BAE SYSTEMS

MARITIME - SUBMARINES

Submarine Drag Modelling and Hull Design

Nuffield Research Project

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Date of Issue:	17/08/2012

Table of Contents

1. Abstract ____ 1

2. Introduction ____ 2
2.1 Background 2
2.2 Purpose 2
2.3 Scope 2
2.4 Document Overview 3
2.5 Research Process 3

3. Drag Theory ____ 4
3.1 What is drag? 4
3.2 Why it is Beneficial to Minimise Drag on a Submarine 4
3.3 The Different Types of Drag Forces 4
3.3.1 Skin Friction 5
3.3.2 Form Drag 5
3.3.3 Interference Drag 6
3.4 Flow around a Body 6
3.4.1 Laminar and Turbulent Flow 7
3.4.2 Boundary Layer Separation 7
3.4.3 Flow Separation 8
3.4.4 Reynolds Number 8
3.4.5 Length-to-Diameter Ratio 9

4. Modelling Drag on a Submarine ____ 10
4.1 Background on Modelling Drag on Submarines 10
4.2 Method 11

5. Design Changes to Reduce Drag ____ 12
5.1 Redesigning of External Structures 12
5.1.1 Bow 13
5.1.2 Control Surfaces 14
5.1.3 Bridge fin 14
5.1.4 Flank array 15
5.1.5 Pylon 15
5.1.6 Body Curvature 15
5.1.7 Reducing the Drag Effect of Gaps in Submarine Casing 15
5.2 Drag Reduction Technologies 15
5.2.1 Polymer Addition 16
5.2.2 Micro-bubbles 17
5.2.3 Supercavitation 18
5.2.4 Flexible/Changeable Outer Casing 19

5.2.5 Electromagnetic Turbulence Control (EMTC) 19
5.2.6 Rotating Submarine 19

6. Summary 20
6.1 Evaluations 20
6.2 Conclusion 20
6.3 Further Research 21

7. Acknowledgements 22

Table of Figures

Fig. 1 Fluid Flow Over a Body………………………………………………………………….5

Fig. 2 Shear Stress Distribution………………………………………………………......5

Fig. 3 Form Drag on streamlined and non-streamlined bodies……….……………………….6

Fig. 4 Laminar and Turbulent Flow……………………………………………………….…….7

Fig. 5 Graphical Representation of Flow Separation…………………….…………………......7

Fig. 6 How a Change in Reynolds Numbers affects the Coefficient of Drag…………….......8

Fig. 7 Length: Diameter Ratio and Drag…………………………….……………………....9

Fig. 8 Finite element mesh consisting of thousands of tetrahedral elements……….………11

Fig. 10 HMS Astute Plan……………………………………………………………….….…….13

Fig. 11 Effect of changing Reynolds numbers for poly(ethylene oxide) on DR……….…..…..17

Fig. 12 Supercavitation…………………….………………………………………………………18

Fig. 13 Super fast supercavitating submarines of the distant future………………………….18

Figure	Reference
1	http://www.grc.nasa.gov/WWW/k-12/airplane/boundlay.html
2	http://www.civil.uwaterloo.ca/enve214/Files/Reynolds_Number_and_Drag.pdf
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I would also like to reference my discussions with BAE members of staff. These people have helped me gain a wider understanding of the topic and specific aspects of my project:

