vessel by an angle which is linked to the Froude number of the vessel's relative motion through the water.
- The term: 'relative motion' means that both the vessel and the water can be moving.



Bow waves

Short waves and transverse waves

- Waves with a shorter wave length are generated by the bow of the vessel.
- Transverse waves (stern waves) fill the space inside of the V (above diagram).
- Each of these transverse waves resembles an arc of a circle.
- This part of the pattern was considered by Lard Kelvin to be independent of the speed and size of the vessel.

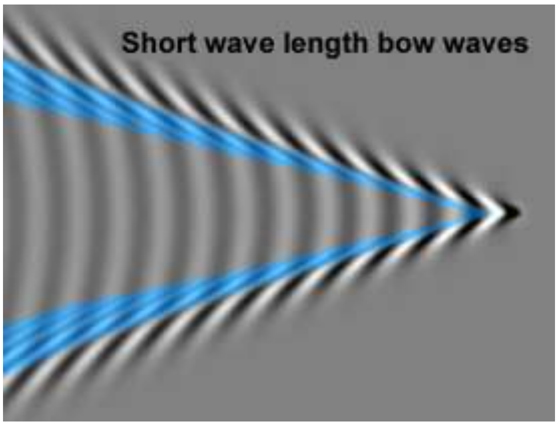


Longer wave length hull waves

Movement of the longer waves

- The waves that have a longer wave length are likely to be generated by the expanding width of the vessel pushing the water away from the hull; hence the term hull wave (as used in this document),
- The length of these waves depends on the length of the vessel over which this hull expansion occurs.
- Container ships can have a very rapid hull expansion, while yachts can have a more gradual expansion, but this 'length' may still be less than that on a larger vessel.

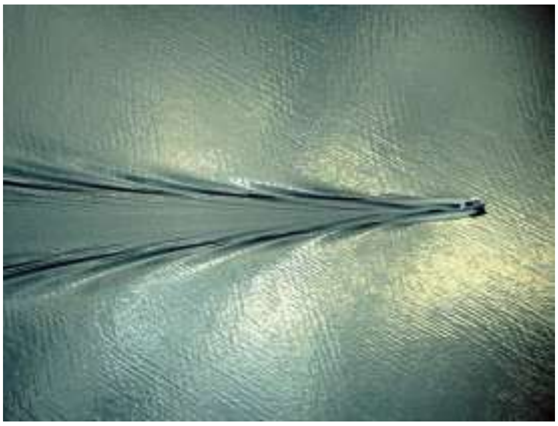
The generation of both short and long wave-length bow waves



Bow waves

Introduction

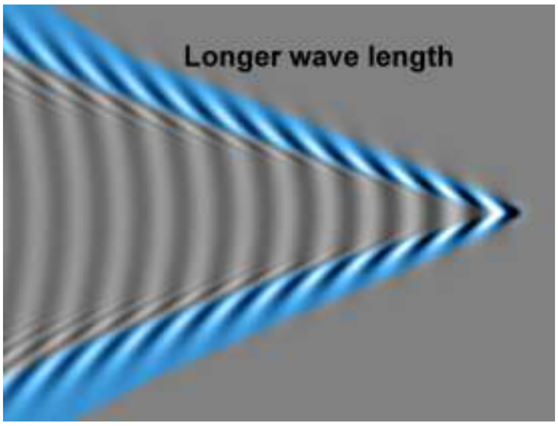
- The Kelvin wake pattern describes the situation where a boat's wake consists of both short wave-length bow waves, and longer wave-length hull waves.



Bow waves

Shorter wave length waves

- The shorter wave length waves are generated by the leading edge of the vessel.
- Consequently, these waves are the first waves to be generated, and they begin the process of building the boat's wake.



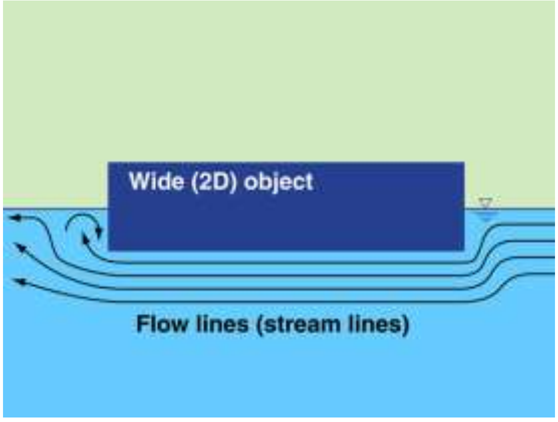
Longer wave length hull waves

Spilling hull waves

Longer wave length waves

- The longer wave length waves are typically generated by the shape of the hull.
- As the water passes (relative to the vessel) along the expanding hull, the water is physically pushed sideways.
- This action creates a combined energy wave and particle wave, which eventually converts into a pure energy wave.
- These long waves are formed after the bow waves are formed.
- Depending on the shape of the hull, these waves can start out as spilling or plunging waves.
- As previously stated, the particle wave component of these waves will eventually convert into normal energy waves, after which their velocity will be governed by their new wave length.
- All these actions cause a delay in the process of these waves forming, which means some time (minutes) can pass before these longer waves begin to overtake the shorter bow waves.

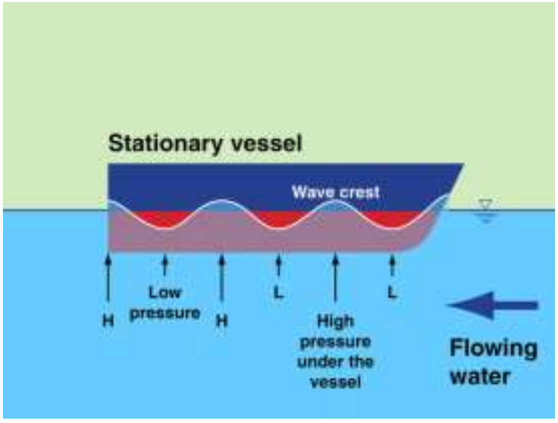
Stern waves formed behind a vessel



Flow under a wide 2D object

Introduction

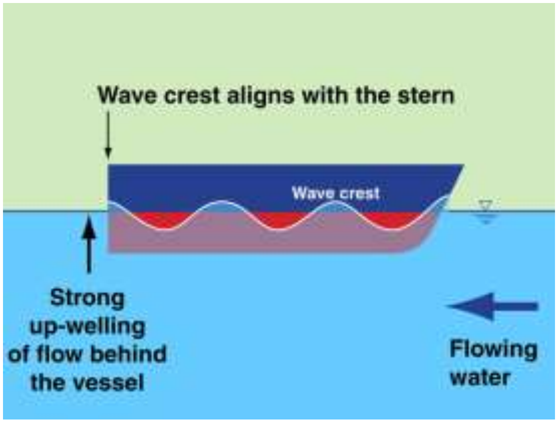
- Stern waves, referred to as transverse waves in the Kelvin wake pattern, are often mixed with the jet wash of the vessel's propulsion system.
- If we studied the fluid mechanics of water passing under a two-dimensional object (i.e. an object that is as wide as the research flume), then we would see that the displaced flow must eventually rise back up to the free water surface after passing under the object.
- This process can be smooth, or turbulent.



Flow under a stationary vessel

Water pressures under the hull

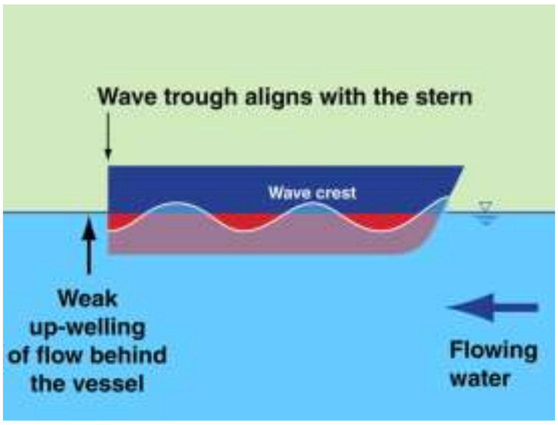
- If we now replace the two-dimensional object with a three-dimensional vessel, and if we hold the vessel fixed while only moving the water, then we will obtain similar results.
- The differences lie in the effects of the bow waves passing along the side of the vessel.
- These bow waves generate high and low pressure zones both along the sides and under the hull of the vessel.



