



SAMPLE A

Diploma Programme subject in which this extended essay is registered: DESIGN TECH

(For an extended essay in the area of languages, state the language and whether it is group 1 or group 2.)

Title of the extended essay: Does Hull trim and balance affect the speed of a boat?

Candidate's declaration

If this declaration is not signed by the candidate the extended essay will not be assessed.

The extended essay I am submitting is my own work (apart from guidance allowed by the International Baccalaureate).

I have acknowledged each use of the words, graphics or ideas of another person, whether written, oral or visual.

I am aware that the word limit for all extended essays is 4000 words and that examiners are not required to read beyond this limit.

This is the final version of my extended essay.

Candidate's signature: _____

Date: 1/12/08

IB Cardiff use only:

A: 44524 B: ✓

Supervisor's report

The supervisor must complete the report below and then give the final version of the extended essay, with this cover attached, to the Diploma Programme coordinator. The supervisor must sign this report; otherwise the extended essay will not be assessed and may be returned to the school.

Name of supervisor (CAPITAL letters) _____

Comments

Please comment, as appropriate, on the candidate's performance, the context in which the candidate undertook the research for the extended essay, any difficulties encountered and how these were overcome (see page 13 of the extended essay guide). The concluding interview (viva voce) may provide useful information. These comments can help the examiner award a level for criterion K (holistic judgment). Do not comment on any adverse personal circumstances that may have affected the candidate. If the amount of time spent with the candidate was zero, you must explain this, in particular how it was then possible to authenticate the essay as the candidate's own work. You may attach an additional sheet if there is insufficient space here.

is an extremely keen sailing competitor in the Severn estuary Sailing Squad. The title of his essay was created through a genuine interest, which he was therefore extremely enthusiastic and well motivated to research. A significant amount of time was spent generating test rigs, including a wind tunnel. These tests produced fairly clear results to the naked eye, but were difficult to photograph and therefore document. Combated this with his Pro Desktop, RP boat & a water tank. A difficult task to undertake, yet completed with an efficient & well thought out plan.

I have read the final version of the extended essay that will be submitted to the examiner.

To the best of my knowledge, the extended essay is the authentic work of the candidate.

I spent hours with the candidate discussing the progress of the extended essay.

* 3 hours workshop supervisor

Supervisor's signature: _____

Date: 1/12/2008.



.



EXTENDED ESSAY
DESIGN & TECHNOLOGY

**DOES HULL TRIM AND BALANCE
AFFECT THE SPEED OF A BOAT?**

Nice, and clearly done by an enthusiastic and knowledgeable student. However, given the topic and scope of the research, it could equally have been written under "Physics - aerodynamics". Aspects which relate to Design and the design cycle have not been sufficiently addressed.

Name:

Word Count:

3731

Candidate Number:

Session:

May 2009

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ABSTRACT

There are many tips for sailing a boat as fast as possible; the most notable is a fast boat = a flat boat. I planned to look at **“Does hull trim and balance affect the speed of a boat?”**

The aim of my essay was to determine whether keeping a boat perfectly flat lead to the greatest speeds. I investigated this by consulting several different resources related to fleet racing, performance sailing and emailed engineers and design departments linked to high performance yachting. I found some exceptions to a flat boat = a fast boat rule, such as racing yachts and hydrofoiling dinghies. Once I had gathered suitable information, I compared what I had found and set up a couple of tests to validate theories or prove otherwise.

RQ ✓

I built a water tank, a wind tunnel and a model boat. I designed the water tank and wind tunnel on 2D design and made them out of acrylic, cut on the laser cutter. The model boat was formed on a 3D printer once I had drawn it on ProDesktop. I towed the boat through the water tank and found that placing ballast centrally and forward that the boat moved through the water quickest, while placing the ballast backwards or to the side, the times were slower. The wind tunnel, although it didn't work properly showed that there was increased amounts of turbulence in the airflow, simulating that when the back digs into the water, it would decelerate.

scope ✓

I concluded that normally a flat boat is a fast boat, and with increased degrees of heel or trim, the boats performance significantly changed. There are cases where a boat shouldn't be sailed perfectly flat, but a flat boat = a fast boat is a reliable rule and worth remembering.

results ✓

Abstract fully
complete

INTRODUCTION

With the success of British sailors this summer in the Beijing Olympics and the growing coverage on television and in magazines, the popularity of the sport of sailing is rapidly growing particularly as it is becoming more and more accessible to everyone. What I plan to investigate is **"Does hull trim and balance affect the speed of a boat?"** In essence I want to find out if a flat boat is a fast boat.

Every sailing manual that I have learnt from or am now teaching from has maintained the statement that a flat boat is a fast boat. It's an easy to learn and remember statement which, as a general rule, is fine. However, there are cases in sailing where the boat sailed at her maximum speed is not flat. Americas Cup yachts for example, dubbed by many as the "formula 1 of the sea", are designed to go as quickly as possible yet still be manoeuvrable. Depending on wind conditions and surroundings you may want to sail them with heel to either side to attain maximum speed. Similarly, boats or yachts which are not single hulled designs are never sailed perfectly flat.