John Salisbury

Mike Biddell

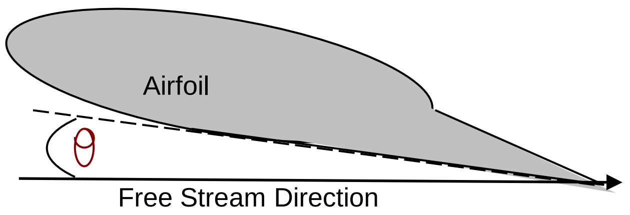
Colin Utting

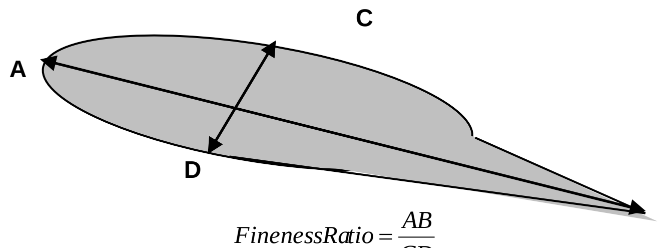
Ed Stamp

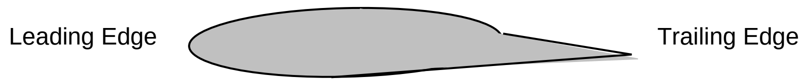
Andy Holmes-Evans

Nick Thomas

Glossary of Terms

Abbreviation/ Term	Definition [1,2]
Aft	Back end of a vessel.
Angle of Attack	 The angle of attack is defined as the angle between the plane of the wing (airfoil/hydrofoil chord) and the direction of motion (free stream velocity).
Boundary Layer	The layer of fluid in the immediate vicinity of a bounding surface where the effects of viscosity are significant.
Bow	Front end of a vessel.
CFD	Computational Fluid Dynamics. The term given to a variety of numerical mathematical techniques applied to solving the equations that govern fluid flows and hydrodynamics.
Casing	The casing of a submarine is a light metal structure, usually incorporating a deck, built-up and-over the upper surface of the vessel's pressure hull.
Control Surfaces	Exterior surfaces such as hydroplanes and the rudder which can be manipulated to control the movement of the submarine.
Density	The mass per unit volume of a material. The density of seawater ranges from 1020–1029 kg/m^3
Drag Coefficient (C_d)	A dimensionless quantity that is used to quantify the resistance of a body in a fluid environment. It is used in the drag equation, where a lower drag coefficient indicates the body will have less hydrodynamic drag. $$C_d = \frac{F_d}{\frac{1}{2}\rho A V^2}$$
Drag Equation	A practical formula used to calculate the force of drag experienced by a body due to movement through a fully enclosing fluid. $$F_d = \frac{1}{2}\rho v^2 C_d A$$

Abbreviation/ Term	Definition [1,2]
DR	Drag Reduction
Eddies	An eddy is the swirling of a fluid and the reverse current created when the fluid flows past an obstacle. The moving fluid will create an area devoid of downstream flowing fluid behind the body.
FEA	Finite Element Analysis. A numerical technique for dividing up a very complicated problem into small elements which can be solved in relation to each other.
Fineness Ratio	 $FinenessRatio = \frac{AB}{CD}$ The ratio of the length of a body to its maximum width, which is used to describe the overall shape of a streamlined body. Typically a fineness ratio of around 6 is favored for the most hydrodynamic hull design.
Free Stream	The free stream is the fluid far upstream of a body flowing normally before the body has a chance to distort or slow down the fluid.
Hydrophone	A microphone including a piezoelectric transducer designed to detect underwater sound. They are placed on the nose, flank array, and towed array on a submarine and pick up signals from other vessels in the surrounding vicinity.
ITTC 1957 Model-Ship Correction Line Formula	A formula used when calculating frictional forces acting on a body and in modelling drag. $$C_F = \frac{0.075}{(Log_{10}\,\mathrm{Re} - 2)^2}$$
Kinematic Viscosity	The kinematic viscosity characterises situations involving the ratio of the inertial forces to the viscous forces. $\nu = \frac{\mu}{\rho}$ (The unit of ν is m^2/s)
Pressure Hull	The cylindrical structure inside the outer casing on a submarine which withstands the outside pressure and maintains normal atmospheric pressure inside.
Prevailing Flow	The flow around the front section of a body moving in the same direction as the free stream.
Laminar Flow	A flow regime occurring when fluid flows orderly in parallel layers with no disruption between them.