Wave crest positioned at the stern

Flow conditions if a wave crest exists at the stern

- If bow waves cause a wave crest to align with the stern of the vessel, then there will be an increased water pressure at the stern, which would:
  - increase the up-welling forces
  - increase the resulting turbulence.
- Water is likely to tumble in behind the vessel causing the water level to reach normal water level conditions.

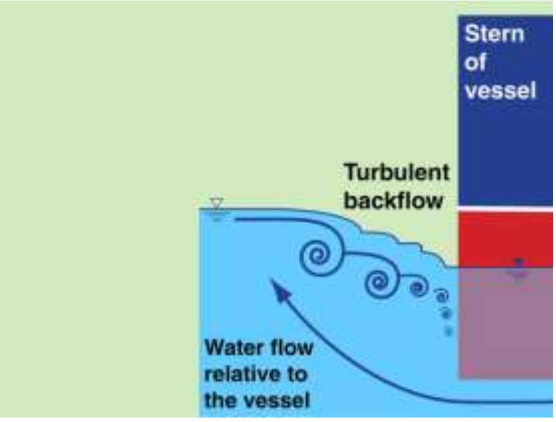


Wave trough positioned at the stern

Flow conditions if a wave trough exists at the stern

- If bow waves cause a wave trough to align with the stern of the vessel, then there will be reduced water pressure, which would:
  - reduce the up-welling forces
  - reduce the likely turbulence.
- The water level behind the vessel may be stable at an elevation less than the normal water level; however, some water may still tumble into this local depression in the water surface.

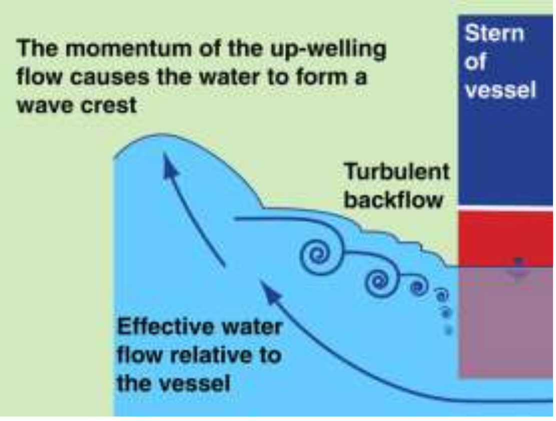
Stern waves formed behind a vessel



Flow condition relative to the vessel

The up-welling of flows passing under the vessel

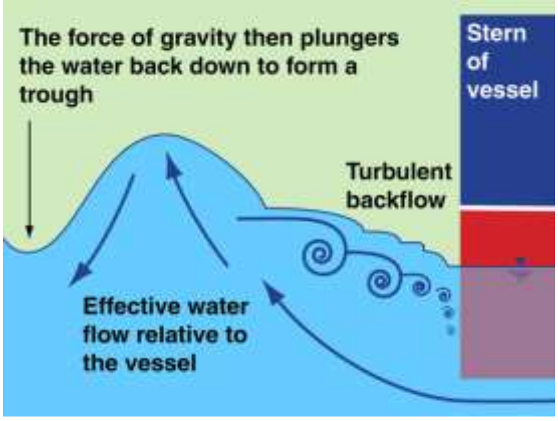
- If we again consider the case of a stationary vessel with water flow passing under the vessel (as on the previous page), then we can see the up-flow of water behind the vessel.



Formation of a wave crest

The formation of a wave crest behind the vessel

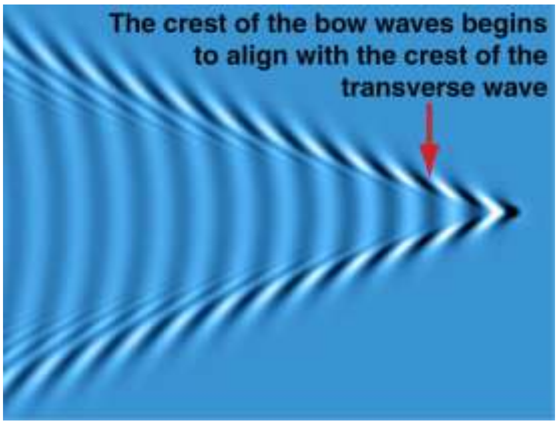
- If this up-flow has sufficient energy, then the rising water will build momentum as it rises, which will carry the water above the mean water level, thus forming a wave crest.



Formation of a wave trough

The formation of a subsequent wave trough

- As is the case for all surface waves, the force of gravity will eventually carry the water back down towards the mean water level.
- However, once again the water will build momentum, which will carry the water below the mean water level, eventually forming a trough.
- And so the process continues, forming wave crests and troughs.

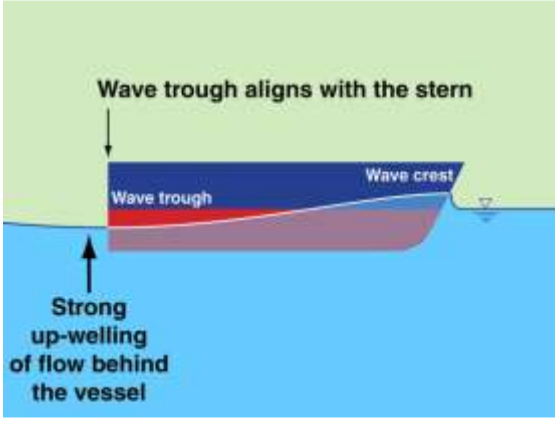


The merging of wave crests

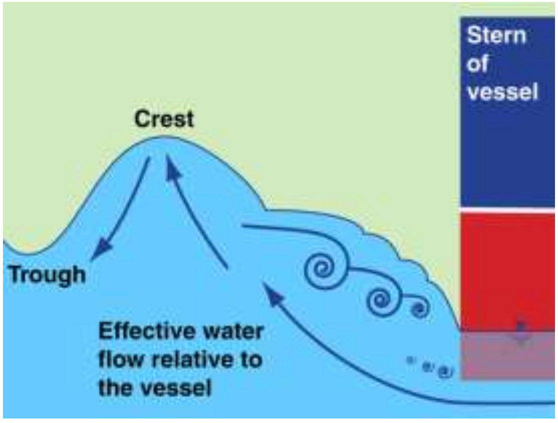
The alignment of the various wave crests

- Behind the vessel, the crests of the two bow waves, and the crest of the stern wave will merge (because the water does not want to maintain a discontinuity in the water surface).
- Consequently, stern waves can bend (as shown in this image) because the bow waves will have a different forward velocity compared to the centre of the stern waves.

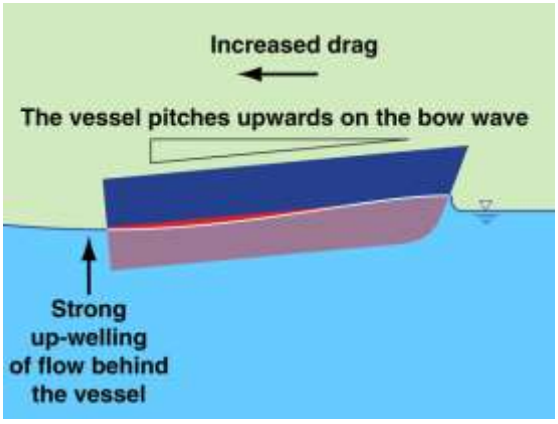
The concept of hull speed



Wave trough at the stern



Low waterline at the stern



Vessel pitches on the wave

Sail boat

Introduction

- Hull speed is defined as the speed of a vessel at which point the wavelength of the bow wave equals twice the waterline length of the vessel.
- This means a wave crest is positioned at the bow, while the associated wave trough is located at the stern.
- (I note that some authors say that it is when the bow wave equals the vessel length, but the wave length is measured from crest to crest, not crest to trough.)