These cases make me wonder whether in fact the common statement is true. With the increased popularity in the sport, more and more children and adults are starting to race, whether at club level or in junior government funded fleets, and with the increased interest in coaching, I am getting more and more chance to teach students wanting to learn to race. Ensuring that the flat boat = fast boat statement is true is therefore of paramount importance to me.

The British sailing team had its most successful Olympic regatta winning four gold medals, one silver and one bronze in Qingdao showing a marked increase in the standard of the top British sailors. There could even have been more medals considering the team had a chance in every single class leading into the final race of the regatta. Would these extra medals have been won if the boats had been sailed less of more flat?

Through the course of my essay I will look at what affect hull trim and balance has on the speed of a boat and see whether a flat boat is in fact the fastest boat.

RA clearly stated
Introduction clearly explains the
significance of the topic

Interest -
context -
background -

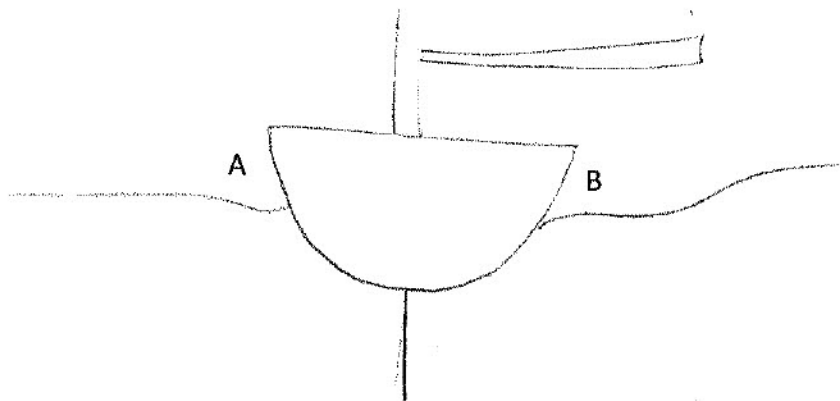
TERMINOLOGY

There are five essentials to remember when racing to get round a course or from point A to point B the quickest. They are;

- Boat Balance
- Trim
- Sail Setting
- Centreboard
- Course Made Good

"Boat Balance"

Balance is the angle that the boat is kept windward to leeward, whether (looking from the back) the boat is leaning on top of the crew or the boat is lifting the side with the crew on out of the water. If in the diagram you suppose the wind is coming from the left, the left side becomes the windward side and the right side becomes the leeward side.



On diagram: If A were to drop the boat would tip to the windward side, whereas if the boat were to tip towards B, this would be heeling over to leeward.

"Trim"

Trim is the angle that the boat is leaning towards the front or back. The helm and crew in the boat can adjust trim by moving their body weight forwards or back. By moving backwards, the bow can be lifted out of the water, and by moving forwards the bow can be dug into the water.

"Sail Setting"

Sail Setting is positioning the sails to maximise the impact of the wind. On a beat (going towards the wind) you have the sails tight in, while on a run (going with the wind) you have the sails fully out. You adjust the sails differently depending on wind conditions and the angle that you are heading to the wind.

getting
jargon -
heavy.

"Centreboard"

The centreboard is the large plate hanging from the centre of the hull to limit the boat from slipping sideways in the water. It also helps keep the boat more stable when being sailed. You vary the depth that this digs into the water by lifting it up or putting it down depending on which point of sail you are on. Heading upwind you will have it right down whereas heading downwind you will lift it up as it speeds you up.

|| why?

"Rudder"

The rudder is the board off the back of the boat which makes the boat turn by moving from side to side. It is usually attached by hinges to the back of the boat.

"Port"

Port is the left hand side of the boat.

"Starboard"

Starboard is the right hand side of the boat.

"Bow"

The bow is the front of the boat.

"Stern"

The stern is the back of the boat.

"Windward"

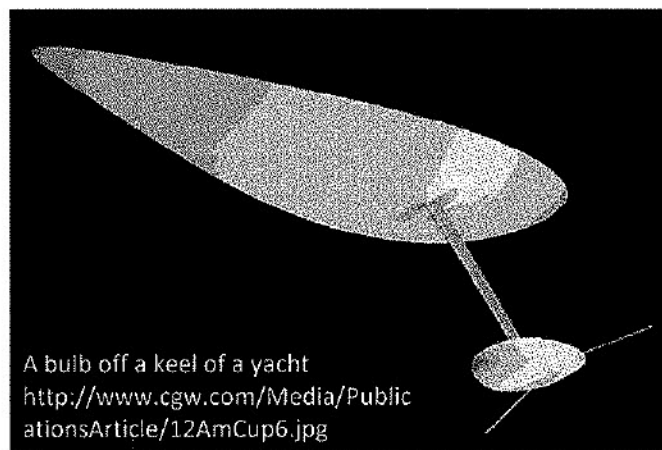
The side that the wind would be coming from if sails were up and filled. Also the side that the helm would sit on when sailing the boat.