Abbreviation/ Term	Definition [1,2]
Leading/Trailing Edge	The leading edge is the section of the body which first comes into contact with the fluid. The trailing edge is the section of the body which last comes into contact with the fluid. 
Retrograde Flow	The flow around the back section of a body moving in the same direction as the body.
Reynolds Number	A dimensionless number that gives a measure of the ratio of inertial to viscous forces acting on a body and consequently provides a way to distinguish and compare different flow regimes for Newtonian fluids. $$\mathrm{Re} = \frac{F_i}{F_v} = \frac{\rho V L}{\mu} = \frac{VL}{\nu}$$
Stagnation Point	A point in a flow field where the local velocity of the fluid is zero. A stagnation point will occur where the free stream meets the front surface of a body head on.
Shear Stress	Defined as the component of stress coplanar with a material cross section. Any fluid moving along a solid boundary will incur a shear stress on that boundary. Shear Stress, $\tau = \mu \frac{\partial u}{\partial y}$ (Pa = N/m^2)
SSBN	Ship Submersible Ballistic Nuclear. A submarine equipped to launch ballistic missiles.
SSN	Ship Submersible Nuclear. A nuclear powered attack submarine.
Surfactant	Compounds that lower the surface tension of a liquid and the interfacial tension between a liquid and a solid.
Turbulent Flow	A flow regime that is characterised by chaotic and swirling changes in the fluid.
Vector/Flow Field	A vector field is an assignment of a vector to each point in a subset of 3-dimensional space. An example of a vector field is a flow field, which is used to show local velocities of particles of fluid in fluid flow.
Viscosity	Viscosity is a measure of the resistance of a fluid which is being deformed by forces such as shear stress.
Vortex	A vortex is a spinning flow of fluid which creates a spiral motion with closed streamlines.

1. Abstract

A project has been conducted to assess potential ways of reducing drag on a submarine. Drag reduction (DR) is a critical factor to consider in submarine hull design, primarily to reduce costs associated with powering the submarine and also to improve manoeuvrability. In this report, a number of ideas have been discussed related to modifying the hull geometry, such as evolving the design of the hull closer to that of a tear drop shape, casting the bow in a single piece to reduce drag from acoustic tiles, and also the introduction of X-planes. In addition, new technologies such as polymer and micro-bubble injection have been identified as potential systems to employ for drag reduction. Novel systems like supercavitation and EMTC are promising ideas that are also assessed.

2. Introduction

2.1 Background

Submarine designs are constantly being reconsidered and improved. This process is powered by the need for them to carry out a specific function more efficiently, but also the requirement for our own submarine technology to stay one step ahead of the enemy's. Some important factors to consider when designing a submarine are stealth and manoeuvrability; and drag plays a fundamental part in both of these areas. The amount of hydrodynamic drag governs the size and power output of the propulsion system required, which in turn determines the size of the rest of the vessel. Work is always being done against drag, and therefore more drag means higher fuel consumption. A bigger drag profile also means the nuclear reactor (on SSNs and SSBNs) powering the submarine must be larger or more efficient to maintain the same top speed. This can have huge implications for the costs associated with building and refuelling of a submarine, and can limit the space available on the submarine for other equipment.

Drag is related to turbulent flow in the boundary layer, and this is the main source of submarine self-noise. This increases the submarine's acoustic signature making it more difficult for the operators to determine incoming signals against the background of self-noise and makes the submarine more easily detectable by enemy sonar. DR offers tactical advantages for submarines, since it delays the transition from laminar to turbulent flow when the speed of the vessel is increased.

If the purpose of future submarines is to be both fast and silent, then DR will become an essential design criterion. These main reasons are why DR techniques are so sought after and important to the design of a successful submarine.

2.2 Purpose

The purpose of this report is to study the following topics and present the information gained from my research.

- What drag is and how it works
- Why drag DR is beneficial
- How drag affects submarines, and the details of fluid dynamics related to submarines
- How drag on a submarine is modelled
- How the Hull/Casing design of a submarine could be modified to reduce drag
- What technologies would be useful for reducing drag

2.3 Scope

In this report I will consider DR techniques related to the design of the outer casing of a submarine. I will concentrate on how the geometry of the casing could be altered, how the control surfaces could be changed, and what technology could be introduced to the exterior of the submarine for the purpose of DR. I will consider the shape of the casing on the small-scale but I will not investigate suitable materials or coatings, and how these could be applied.

2.4 Document Overview

• ***Introduction***

A brief outline of what I am investigating, what I hope to find in doing this research, and what the limitations are.

• ***Main body***

- Drag Theory: This will explain the physical concepts of drag on submerged bodies such as a submarine and explain why DR is so beneficial. It will be mostly theory based and the main topics covered are;

  1. A description of drag
  2. Why DR is beneficial
  3. The types of drag forces acting on a body
  4. Flow around a body

  This section should provide a general background to drag and flow. Additionally it will act as a basis for some of the new DR ideas discussed later in the report.

- Modelling Drag on a Submarine: This will review the current drag modelling systems in use that help with the designing of a hydrodynamically shaped casing for a submarine. It will also explain the method for modelling drag.