Consequences of hull speed

- As discussed on the previous pages, if a wave trough is positioned at the stern of a vessel, then the force of up-welling of water at the stern is increased, and the likelihood of an exposed stern is increased.
- Having an exposed stern (i.e. the waterline at the stern is well below the normal sea level), means there is a reduction in the hydraulic pressure pushing on the stern, which increases the overall hull drag.

Boats 'climbing' the bow wave

- Hull speed conditions also mean that the vessel will tilt backwards because it is effectively sitting on the downstream side of the bow wave.
- In these conditions, the effects of gravity will have an effective drag component.

Sail boats

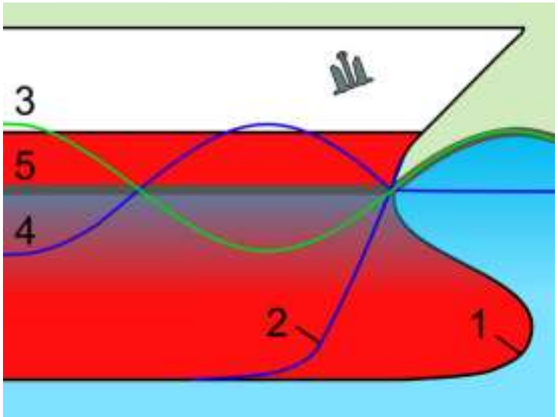
- The practical application of hull speed is generally limited to sailing vessels.
- However, power boats will also experience an increase in drag as they operate at a speed that positions the vessel on the downstream side of the bow wave.

4. The Currently-Accepted Theory of Bulbous Bow Hydraulics

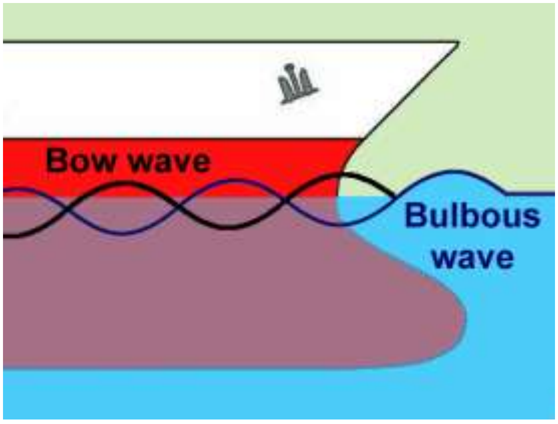
(Which I believe is misleading)

Introduction

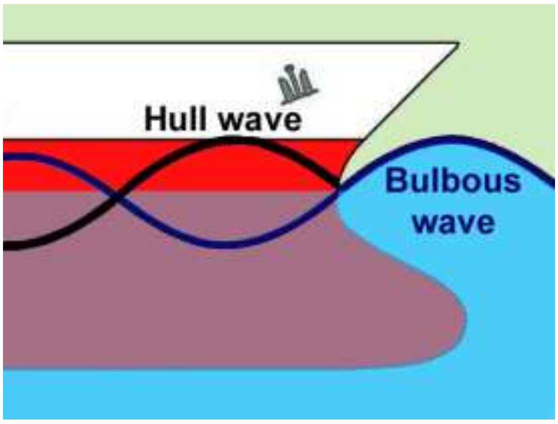
Wikipedia – Bulbous bow (2025)



Destructive wave interference



Wave trough positioned under the bow



Wave trough positioned aft of the bow

Introduction

- The following discussion (explanation) of the bulbous bow was extracted from:
  - Wikipedia (2025)
  - Alfred M. Kracht, 1978. Design of Bulbous Bows, SHAME Transactions, Volume 86, 1978
  - various YouTube videos presented by naval architects
  - various web-published documents prepared by naval architecture businesses.

The 'reported' fluid mechanics

- The inclusion of a bulbous bow extension [line 1] forces the water to flow up and over the protrusion, forming a wave crest [line 3].
- The bulb is positioned such that the subsequent trough aligns with the wave crest formed by the bow [line 4].
- The destructive interference of the combined bow wave crest and the bulbous wave trough wave generates what is often a non-wave condition [line 5].

Bow waves or hull waves?

- In the discussions that I have read, none of the authors appear to distinguish between what I have referred to as:
  - bow waves
  - hull waves.
- I believe that any discussion about destructive wave interference depends on whether you are 'destructing' bow waves or hull waves (refer to the discussion over the page).

Reported adverse effects

- The reported adverse effects of a bulbous bow include:
  - increased wetted surface area
  - increased frictional drag, but this depends on the length of the hull wave (the wave profile that exists along the side of the vessel)
  - potential increase in splash while in rough seas—bulbs are typically V-shaped on the bottom to minimise splash in rough seas.

A review of bow wave formation

Combined bow and hull waves

Introduction

- Some authors may consider hull waves to be just a component of the overall bow waves.
- In order to improve the clarity of the following discussion, I have chosen to separate the effects of bow-forming waves, and hull-forming waves.

Bow wave

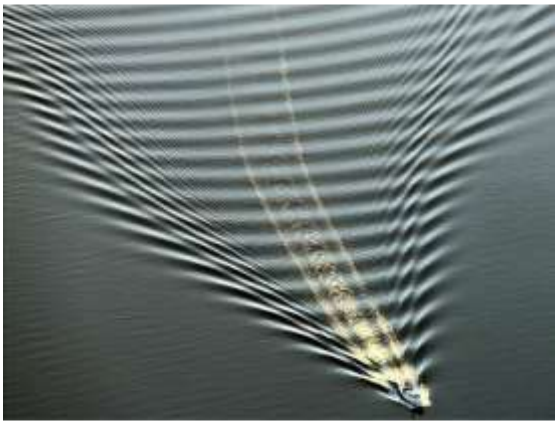
The formation of bow waves

- When I refer to a bow wave I am referring only to the wave that is generated by the leading edge of the bow, but excluding any bulbous bow extension.
- Bow waves are generated by the elevated water pressure that forms in front of the submerged section of the bow.
- This pressure increase causes a rise in the water level at the bow, which subsequently forms a trough when gravity finally pushes the water down towards normal sea level.

Hull wave

The formation of hull waves

- A hull wave is generated by the expanding width of the hull, which pushes the water laterally away from the hull.
- Part of this wave initially moves as an energy (pressure) wave, while the upper portion of the wave may initially move as a physical ‘spilling’ wave, especially if the vessel is moving at a supercritical speed.
- This spilling portion of the wave moves as a particle wave, not as an energy wave; but, it will eventually integrate into the underlying energy wave.

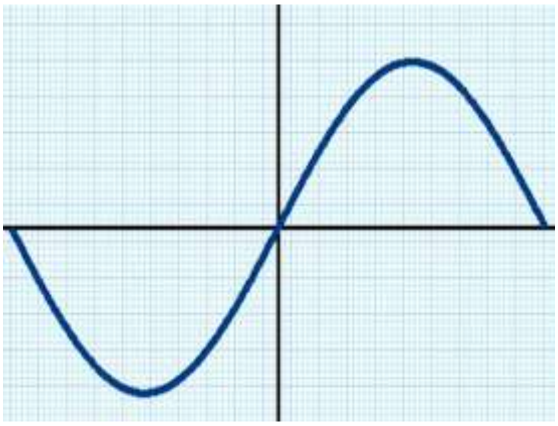


Combined bow, hull and stern waves

The cause of vessel drag

- The drag of a vessel can only be generated by three actions:
  - air/wind drag
  - water friction
  - water pressure.
- Both the water friction and the water pressure apply directly to the hull of the vessel—**nothing** that happens to the hull waves or bow waves after they leave the surface of the hull can contribute to the vessel’s drag.