"Leeward"

The side that the sails would lie on if sails were up and filled. The opposite side to where the helm sits.

"Bulb"

All yachts have keels with lead weights at the bottom to keep the boat from turning over. The large weight at the bottom is known as the bulb.



A bulb off a keel of a yacht
<http://www.cgw.com/Media/PublicationsArticle/12AmCup6.jpg>

Does hull trim and balance affect the speed of a boat?

The theory that a flat boat is a fast boat

The statement "flat boat is a fast boat" is widely accepted to be true and is a truism which is easy to coach and easy to understand. However, there are cases where you disregard this rule depending on wind conditions and the situation you're sailing in. Sails play a key part in maintaining boat speed. In light winds, for example, you want to heel the boat away to windward slightly so that the sails maintain their best shape and supposedly give the most power.

Speed with heel: Americas Cup yachts

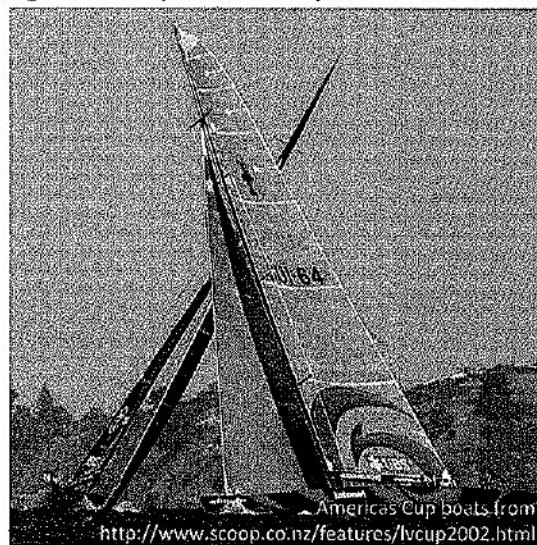
There are cases, however, even where the wind is strong that a heel to leeward seems to result in greater boat speed. The most obvious example is the America's Cup yachts. For the last campaign, the typical boat length was about 75ft and the mast height was around 110ft. These boats are designed purely for speed; they are stripped down to the bare minimum to get every ounce of speed out of the boat. Yet these boats sail with a leeward heel of between 30° and 31°.¹ In fact, the heel is so much that the top to the mast is 17 metres to leeward of the hull when the boat is sailing at top speed upwind.²

style.

is this the correct parameter?

The reason for this heel is the power generated by the vast sail area, 320 square metres upwind and 480 square metres downwind³. The power generated by the sails is such that a 19 tonne bulb³ is needed to keep the boat as upright as possible. The bulb is controlled by a hydraulics system which, as the speed picks up and the boat starts to heel, moves to the windward side to hold the boat at around 30°. The bulb could have been designed to move further if the designers had so wanted, however 30° seems to have been chosen as the optimum angle. There must be reasons why the angle has been selected as 30°. The Americas Cup teams are heavily funded with the majority of their budget spent on the design so this angle must be a carefully calculated figure. This angle must optimise the power in the sails and the effect of the hull on the water.

I know through my personal sailing experiences that, with a large amount of windward heel, the boat will naturally want to head up into the wind which leads to having to counteract the turning by changing the angle of the rudder which increases drag. So it would seem that the designers have found the balance between sail power generating speed and hull turbulence reducing boat speed.



Americas Cup boats from <http://www.scoop.co.nz/features/lvcup2002.html>

¹ Daniel Bernasconi (team Alinghi designer), personal email, 28th August 2008

² Philippe Mourniac, Americas Cup jury notice JN064, 6th April 2007

³ Anon, BBC sport, 16th April 2007

Speed with heel: Hydrofoiling dinghies

At the different scale of the boating world to the Americas Cup yachts are hydrofoiling dinghies. A boat which hydrofoils is one that has a specially designed piece on the rudder so that when the boat is travelling quick enough, it can lift out the water and just skim along the which reducing the drag completely and increasing the top speed. It is generally accepted and promoted by the leaders in the field of international hydrofoiling moths, such as Rohan Veal and John Harris, that a slight heel to windward is needed to generate enough speed for the boat to lift itself out of the water.

7

line missing?

It would thus seem that if the hydrofoiling sailors are pulling the boat on top of them slightly to maximise power, then the hulls should be designed so that at a slight heel they slide through the water just as fluently as if the hull was perfectly flat. So, sailing the boat pulled slightly to windward could be quicker than sailing the boat perfectly flat.



Testing the importance of balance and trim

This is the theory that I have decided to test. I needed to set up a test rig so that I could carry out an experiment myself. To do this experiment I had to make a water tank and a model boat. I also needed to develop a system to change the trim of the boat and to pull the boat through the water at a steady pace.

The test: the water tank

When I got in touch with Daniel Bernasconi by email (28th August 2008), I was told that I would have to use a towing tank to test a hull to get meaningful figures. This meant I needed to design a tank which I could drag a model boat through and time from one end to the other. The shortest length of time would mean the least drag. On 2D design I drew a 60cm x 10cm x 10cm open topped box with a small hole at each end so I could attach a line from my boat to weights to drag the boat through the water.