- Design Changes to Reduce Drag: In this section I will present the research that I have done on possible changes to the submarine's casing design that could reduce drag. It will be subdivided into the following sections:

  1. Redesigning of External Structures
  2. Reducing the Drag Effect of Gaps in Submarine Casing
  3. DR Technologies

• Conclusions

- Recommendations: Which ideas for DR are the most promising and worthy of more research and which are more far-reaching.
- Summary: A concise conclusion of all the research I have conducted.
- Further Research: Topics leading on from those covered in the report that would be useful to look at when considering DR.

2.5 Research Process

I have gone about researching topics in this report in a number of different ways. I have discussed topics, such as how drag affects a submarine, with my colleagues at the Weymouth office and also with experts in their field when I visited different BAE sites. I have read books related to naval architecture and fluid dynamics and watched videos explaining some physical concepts such as skin friction and form drag. There are also many online resources which have proved useful, including research studies on faculty and scientific institution websites, as well as general information found on websites such as Wikipedia.

3. Drag Theory

3.1 What is drag?

A general definition of drag is: a mechanical force generated by the interaction and contact of a solid body with a fluid [3]. The total drag on a body is made up of a number of different types of resistance forces which always oppose the direction of motion of the body (the main three of which are explained in section 3.3). Drag is a force, and therefore a vector quantity, that is generated by every exterior part of the body and acts to slow it down as it travels through a fluid. The amount of drag on a body is directly related to the medium in which it is travelling, the size and shape of the body, the body's inclination to the flow and the square of the relative velocity of the body. Therefore the resultant power needed to overcome this drag will vary with the cube of the velocity. By using the drag equation, the force experienced by a body travelling through a fluid at high Reynolds numbers (explained in section 3.4.1) can be calculated.

3.2 Why it is Beneficial to Minimise Drag on a Submarine

A large body such as a submarine will encounter a similarly large resistive force as it tries to move through the water. The total resistive force, or drag, will be a factor, along with the weight of the vessel, which determines the amount of power needed to propel it though the water. Therefore it follows that an increase in drag results in a larger or more efficient propulsion system being required to push the same volume of submarine along. An improved powering system will come at a cost and it may be more cost effective to implement drag reduction (DR) techniques. Another benefit of DR is that the propulsion system can be smaller and lighter, leaving more space for other equipment and weapons systems within the hull.

Reducing the drag involves changing the flow conditions around the submarine which can also have a positive effect on noise reduction. For most submarines it is important to keep a low profile, and this means reducing the water disturbance around the surface as much as is possible. Improved flow regimes over the casing, not only lowers drag, but lowers the noise profile of the submarine making it harder to detect. Another added benefit to this noise reduction is the improved sensitivity of onboard sonar systems. Smooth flow past the different arrays means that there is less noise interference and a better picture of the surrounding environment can be achieved.

The last benefit might seem obvious when discussing DR but is an important factor nonetheless. Lower drag forces amounts to better manoeuvrability and a higher top speed. The submarine will be able to change direction and move more quickly which gives it a big tactical advantage. It will be able to get from point A to point B faster than an enemy vessel with inferior DR technology.

3.3 The Different Types of Drag Forces

Bodies moving in fluids will encounter a number of different drag forces. One of the main forces is 'skin friction', which arises from the surface of the body interacting directly with the fluid, and is a kinetic interaction as it involves transfer of momentum by **viscosity**.

Another is 'form drag', which is related to the pressure differences over the entire body, and is a dynamic interaction as it involves **inertial** forces and the transfer of energy.

These main forces associated with drag are explained in more detail below:

3.3.1 *Skin Friction*

Skin friction (or friction drag) is a force that acts on a submerged body moving within a fluid due to the **viscous shear forces** acting along the surface of the body [4]. It is a result of the partials of fluid and the surface of the body interacting directly transferring momentum and creating a force. Hence for a given volume of hull it is desirable to reduce the surface area as much as possible. It is also beneficial to retain a smooth surface, free from sharp discontinuities, and to have a slowly varying form so that no adverse pressure gradients are built up causing drag through flow separation from the hull [5].