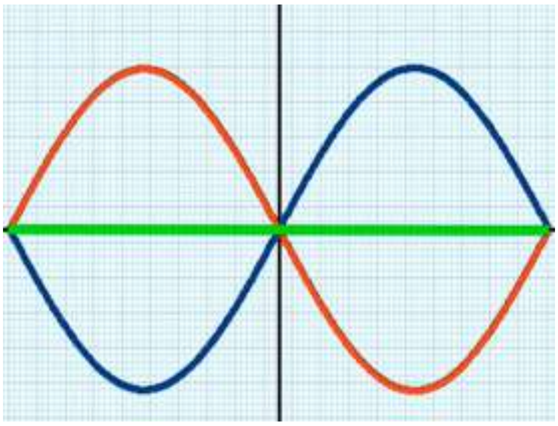
Review of constructive and destructive wave interference



The formation of a double-height wave

Constructive interference

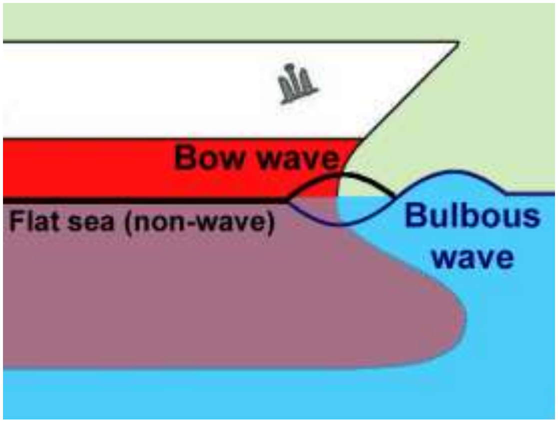
- Constructive wave interference is the superposition of the 'positive' aspects of multiple waves, or the 'negative' aspects of multiple waves.
- Constructive interference is most commonly associated with the doubling of peaks and troughs when two waves meet.
- Constructive interference can occur on merging energy waves.



Two destructive longitudinal waves

Destructive interference

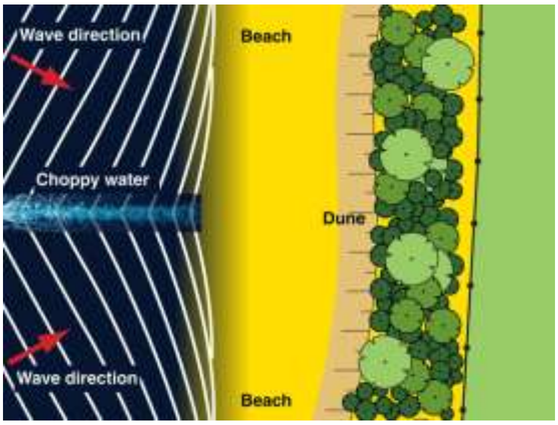
- Destructive wave interference is the superposition of a 'positive' aspect of one wave with a 'negative' aspect of an intersecting wave.
- Destructive interference is most commonly associated with the production of a zero-amplitude wave when a wave crest intersects with a wave trough of the same amplitude.
- Destructive interference can occur on merging energy waves.



Suggested destructive wave interference

The interference of energy waves

- Energy waves are the only waves that can cross the path of other energy waves without loss of energy, or a change in direction.
- Energy waves are the only waves that can experience the type of destructive interference often associated with the function of bulbous bows.

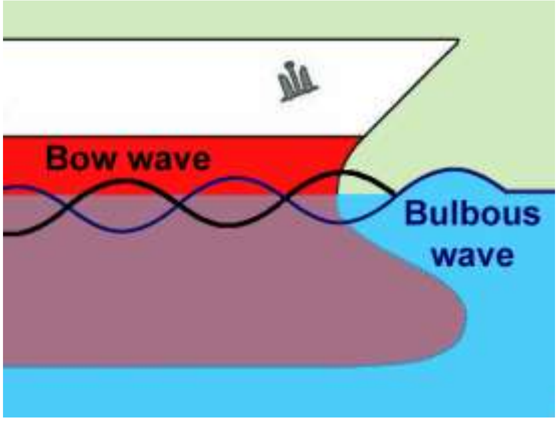


The 'collision' of two broken waves

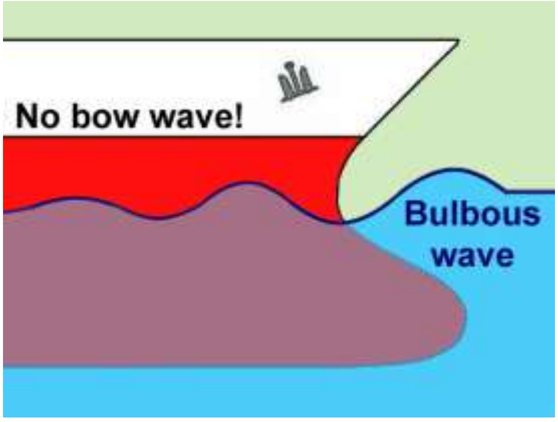
Coastal (broken) waves

- Once a wave breaks, and the upper waters of the wave tumbles forward, the water becomes a particle wave.
- Similarly, a 'spilling' wave is considered a particle wave, not an energy wave.
- Therefore, the energy wave generated by a bulbous bow CANNOT destructively interfere with a particle wave generated by the bow or hull, until this spilling action has converted into an energy wave, which occurs well-away from the hull, and therefore cannot affect the vessel's drag.

Destructive wave interference of bow waves



Wave trough positioned under the bow



Observed flow conditions

Turbulent surface backflow

Caution!

The bow wave claim

- If it is being claimed by other authors that the bulbous wave causes the destructive interference of bow waves (i.e. excluding the effects of hull waves), then the popular diagram used in many of these articles should look like that shown here.
- In such a case, the trough of the bulbous wave would lie at the base of the bow.

Problem 1

- If this is the hydraulic effect that is being claimed by these authors, then I dispute such claims because, from my observations, the trough formed by the bulbous wave is usually positioned at the base of the vertical section of the bow, which:
  - prevents a significant amount of water striking the vertical bow, which
  - prevents the formation of a traditional bow wave, and so
  - there is no bow wave that needs to be destructed.

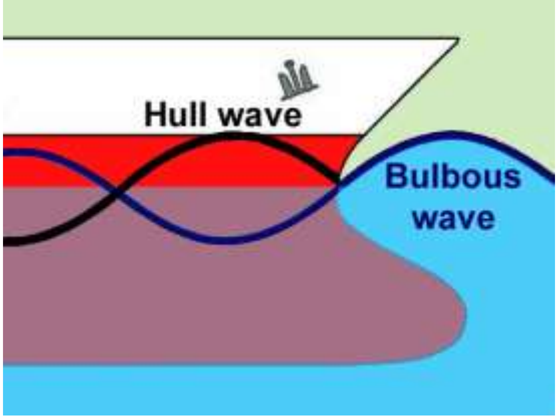
Problem 2

- It would appear from my observations that the variable cross-sectional area of some bulbous bows will cause a minor flow expansion near the base of the vertical bow, which:
  - can cause turbulent surface water (possibly generated by the hull wave), to backflow into the bulbous wave trough, which
  - can give the visual appearance of a near horizontal water surface (i.e. a non-wave outcome).

Caution!

- Note; my observations may be limited to photographs of bulbous bow vessels travelling a low (in-harbour) speeds.
- I acknowledge that it may be possible that at normal operating speeds, sufficient water does strike the vertical bow, thus generating a traditional bow wave that could integrate with the bulbous wave to form a destructive wave outcome.
- However, if this were the case, then destructive wave interference would still not be the ‘cause’ of the ‘effect’.

Destructive wave interference of hull waves



Wave trough positioned aft of the bow

The hull wave claim

- If it is being claimed by other authors that the bulbous wave causes the destructive interference of hull waves (i.e. excluding the effects of bow waves), then the popular diagram used in many of the articles should look like that shown here.
- In this case, the trough of the bulbous wave is positioned just behind the bow.

Hull-generated particle waves

Problem 3

- If the hydraulic effect that is being claimed by other authors is being attributed to an effect on hull waves, then I dispute such claims because:
  - hull waves are generated by the hydraulic pressure generated by the hull pushing the water out of its way
  - and, the formation of a bulbous wave CANNOT change this effect because the water still needs to be pushed out of the way.

Hull-generated particle waves

Problem 4

- Close to the surface of a vessel, hull waves consist of:
  - an upper 'spilling' wave, which operates as a particle wave, and
  - a lower energy wave.
- Even if the bulbous wave mixes with a hull wave to form a near-level, non-wave water surface, such a hydraulic effect CANNOT reduce the drag effect generated by the underlying hydraulic pressures exerted on the hull that caused the hull wave.