Candidate demonstrates adequate background knowledge

The test: the boat

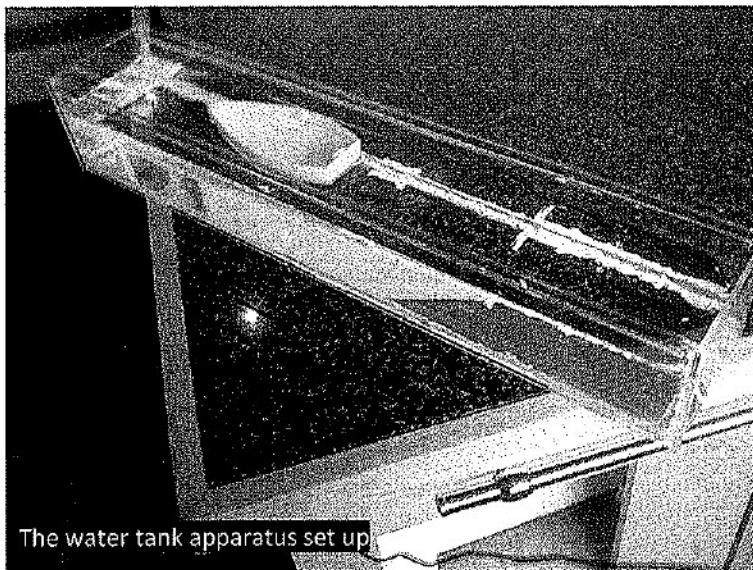
I decided to build a model of a Firefly. A Firefly is the boat that I sail at school so is relevant to me but is also sailed countrywide in school and university events. The original plan was to carve a model out of jelotong, 14cm long, 6.3cm across and 2.5cm tall, but then my school bought a 3D printer towards the end of the term, so I decided it would be much easier to use this. A model was built on Pro/Desktop using the original dimensions. Due to the complex design of a Firefly, or any boat hull, with smooth curves in multiple directions, the model was not exactly accurate but still resembled a Firefly.

I added four notches about the hull. The ones front and back were for attaching string to with weights tied on to drag the boat through the tank. The other two notches on the sides were for adding heel to the boat, although these became redundant as I later found a simpler method to alter heel. As I was just testing the hull of the dinghy there was no mast added onto the model.

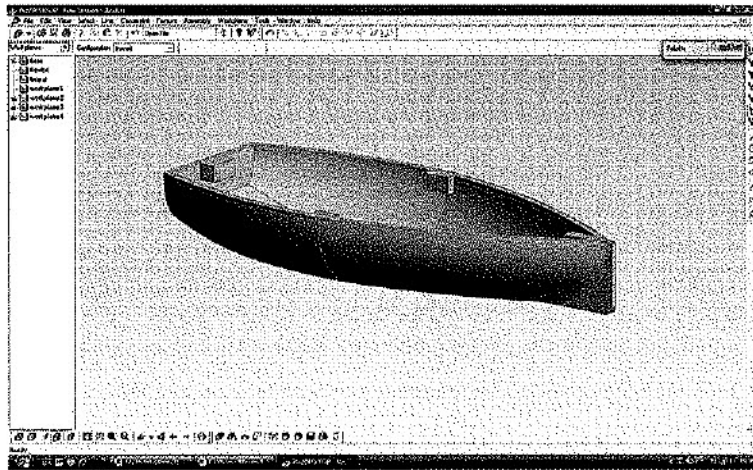


My crew and I sailing a Firefly at Itchenor Sailing Club.

*Direct
practical
activity*



The water tank apparatus set up



Design of the boat on Pro/Desktop

Once the boat was designed I set it to print on the 3D printer. A 3D printer works by laying down successive layers of plastic to build up the shape. Whilst this meant that I wouldn't have a perfectly smooth surface, for the tests that I planned to carry out the small contours on the hull of the scale model wouldn't matter. Their effects were negligible.