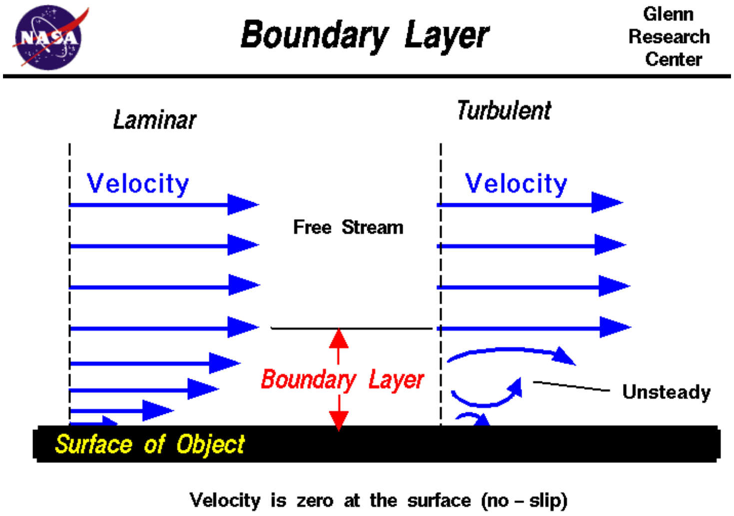


Fig. 1 Fluid Flow Over a Body

It is a kinetic interaction in which the partials of fluid (represented by horizontal black arrows on Fig.1) are held together by viscous shear forces down the gradient line. The partials near to the boundary surface of the body adhere more strongly than those further away and therefore a force is generated as the fluid moves past the body. If the shear stress distribution is known then the total frictional force can be found by summing the shear stresses over incremental positions on the body.

Any real fluids moving along a solid boundary will incur a **shear stress** on that boundary. There is a 'no slip condition' which states that the velocity of the fluid at a point on the boundary layer will be zero, and as the distance from the boundary increases the velocity will rise until there is another point where the velocity of the flow is equal to the free stream velocity. The region between these points is named the **boundary layer**. The shear stress (τ) for a Newtonian fluid such as sea water at the surface parallel to the flat plate is given by the equation:

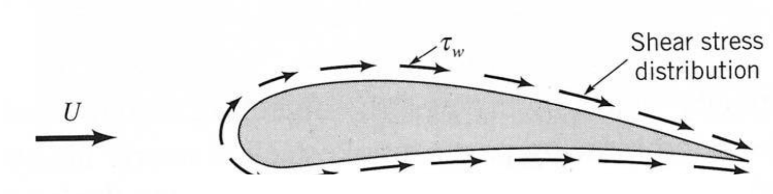


Fig. 2 Shear Stress Distribution

$$\tau = \mu \frac{\partial u}{\partial y}$$

Where:

μ is the dynamic viscosity of the fluid
u is the velocity of the fluid along the boundary
y is the perpendicular height above the boundary

3.3.2 *Form Drag*

Often referred to as *pressure drag,* this type of drag is part of the total drag force acting on a body and is due to the pressure applied to the body as it moves though the fluid [4]. A net drag force is created as a result of the total difference of the sum of the pressure forces on the leading and trailing edge of the body. It is a dynamic interaction as it is involves the transfer of energy and the distortion of the flow fields around bodies.

When fluids flow past a body they will lose energy. If we consider a particle of fluid approaching a streamlined body head on, we will see that there is a point of maximum pressure on the leading edge of the body where the particle of fluid meets the body's surface and is decelerated until its relative velocity is zero. This is called a **stagnation point**, and is found on the very tip of both the leading edge and the trailing edge. From this point onwards other particles either side of the stagnation point will undergo an increase in velocity (in relation to the free stream) as they follow a path around the leading edge of the body. The local pressure will be decreasing until the particles' velocities match up with the free stream velocity and a region of minimum pressure is formed. This region is normally found on the top and bottom of the body assuming it is of a regular shape. The pressures from this point onwards will increase by different amounts, depending on the shape and texture of the trailing surface.