Bulbous waves mixed with hull waves

Problem 5

- If the hydraulic effects being claimed by other authors are linked to the destructive interference of hull waves, then:
  - it needs to be noted that 'destructive wave interference' can only occur through the interaction of two energy waves
  - however, a type of destructive wave interference can occur between an energy wave and a particle wave, with the particle wave usually passing over the energy wave.

The laws of physics

Looking more closely

Introduction

- In reality it does not matter if the current explanation of the bulbous bow effect refers to the destructive interference of a bow-formed wave, or a hull-formed wave, there is still a fundamental problem with this explanation that breaks the laws of physics.
- The physics laws that I am referring to are the laws dealing with work and energy, and indirectly, the conservation of energy.

Questionable claim

The broken law of physics

- The currently-accepted explanation of the bulbous bow effect suggests that:
  - the generation of a bulbous wave will destructively interfere with a bow wave
  - the ultimate dissipation of the bow wave will cause a reduction in vessel drag.
- Even if it could be shown that a bow wave passing along the side of a vessel was able to generate significant amounts of drag (which I do not believe), there is a basic problem with the above logic.

Caution

The failed logic

- What is being suggested here is that if energy is being expelled to form a bulbous wave, <u>and</u> energy is being expelled to form a bulbous wave, then when these two waves join, the energy (that has already been expelled) will now magically not appear as drag on the vessel.
- Wrong!
- Once energy has been used to form a wave, then any subsequent destruction of that wave CANNOT reduce the original input of energy (i.e. the vessel drag).

Light 'bulb' moment

The correct logic

- If you worked on a tow tank or hydraulic flume, and you generated two sets of waves, which eventually met causing destructive interference, then the energy required to generate those two sets of waves does not disappear!
- The only way that a bulbous bow can reduce drag is for the bulbous bow to reduce the pressure and frictional forces placed on the vessel's hull, which it does by preventing or minimising the initial formation of a bow wave.

What I believe are false or questionable claims made by other authors

False claim

A false claim

- **The claim:**
  - *'The wave length of the bow wave must increase with the speed of the boat so that the wave speed can be maintained at the same speed as the boat.'*
- This statement is simply wrong!
- The bow wave does not operate independent of the vessel.
- The bow wave is generated by the vessel, and remains attached to the vessel, independent of its wave length.

Questionable claim

A questionable claim

- **The claim:**
  - *'A difference of just two knots from your design speed is enough to make the bulb useless.'*
- I believe this claim is highly questionable.
- If modelling has indicated such an outcome, then that would suggest that the shape of the bulbous bow is inappropriate, not that the design speed should have a very narrow margin.

Questionable claim

A questionable claim

- **The claim:**
  - *'Of course, having a constant wave on the side of the hull is an issue, as it will increase the drag of the vessel.'*
- I just cannot understand how 'a constant wave on the side of the hull' can possibly increase drag, because:
  - it does not change the net hull pressure
  - it does not significantly change the wetted surface area.

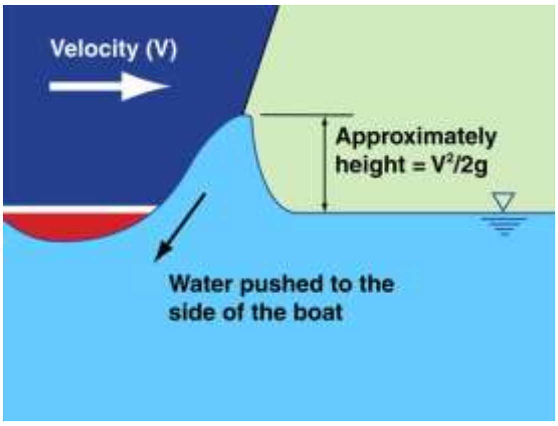
Questionable claim

A questionable claim

- **The claim:**
  - *'What is important to have in mind, is that those two waves only line up at one speed.'*
- I believe such statements are misleading because:
  - it gives the impression that there is a very narrow range of design speeds
  - and I believe that the function of a bulbous bow is not linked to the actions of destructive wave interference.

5. My Explanation of the Bulbous Bow Hydraulics

A review of the components of a vessel's wake



Bow wave formation

Bow waves

- Bow waves are formed through the following process:
  - a moving vessel exerts pressure on the approaching water
  - which causes the water surface to ride up the bow of the vessel forming a wave crest
  - gravity causes this water to fall once it is pushed to either side of the hull
  - the falling water gains momentum which then forms a wave trough, etc.

No bow wave is being formed here!

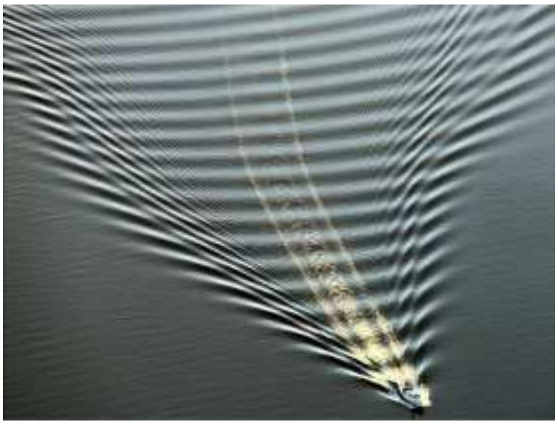
Bulbous waves

- The bulbous wave is that portion of the collective 'bow wave' that is generated solely by the existence of the bulbous bow.
- A traditional bow wave is only formed if water is lifted up the bow of the vessel.
- If the vessel is moving at a slow velocity, then the observed bow wave is actually a 'hull wave' formed by the expansion of the hull.

Hull wave formation

Hull waves

- Hull wave are generated by the hull of the vessel physically pushing the water away from the hull.
- At slow speeds, these waves consist of smooth-surface energy waves.
- At normal cruising speeds, these waves start out as particle waves, which causes water to spill, in a turbulent manner, over the surface water.
- Eventually these particle waves convert into long wavelength energy waves.

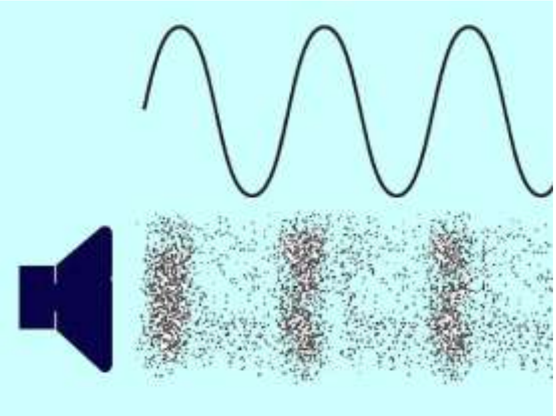


Stern waves

Stern waves

- As waves move along the side of a vessel, they generate a pressure gradient under the hull.
- As the stern of a vessel moves through the water, it causes an up-welling of water behind the vessel, which can be amplified by the positioning of a wave crest at the stern.
- The formation of a wave crest behind the stern subsequently forms a wave trough, and the process continues.

A review of the importance of the speed of causality



Sound waves (pressure waves)

Introduction

- In fluid mechanics it does not matter what type of fluid is moving, the basic principles of fluid mechanics still apply.
- These fluids include:
  - water flow
  - air flow
  - the movement of objects in space.
- What makes the motion of vessels through water a special case is that this motion occurs at the interface between two fluids (air and water).

Aircraft shock wave

The speed of causality

- The speed of causality is the speed of the primary driving force.
- In air, the primary force is the speed of a pressure wave (i.e. a sound wave).
- In space, the primary force governs the speed of light.
- At an air–water interface, the primary force is gravity, which controls the speed of a pressure wave passing through the water.

Boeing 747B

Subsonic flight

- In subsonic flight, the air that is forward of the aircraft is aware of the imminent arrival of an aircraft because the pressure wave is able to move ahead of the plane.
- This means that the air begins to move out of the way of the approaching aircraft before the aircraft arrives.
- Which means that subsonic aircraft can have an abrupt, but rounded nose, and still be considered streamline.