*Supposio-? of useful sticky?
of evidence-based?*

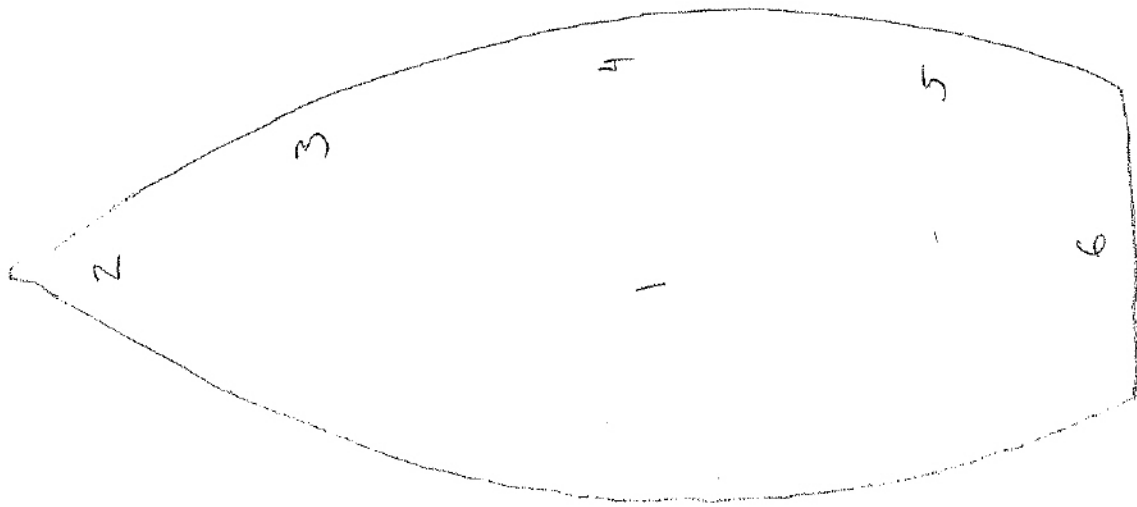
The test: the method

As well as experimenting with the balance, this test allowed me to examine the effects of altering the trim of the dinghy. I filled the tank with water so that the boat sat flat on the top of the tank with the string attached to the boat and threaded through the hole as near to horizontal as possible. To change the trim and balance of the hull, I simply shifted a small mass of weight (ballast) about predetermined positions in the model hull. To tow the boat through the tank I used a low friction string, such as fishing line, to cause the smallest differences to the results. I attached the string to the notches on the hull at the front and back of the boat so it could drag the boat through the tank in a straight line. The most important part of the towing tank is that the hull that is being tested is pulled through the water with the same strength so that the times are all comparable. The time measured was that between the boat touching both ends of the tank. To pull the boat through the tank at a consistent force every test, I attached weights to both the stern and bow lines, the latter being a little heavier than the former. In the starting position the stern weight was hanging and I was holding the bow weight from pulling the boat through the tank. I released the bow weight and started timing, finishing when the bow touched the end.

I used three different ballasts in the hull, 5g, 10g and 15g. I put the ballast in six different positions around the boat, from the front to the middle to the back, through the centre of the boat and to one side. I ran the tests three times for each weight in each position.

WATER TANK RESULTS

Weight (g)	Position (1-6)	Time (seconds)			Other observations
		1	2	3	
5	1	1.87	1.82	1.80	
	2	1.95	1.80	1.64	
	3	1.88 1.91	1.84 1.81	1.81	
	4	1.80	2.00	1.87	
	5	1.87	1.90	1.87 1.86	
	6	1.90	1.75	2.06	
10	1	1.85 1.85	1.98	1.81	larger water than before
	2	1.80	1.91	1.50	
	3	1.83	2.02	2.10	moving left
	4	1.75	1.98	2.01	pulling left
	5	1.90	2.20	2.34	
	6	2.00	1.80	2.18	
15	1	1.95	2.20	1.86	
	2	2.10	1.99	1.83	
	3	1.97	2.02	1.92	left
	4	2.11	2.26	2.27	left
	5	2.36	2.35	2.39	left.
	6	2.06	2.24	2.20	



The test: the results

See raw results on previous page.

Weight (g)	Position (1-6)	Time (seconds)			Other observations
		1	2	3	
5	1	1.87	1.82	1.80	
5	2	1.95	1.80	1.84	
5	3	1.80	1.91	1.81	
5	4	1.80	2.00	1.87	Slight move left
5	5	1.87	1.90	1.96	
5	6	1.90	1.78	2.06	
10	1	1.85	1.98	1.81	
10	2	1.82	1.91	1.78	
10	3	1.90	1.86	2.00	Pulling slightly left
10	4	1.83	2.02	2.10	Turning to the left
10	5	1.96	2.20	2.34	Turning left
10	6	2.00	1.80	2.18	
15	1	1.95	2.20	1.86	
15	2	2.10	1.99	1.83	
15	3	1.97	2.02	1.92	Going left
15	4	2.11	2.26	2.27	Going left
15	5	2.36	2.35	2.39	Going left
15	6	2.06	2.29	2.20	

Raw data typed up

Ballast (weight) (gram)	Average time for each position (seconds)						Order of results
	1	2	3	4	5	6	
5	1.83	1.86	1.84	1.89	1.91	1.90	1,3,2,4,6,5
10	1.88	1.84	1.92	1.98	2.17	1.99	2,1,3,4,6,5
15	2.00	1.97	1.97	2.21	2.37	2.18	2+3,1,6,4,5

The average times taken per position per weight and the order of results

To analyse these results I decided to create a scoring system as follows;

- 1st = 1 point
- 2nd = 2 points
- 3rd = 3 points
- 4th = 4 points
- 5th = 5 points
- 6th = 6 points

In the case of a tie, the combined points of the two positions were halved, e.g. if 3 and 4 tie, each position gets 3.5 points.

The position of ballast that achieved the lowest amount of points was deemed to be the best performing position of weight for boat speed. The results of the scoring system are shown below.