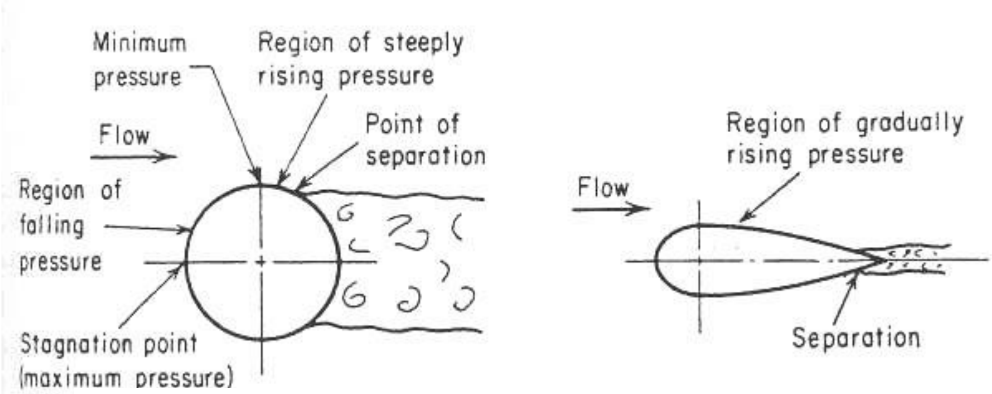


Fig. 3 Form Drag on streamlined and non-streamlined bodies

If a body has a sharp edge on its trailing surface, the fluid moving along the boundary layer may not have enough energy to remain attached to the surface and can separate from the body (see section 3.4 for more information on separation points). This separation results in a turbulent wake forming behind the body, which is a region of relatively low pressure. If a body has many sharp discontinuities then the wake will be formed much earlier on the trailing edge and as a result the wake will be larger.

Therefore it is evident that to reduce the size of the wake, the body should be a more streamlined shape so that the pressure rises more gradually and the separation point is as close to the tail as possible. The size of the turbulent wake not only has an impact on the sound generated by the body moving through the water, but affects the amount of form drag on a body – typically the larger the wake, the greater the pressure difference between the upstream and downstream conditions and the greater the form drag. It follows that for a lower form drag profile the form of the body must be as streamlined as possible so that the size of the wake is reduced.

3.3.3 Interference Drag

Interference drag arises when two bodies (e.g. bridge fin and casing) join together, which disrupts the flow around the entire body. There is less physical space for the fluid flowing around the body to go and this creates a bigger force than that would be created if the two bodies were considered separately. This can be reduced by making the transition from one body to the other as smooth as possible.

3.4 Flow around a Body

To understand how drag affects a submarine it is essential to understand in more detail how flow around an immersed body works. This section will develop ideas from the previous section and explain the difference between laminar and turbulent flow, describe separations from the body, introduce the Reynolds number, and present the perfect shape for a body in a flow system.

3.4.1 Laminar and Turbulent Flow

There are two main flow regimes in fluid dynamics – **laminar** flow, and **turbulent** flow. Studying these types of flow allows you to estimate the drag forces acting on a body and model flow in a way which allows you to predict the design of a body shape which will yield the lowest drag and create the least noise.

Laminar Flow

Laminar flow occurs at low velocities, or low Reynolds numbers, (see section 3.4.4) and is characterised by the parallel flow of the fluid in uniform layers, with no disruption between the layers. The motion of the particles is very orderly as layers slide over each other easily and without disturbance. It is a flow regime with high momentum diffusion and low momentum convection, and occurs before turbulent flow. Although laminar flow would be beneficial for DR, it is not often possible to have perfect laminar flows over large bodies travelling at relatively high velocities.

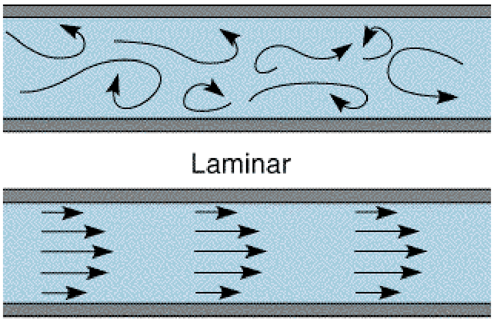


Fig. 4 Laminar and Turbulent Flow

Turbulent Flow

As laminar flow becomes less orderly it first enters a transitional stage then becomes turbulent flow. Turbulent flow is a flow regime characterised by chaotic property changes and as a result has low momentum diffusion, high momentum convection, and rapid changes in velocity and pressure. It occurs at high Reynolds numbers (approximately Re > 4000) and on large bodies such as a submarine the transition to turbulent flow in the boundary layer occurs very close to the leading edge. Turbulent flow is found in the wake of a submarine and consists of swirling fluid flows known as 'vortices'.