The F5 fighter jet

Supersonic flight

- In supersonic flight, the air that is forward of the aircraft is unaware of the imminent arrival of an aircraft because the pressure wave is unable to move ahead of the plane.
- This means that the air does not begin to move out of the way of the aircraft until the aircraft arrives (i.e. hits the air).
- Which means supersonic aircraft need to have a sharp, pointed nose in order to be streamline, and thus reduce the resulting shock wave.

A review of the critical velocity of water flow

Supercritical flow down a road

Introduction

- In open channel flow, the speed of causality is referred to as the critical velocity of the water flow.
- This condition does not apply to water flowing through a conduit (pipe), unless that pipe is flowing partially full.
- The critical velocity of the water is based on the speed of a pressure wave, which is dependent on gravity, water viscosity, and the wave length (however, water viscosity is often ignored in these cases).

Water flow past a bridge pier

River flow approaching a fixed object

- If river flow were to approach a fixed object, such as a bridge pier, then the resulting fluid mechanics would depend on the speed of the water relative to the water's critical velocity.
- If the water is pre-warned about the approaching object, then the flow transition should be smooth.
- If the water is not pre-warned about the approaching object, then the flow transition is likely to be turbulent, resulting in shock waves.

Subcritical flow around a bridge pier

Subcritical flow conditions

- If subcritical flow conditions approach a bridge pier, then depending on the shape of the bridge pier:
  - an increase in the water elevation may occur in front of the pier because part of the flow's kinetic energy is being converted into potential energy
  - streamlines will be relatively smooth
  - turbulent surface flow conditions may exist near the downstream face of the bridge pier (seen under the bridge).

Supercritical flow hits a light pole

Supercritical flow conditions

- If supercritical flow conditions approach a bridge pier, (or in this example, a street light pole) then depending on the shape of the object:
  - a significant portion of the flow's kinetic energy is converted to potential energy causing an up-welling of water on the upstream face of the object
  - a shock wave (surface wave) will radiate out from the object
  - significant turbulence will exist downstream of the object.

A review of the flow conditions associated with a moving vessel

Subcritical flow with a bulbous bow

Point of reference

- According to the laws of motion, it does not matter if you study the dynamics of a vessel moving through still water, or if you study the dynamics of water moving past a stationary vessel.
- The only issue that matters is the relative velocity between the vessel and the water.
- The fluid mechanics are identical for a vessel moving through stationary water, and for a stationary vessel resting in a flowing river.

Subcritical flow conditions

Subcritical vessel motion

- If a large vessel moves through water at a subcritical velocity, then:
  - smooth streamlines will exist in front of the vessel
  - a minor lifting of the water surface will occur at the bow
  - bow waves may originate from the bow
  - hull waves will still be generated by the expanding hull of the vessel.

Supercritical flow conditions

Supercritical vessel motion

- If a large vessel moves through water at a supercritical velocity, then:
  - a significant portion of the vessel's kinetic energy will be passed into the water as potential energy causing an up-welling of water at the bow
  - a shock wave (bow wave) will radiate out from the object
  - hull waves will be generated by the expanding hull of the vessel.

Supercritical flow with a bulbous bow

Supercritical motion of a vessel with a bulbous bow

- If a vessel with a bulbous bow moves through water at a supercritical velocity, then:
  - the water surface will likely ride-up over the bulbous bow (depending on its depth below the water surface)
  - water flow upstream of the bow will be pushed either side of the bow
  - a shock wave (bow wave) may, or may not be generated by the bow.

The importance of pre-warning supercritical flow of changing conditions

Warning sign

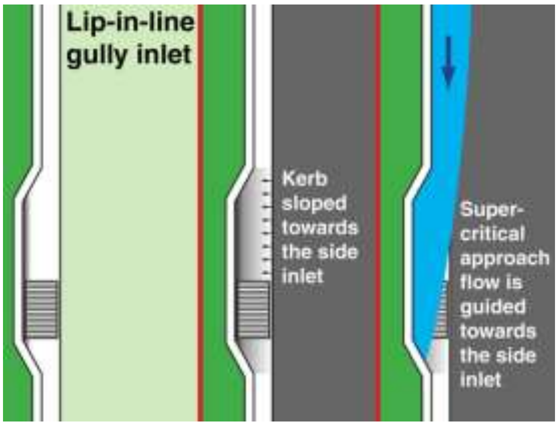
Introduction

- Water uses pressure gradients in order to generate movement.
- If an 'action' is about to be forced upon water faster than the water would like to respond to such an action, then it is best to pre-warn the water that such actions are about to occur.
- I have used the term 'pre-warn', because it is important that the warning occurs well before the flow arrives at the action, obstacle, or force.

Note long engine intake tunnel

Pre-warning air flow prior to its entry into a jet engine

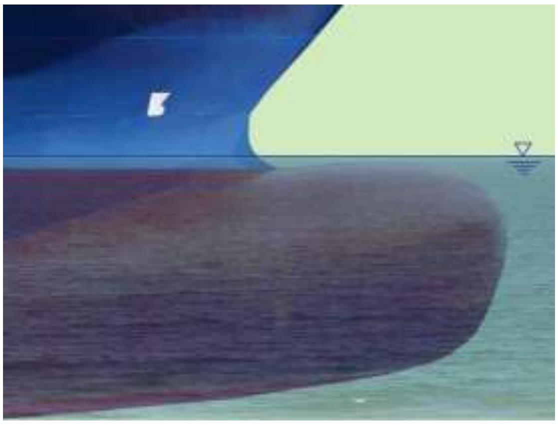
- In order for a jet engine to work, it is necessary for the air flow into the engine to arrive in a subsonic condition.
- Obviously this presents a problem for the designers of supersonic aircraft.
- The answer is to use boundary layer effects to slow the air flow prior to its entry into the engines, which is why the engines are positioned towards the rear of the aircraft, and often at the end of long intake tunnels.



Flow condition if the kerb is tilted

Pre-warning water flow down a roadside before is arrives at a gully inlet

- If the water flow passing down a roadside gutter is flowing at a supercritical velocity, then in order to get this flow to change direction and enter a roadside gully inlet, the kerb-channel up-slope of the gully must be sloped outwards towards the footpath.
- This simple process causes the high-velocity water to start moving towards the gully inlet well-before the flow arrives at the gully.

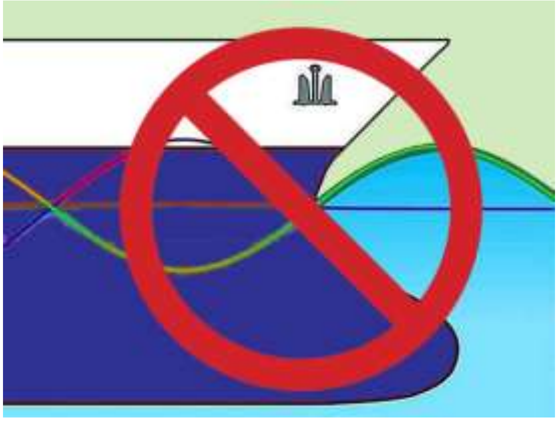


Bulbous bow

Pre-warning still water before a vessel hits it at a supercritical velocity

- If a vessel is passing through still water at a supercritical velocity, then a shock wave (bow wave) will be generated at the leading edge of the vessel.
- To avoid such shock wave conditions, it is necessary to pre-warn the approaching water so that it starts to move out of the way of the vessel before the vessel arrives (i.e. get the water to start doing what the vessel is about to force the water to do).

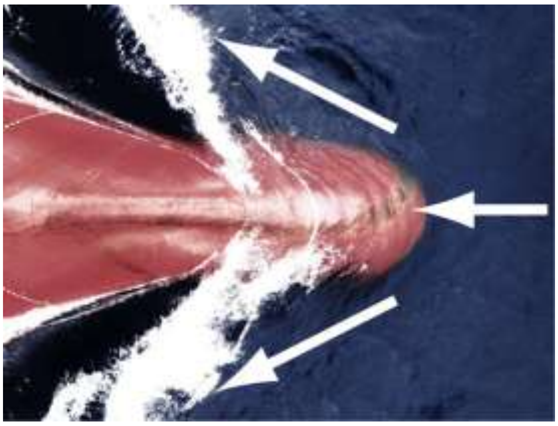
The hydraulic function of a bulbous bow



No destructive wave interference

Introduction

- The primary purpose of a bulbous bow is to:
  - give the water advanced warning of the approaching vessel
  - prevent the formation of a traditional bow wave.
- The wave formed by a bulbous bow does NOT cause the destructive interference of the bow wave because it aims to prevent the bow wave forming in the first place.