Place	Ballast Position (1-6)	Points	Results (5g, 10g, 15g)
1 st	2	5.5	3 rd , 1 st , 1 st equal
2 nd	1	6	1 st , 2 nd , 3 rd
3 rd	3	6.5	2 nd , 3 rd , 1 st equal
4 th	4	13	4 th , 4 th , 5 th
5 th	6	14	5 th , 5 th , 4 th
6 th	5	18	6 th , 6 th , 6 th

The placing of the positions according to points system

The test: the analysis

These results clearly show that if the ballast is either dead centre or towards the front of the boat then the time taken for the boat to travel the length of the hull is less. Similarly, if the ballast is towards the stern then the time taken is much longer. Within the top three places there is very little differential (one point) but there is a big gap between the third place in points (position 3 with 6.5 points) and the fourth (position 4 with 13 points).

One thing that I noticed with position 1 (dead centre) is that as the weights increased, it slipped from 1st to 2nd and then to 3rd. This could be due to apparatus set up. The test rig was set up with the line horizontal with no ballast in the boat. As the ballast was increased, more pressure was on the string as the line was at a steeper gradient leading to slower times. However, even due to potential slight experiment issues, I think that the test worked well. The results showed that every position of ballast had fairly even results.

A further observation was made was that when the ballast was to one side, the boat started to turn to the other side (as a boat does with sails filled). This suggests that by increasing degrees of heel to the boat you can help it to turn through the water. By using this method during racing for small changes in direction rather than using the rudder (which acts as a brake), you can maintain a constant speed, helping you gain the crucial seconds.

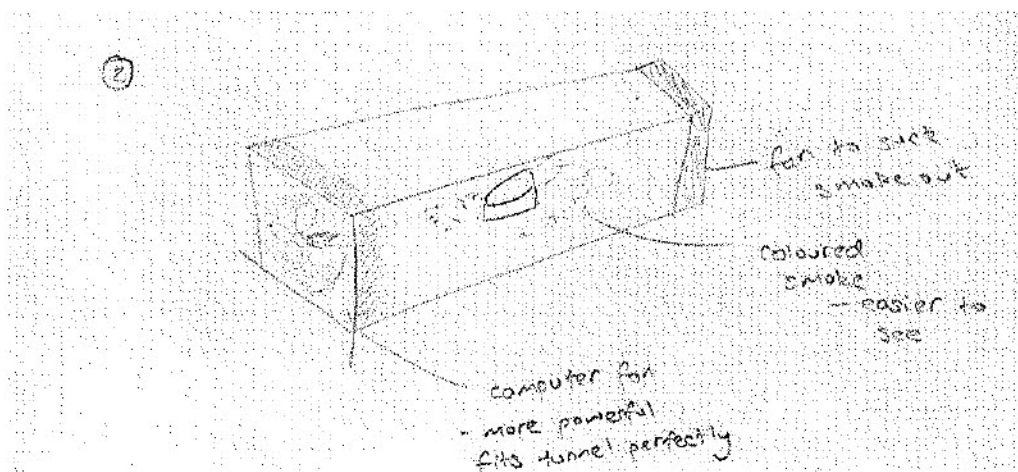
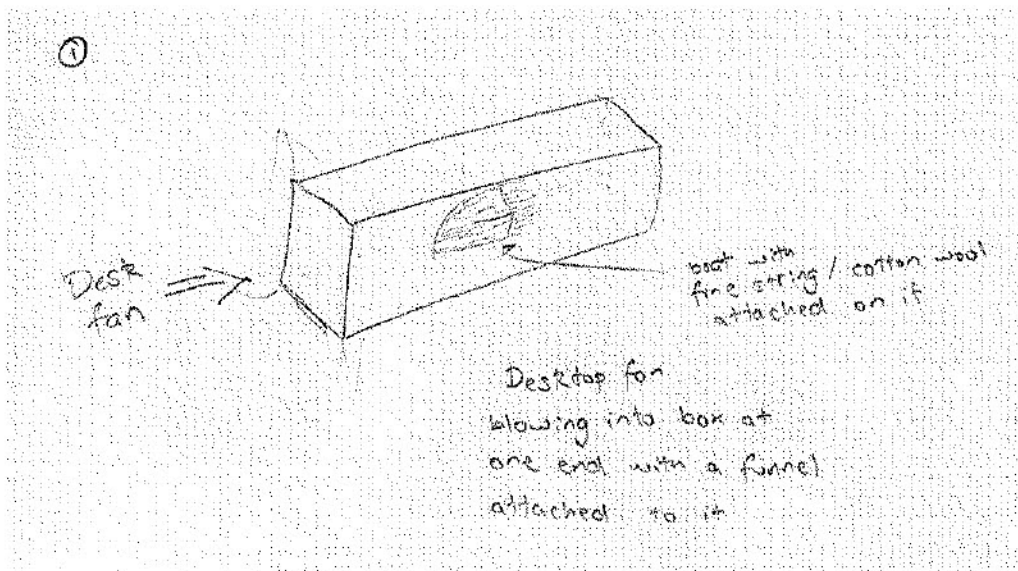
My results show that ballast position 2 was the fastest boat, where the boat was flat but the weight was moved forward. The second quickest boat was position 1. These results would suggest that as long as the boat is kept balanced and the weight isn't towards the back then there is least effect on the water from the hull.