3.4.2 Boundary Layer Separation

This occurs when a portion of the boundary layer closest to the leading edge reverses its direction [6]. It is caused by the friction of between the fluid and the body and the loss of energy of the fluid, and causes the boundary layer to thicken and be forced off due to the reversed flow direction near the surface.

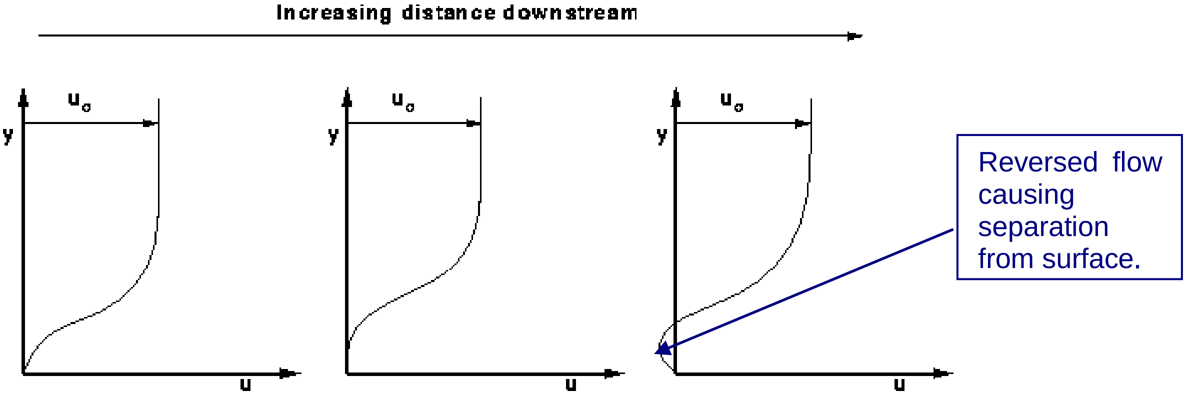


Fig. 5 Graphical Representation of Flow Separation

3.4.3 Flow Separation

This boundary layer separation can be one of the causes of flow separation which causes a wake to form behind the body. For it to happen, an adverse pressure gradient must also build up so that the fluid becomes detached and forms eddies and vortices.

This separation, as mentioned earlier, is bad for the hydrodynamics of the body and increases the form drag. This is an important factor in submarine hydrodynamics and therefore there has been a lot of research into the best design of exterior surfaces which delay the flow separation when the velocity of the body increases.