The lateral redirection of flows

Preventing the formation of a shock wave at the leading edge of the bulbous bow

- The purpose of the bulbous bow is to gently encourage the water to start moving out of the way of the approaching vessel before the vessel arrives.
- This 'encouragement' avoids the water experiencing the 'shock' of being hit by the approaching vessel.
- This action prevents a shock wave from being generated at the bow.

The generation of hull waves

Introducing lateral movement (port and starboard) into the water ahead of the bow

- The process of introducing early lateral movement of the approaching water can slightly reduce the intensity of hull waves.
- However, hull waves will still be generated because the bulbous bow is rarely close to being the same width (beam) as that of the vessel's hull.

Reduced flow conditions at the bow

Preventing the formation of a classical bow wave

- If the vessel sits in the water at the ideal depth, then the first trough of the bulbous wave should prevent the water flow from crashing into the main bow, thus preventing the formation of a traditional bow wave.

The hydraulic function of a bulbous bow at various depths

Subcritical flow condition

Partially exposed bulbous bow

- In these conditions, the bulbous bow functions in a manner similar to a partially submerged submarine.
- At subcritical speeds, a smooth wave crest will form over the leading edge of the bulbous bow, which could cause a turbulent backflow as shown left.
- At supercritical speeds, the bulbous bow could generate splash (below, left), or at even higher speeds, the flow can ride over the bulbous bow and crash into the bow causing a plunging wave (image below).

Supercritical flow condition

Supercritical flow condition

Submerged bulbous bow

- If the bulbous bow is fully submerged, but the vessel is still riding high in the water, then the bulbous wave will form a trough near the vessel's bow, which ideally will prevent the formation of a traditional bow wave.

Submerged bulbous bow

Well submerged

- If the bulbous bow sits well below the water surface, then a smaller bulbous wave will be formed, but the water flow may hit the bow at supercritical speeds, which can cause:
  - splash (shown, left)
  - spilling wave
  - plunging wave (shown, left)
  - increased hull drag (always).

Well submerged bulbous bow

The hydraulic function of a bulbous bow at various vessel speeds

Subcritical speed

Subcritical speeds

- At subcritical speeds, a smooth wave crest will form over the leading edge of the bulbous bow, which could cause a turbulent backflow as partially shown here.
- This turbulent backflow can be seen more clearly in the images of submarines presented on page 57.

Slightly above supercritical speeds

Slightly above supercritical speeds

- In the example shown here, the flow loses sufficient velocity head as it rides up the bulbous bow that it hits the main bow at a subcritical velocity, which prevents a shock wave from being formed.
- However, because the hull is travelling at a supercritical speed, the hull wave starts out as a spilling wave, which will eventually convert into an energy wave after moving away from the hull.

Supercritical speed

Supercritical speeds

- At supercritical speeds, the flow can ride up over the bulbous bow and crash into the bow causing a turbulent spilling wave, which could form into a traditional bow wave.

High supercritical speed

Even higher speeds

- At even higher supercritical speeds, the bulbous bow could generate splash, or the flow could ride up over the bulbous bow and then crash into the vertical bow causing a plunging wave.

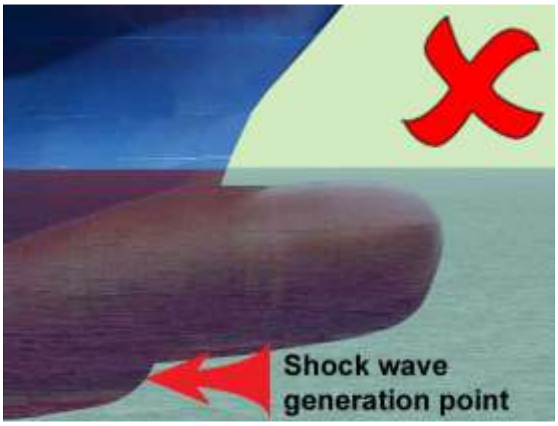
6. My Recommended Design Rules

Design rules 1 to 3

Move forward with caution

Warning

- I need to repeat my warning that I am not a trained naval engineer/architect.
- I am a civil engineer, with training in fluid mechanics and wave mechanics.
- I also have had experience operating physical hydraulic models at a university hydraulics laboratory (Uni of NSW, WRL).
- The recommendations that I present in this chapter should be discussed with your own naval architect, or naval engineer.



Partially exposed bow

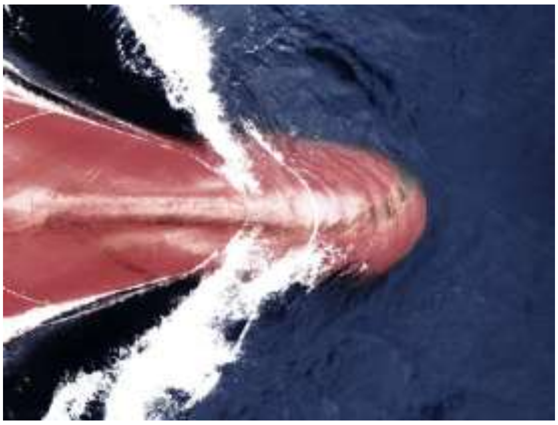
Rule 1

- Rule 1: The bulbous bow should extend to the base of the hull such that the submerged bow is fully covered.
- Reasoning:
  - if part of the traditional bow is exposed to direct water flow below the bulbous bow, and the vessel travels at supercritical speeds (i.e. normal cruise speeds), then this part of the bow will still generate a shock wave, which will exist as a pressure wave, which will increase hull drag.

Turbulent surface water

Rule 2

- Rule 2: The cross-sectional area of the submerged hull must alway increase up to the point of maximum beam; thus the bulbous bow should not have the shape of a light bulb!
- Reasoning:
  - if the wetted cross-sectional area of the bulbous bow reduces before it blends with the main hull, then this will significantly increase the risk of surface water turbulence.



Bulbous bow crest extends to the bow

Rule 3

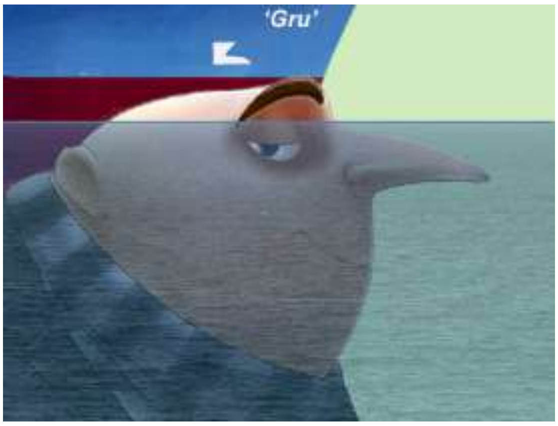
- Rule 3: The crest of the bulbous bow should extend upwards until it meets the bow at the 'design' water level.
- Reasoning:
  - if the crest of the bulbous bow sits below the design waterline, then at normal cruise speeds, it is likely that water will ride-up over the bulbous bow and crash into the main bow, which can generate splash, spilling waves, plunging waves, and which will increase hull drag.

Design rules 4 to 7


Wave crest followed by a trough

Rule 4

- Rule 4: The 'nose' of a bulbous bow should ideally be as sharp as is practical.
- However:
  - it is important that bulbous bow is still able to produce some degree of a shock wave that will lift the water up to form a crest over the bulbous bow, which will then form a trough at the base of the vessel's bow, thus preventing the formation of a traditional bow wave.



The 'Gru' effect!