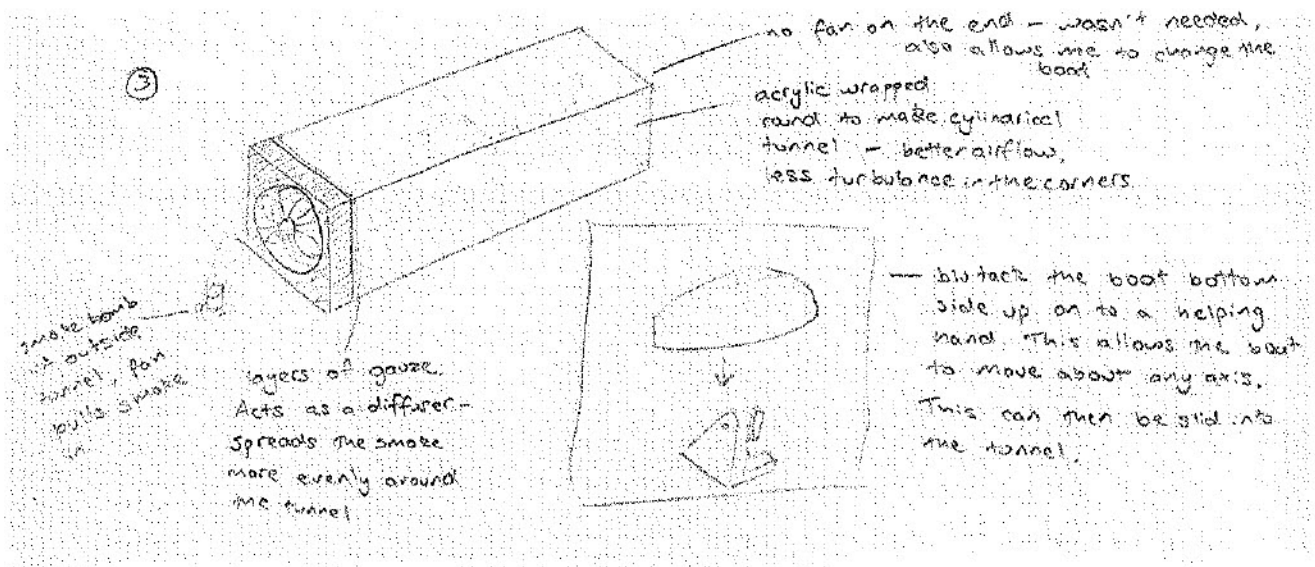
The test: measuring trim with a wind tunnel

What makes the boat speed increase when the weight is moved forward in the boat? The bow digs in more and lifts the stern out of the water. In the Firefly design, as the front is quite pointy and the back is flat, by pushing the nose into the water, the surface area is being lessened, thus reducing the drag of water on the hull. There isn't much said about trim (the position of weight in the boat) in most sailing books, however it is generally believed that you want your weight further forward than back, as by pushing the larger flatter area into the water you are creating a brake. There is a danger of moving too far forward and digging the bow into the water and slowing down, but that is a much smaller risk than that of staying too far back.

How do you know this?

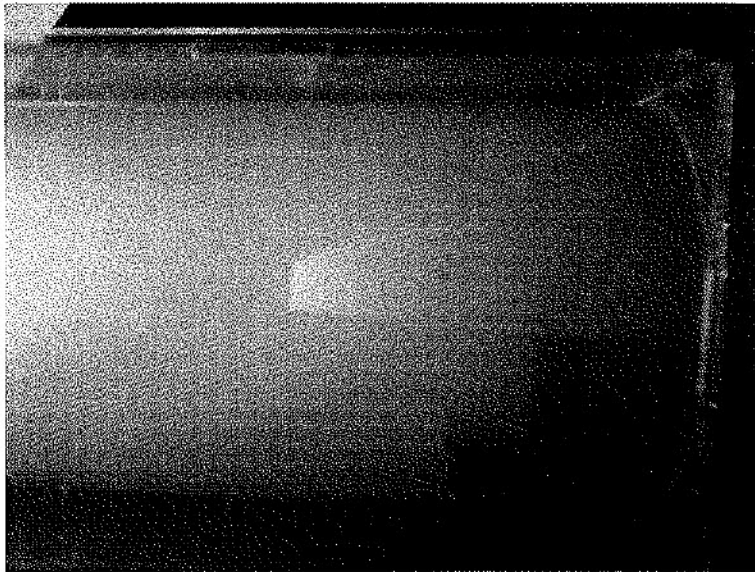
In an attempt to see the effects of trim, I built a wind tunnel from a computer fan and acrylic which was cut on the laser cutter. I designed an open ended box on 2D design which was 40cm long and 15cm tall and wide. I used coloured smoke which could be sent along the tunnel and show the areas of turbulence created by altering the degrees of trim.