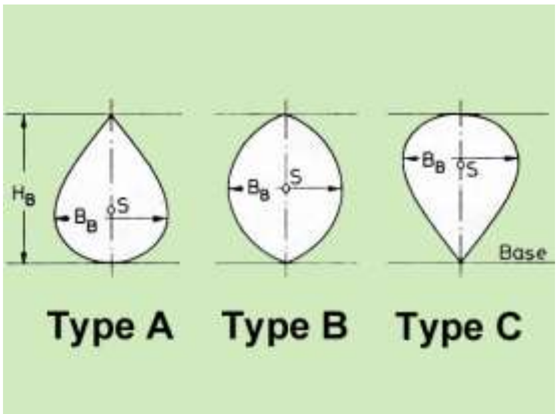
Rule 5

- Rule 5: Hydraulically, the cross-sectional profile of the bulbous bow should progressively increase in size such that the bulbous bow begins to look more like a wedge, if not a pointed horizontal pyramid.
- However:
  - a bulbous bow is likely to maintain something like its current shape in order to 'lift' the water up over the bulbous bow so that this water would then fall to form a trough at the base of the vessel's bow (i.e. not a 'Gru' bow).

Stop and think about its real world use

Rule 6

- Rule 6: A bulbous bow should not have a pointed nose for the reasons stated below.
- Reasoning:
  - because this profile would turn the bulbous bow into a 'ramming spike', which would catch and hold organic matter, including aquatic life, and
  - such a profile would puncture ships below the waterline in the event of a vessel-to-vessel collision.



Bulb forms and parameters

Rule 7

- Rule 7: My recommendation for the preferred bulb form is Type B for flat bottom hulls, and Type C for V-shaped hulls.
- Reasoning:
  - ideally there should be some degree of an inverted wedge shape (Type C) to cut through waves in rough seas
  - however, if the bottom profile is too narrow, and the hull has a flat bottom, then there will be an increase in hull induced drag.

Hydraulics of submarines

Submarine

Supercritical surface movement

The rounded nose of a subsonic jet

Surface movement

Introduction

- In the second version of this document I included a short discussion about the hydraulics of submarines—I was wrong!
- After a few more minutes of thought I realised that if water is being pushed aside by a moving vessel then its 1st preference is to move out of the way by forming a surface wave; its 2nd preference is to accelerate its velocity; and its 3rd preference is to experience physical compression, which is the basis of sound waves.

The four flow conditions

- There are four flow conditions associated with the movement of partly and fully submerged vessels:

1. Subcritical surface movement – In this condition, the vessel moves along the water surface at a velocity that is less than the speed of a surface wave. Water prefers to move out of the way rather than accelerate or compress.
2. Supercritical surface movement – In this condition, the vessel is moving across the water surface at a velocity that exceeds the speed of a surface wave. This would be the flow condition for cruising on the water surface. This flow condition would benefit from a pointed (sharp) bow, such as observed on WW2 submarines.
3. Subsonic submerged movement – In this condition, water flow that passes around a submerged vessel would prefer to accelerate rather than experience compress. This flow condition would be equivalent to subsonic aircraft movement, and thus the bow of a submarine could resemble the rounded nose of a subsonic commercial jet.
4. Supersonic submerged movement – In this condition, water flow ahead of the vessel would experience compression similar to the movement of soundwaves through water. Such flow conditions would exist when a high-velocity projectile (e.g. bullet) is directed into water, which causes significantly more damage to, and deceleration of, the supersonic projectile in comparison to a subsonic projectile.

- **In conclusion**, the current rounded bow of a modern submarine is a logical outcome given its long periods of submerged operation.

7. Glossary of terms

Bow wave	The wave that originates at the bow of a ship as a result of the bow's movement through the water.
Broken wave	A wave where the crest of the wave has moved forward faster than the lower portion of the wave, which allows the crest to 'curl' and fall due to the effects of gravity.
Bulbous bow	A streamlined flaring or protruding bulb at the bow (or front) of a ship just below the waterline. The flare or bulb modifies the way the water flows around the hull, reducing drag and thus increasing speed, range, fuel efficiency, and stability.
Bulbous wave	The wave generated by the existence of a bulbous bow.
Buoyancy	The effect of the 'weight' of an object being neutralised by the upward force produced by its submergence in a fluid.
CFD	Means: 'Computational Fluid Dynamics'
Computational Fluid Dynamics (CFD)	The numerical modelling of fluid flow using finite element analysis. Wikipedia states that it *'is a branch of fluid mechanics that uses numerical analysis and data structures to analyze and solve problems that involve fluid flows'*, but it is a bit more complicated than that description.
Critical velocity (of water)	The average velocity of flow in a section of a channel or partial-full conduit when the flow is at critical depth.
Deep water	Deep water means that the water depth is greater than half of the wavelength.
Destructive wave interference	The combining of a wave crest with an equivalent wave trough, which produces a near-flat, non-wave, water surface.
Energy wave	A surface wave where only the wave energy moves with the form of the wave, while the water particles move only in a circular pattern, without any permanent forward movement.
Fluid mechanics	The study of the physics of fluid flow, specifically water flow.
Heave	The vertical translation of a vessel.
Hull speed	The speed at which the wavelength of a vessel's bow wave is equal to twice the waterline length of the vessel.
Hull wave	The wave primarily generated by the expanding width of the vessel, which pushes the water laterally.
Hydrodynamics	The study of the flow of water. In naval architecture it is the study of water flow around the ship's hull, bow, and stern, and over bodies such as propeller blades or rudder, or through thruster tunnels.
Hydrostatics	The laws of physics that apply to stationary water.
Laws of hydrostatics	The specific hydrodynamic properties of water at rest.
Laws of motion	Generally considered the three laws of motion developed by Isaac Newton.

Particle wave	A surface wave which incorporates the permanent movement of the fluid particles, such as when an energy wave 'breaks' and the water rushes up a beach.
Pitch or trim	Rotation of a vessel about its transverse axis.
Plunging wave	A breaking wave where either the upper portion of the wave overtakes the lower portion of the wave (caused by bed friction slowing the lower portion of the wave), or by a vessel pushing the water as a separate stream over the top of the normal water surface.
Positive displacement wave	Either the upper portion of a plunging or spilling wave, or a wave where the majority of the wave experiences permanent forward movement.
Pressure wave	Another term that describes an energy wave.
Reaction speed of water	The speed of a pressure wave.
Roll or heel	Rotation of a vessel about a fore and aft axis.
Shock wave	A wave generated by the actions of an object interacting with a fluid at a speed that exceeds the critical velocity (i.e. reaction speed) of the fluid.
Speed of causality	The natural speed of the primary driving force. In a fluid, the speed of causality is the same as the terms: 'critical velocity' and 'reaction speed'.
Spilling wave	A breaking wave where either the upper portion of the wave overtakes the lower portion of the wave (caused by bed friction slowing the lower portion of the wave), or by a vessel pushing the water at a velocity that exceeds the speed of a pressure (energy) wave such that it tumbles over the normal water surface.
Stability	The ability of a vessel to restore itself to an upright position after being inclined by wind, sea, or loading conditions.
Standing wave	A surface wave that appears to be stationary relative to the observer, even though it may exist within a flowing waterway.
Stern wave	A surface wave that is primarily generated by the flow of water past the stern (rear) of a vessel. Sometimes referred to as a transverse wave because the wave crest is transverse to the alignment of the vessel.
Subcritical speed	A speed that is slower than the critical velocity of water, whether the speed applies to the water, or to a vessel travelling through the water.
Supercritical speed	A speed that is faster than the critical velocity of water, whether the speed applies to the water, or to a vessel travelling through the water.
Surge	The fore and aft translation of a vessel.
Sway	The transverse translation of a vessel.

Traditional bow	The vertical, or near-vertical portion of a vessel's bow that excludes the bulbous bow extension.
Trim	A measure of the longitudinal inclination of the vessel.
Vessel	Includes every description of watercraft, mainly ships and boats, but also including non-displacement craft, and seaplanes, used or capable of being used as a means of transportation on water.
Water engineering	The field of engineering that deals with water flow, and the design and construction of closed and open channel conduits.
Wetted surface area	The surface area of that portion of a vessel's hull that is below the waterline.
Yaw	Rotation of a vessel about a vertical axis.