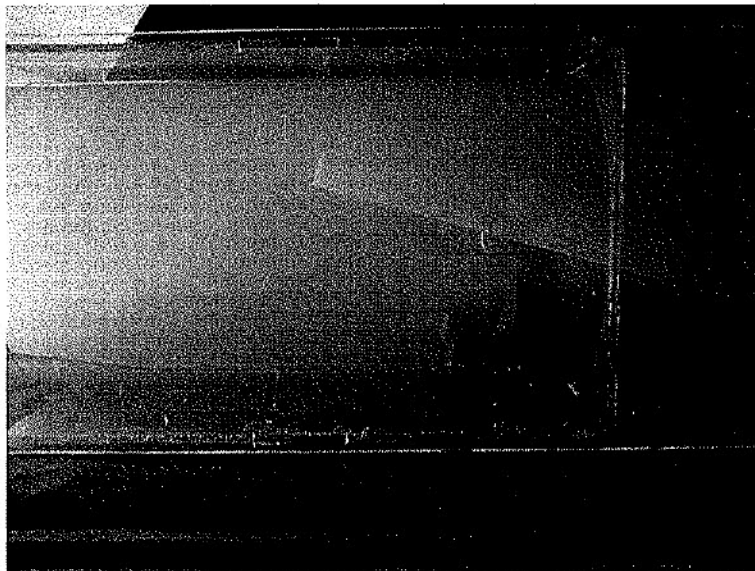


I set off a smoke pellet and switched the fan on which sucked the smoke through the tunnel and then blew it past the boat sitting in the cylindrical inner tubing. I took photos of each increase in degree of trim and compared the differences. Unfortunately it was exceptionally hard to see evidence of any difference between the varying amount of trim due to the glare generated by the acrylic and the thickness of the smoke. Even with different coloured smoke and backdrops it was hard to see any differences. However, the results did support the fact that keeping the boat flat creates a much smoother flow about the surface of the hull than with a large amount of trim. (See photos below).

0° trim



20° trim



The top photo shows a fairly clean flow of smoke past the model hull whereas the second picture, shows a slight disturbance behind the hull where the smoke is thinner.

True: the results of this test are -conclusive.

CONCLUSION

Balance

With respect to balance, the amount of desirable heel to maximise speed depends on the type of boat. For the standard dinghy, not a hydrofoiling dinghy or a yacht of some sorts with a keel, a flat boat is fastest. This was backed up by my test results which also showed that with a slight heel to one side, even without sails, centreboard or rudder, the boat started turning to one side. When sailing a hydrofoiling boat it is preferable to get slight windward heel to aid the boat in getting upwards movement to reach the maximum speed by effectively skimming across the surface of the water. With high performance yachts, such as the Americas Cup class, a leeward heel is preferable as this creates the most efficient balance between boat speed and weight.

Trim

It was found through my towing tank test that the boat leaning towards the bow was preferable to having the stern digging into the water. The more valuable results were certainly gained from the water tank, although the wind tunnel highlighted which areas were most affected by changing the trim. By digging the stern in, the smoke became much more condensed between the model boat and the tunnel itself. This then created an empty space in the smoke behind the boat which, if put into the sailing situation, would create more turbulence and disturbance in the water, thus slowing the boat. Also, by lifting the nose out of the water, it means that the water takes a much clumsier path getting past the boat, rather than just being effectively sliced apart as the boat progresses through the water.

Overall

With respect to the question "Does hull trim and balance affect the speed of a boat?", the test and research that I carried out definitely points to it being beneficial to keep the boat flat. There was up to 0.5 second difference over the short distance from keeping the ballast central and forward, to keeping it to one side and towards the back. If this were applied to a fleet race where all conditions were constant, apart from the balance and trim, there would be vast differences over an hour long race between those who keep their weight centred and forward to those who don't pay much attention to their positioning.

Although not necessarily always the case, the flat boat = fast boat rule is a reliable rule and one worth remembering.

Formal presentation good
Student has demonstrated
a sound understanding
of Design Technology cycle

✓
Not conclusive, but
clear enthusiasm - has
persuaded the author that
the conclusions are valid.

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Assessment form (for examiner use only)

Candidate session number	0	0						
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Achievement level

Assessment criteria

A research question

B introduction

C investigation

D knowledge and understanding

E reasoned argument

F analysis and evaluation

G use of subject language

H conclusion

I formal presentation

J abstract

K holistic judgment

First
examiner

maximum

Second
examiner

2

2

2

2

2

2

2

4

2

2

4

2

2

4

2

1

4

1

3

4

3

1

2

1

3

4

3

2

2

2

3

4

3

Total out of 36

23

23

no awareness of uncertainties
personal view after "stated" without justification
nothing on the design cycle at all.

Name of first examiner: _____
(CAPITAL letters)

Examiner number: _____

Name of second examiner: _____
(CAPITAL letters)

Examiner number: _____