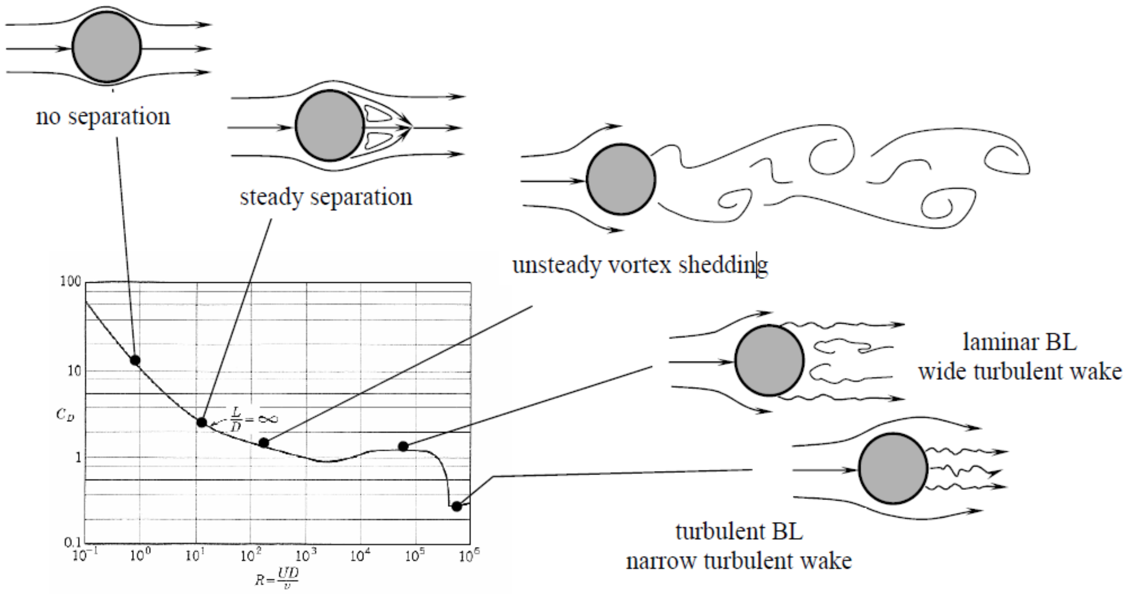


Fig. 6 How a Change in Reynolds Numbers affects the Coefficient of Drag

One of the ways to predict the local flow conditions is to calculate a value known as the Reynolds number (see below).

3.4.4 Reynolds Number

One of the most important numbers in fluid dynamics is known as the Reynolds number (Re). It is a dimensionless number that gives a measure of the ratio of **inertial** forces to **viscous** forces. Consequently, it can be used to distinguish the types of flow regimes that can lead to turbulent and laminar flow. Typically laminar flow occurs at **Re < 2300** and turbulent flow occurs at **Re > 4000**. Transitional flow can occur between these two values where the flow can be either partly laminar or partly turbulent.

The Reynolds number is critical for working out the amount of drag because the coefficient of drag (C_d) which is used in the drag equation is a function of the Reynolds number.

The concept was introduced by George Gabriel Stokes in 1851, but the Reynolds number is named after Osborne Reynolds, who popularised its use in 1883 [7].

The Reynolds number is defined as:

$$\mathrm{Re} = \frac{F_i}{F_v} = \frac{\rho V L}{\mu} = \frac{VL}{\nu}$$

Where:

F_i is the inertial forces **(N)**

F_v is the viscous forces **(N)**

L is the characteristic linear dimension (travelled length of the water) (**m**). For spheres, cylinders and discs, L is the diameter.

μ, the dynamic viscosity **(kg/m·s)** and ρ, the density **(kg/m³)** will be constants and they are set by the sea water through which the submarine will move.

V is the velocity of the body. (**m/s**)

ν is the kinematic viscosity. $\nu = \frac{\mu}{\rho}$ **(m²/s)**

3.4.5 Length-to-Diameter Ratio

The length-to-diameter ratio, also known as the **fineness ratio**, has a big impact on total drag on a submarine. Because a greater surface area of the body will provide a greater skin friction force, a shorter, fatter shape is better than a long thin shape of the same volume. However this shorter shape will not be as streamlined, and may create more form drag. Additionally the diameter of the hull is also determined by the decks and equipment stored inside the hull so a longer thinner shape may not be practicable.

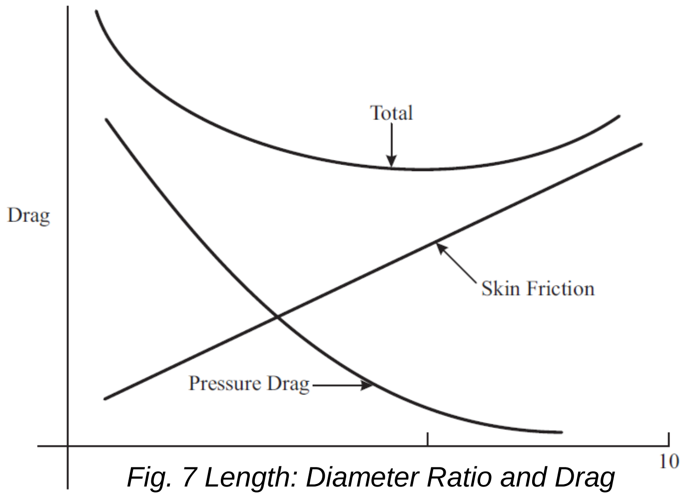


Fig. 7 Length: Diameter Ratio and Drag

The fineness ratio can be used to design a body shape that best reduces the drag. It is shown in Fig. 7 that a **L:D ratio of about 6** is ideal for reducing the total drag coefficient to a minimum. Also, a **teardrop-shaped hull** is widely considered to be the best shape for DR, although the constraints of the layout of the internal structures means this shape may not be practicable and so a compromise must be made.

4. Modelling Drag on a Submarine

Now that the principles of drag in a general sense have been established, we can look at how drag affects a large, complex body such as a submarine and how it is possible to model this. This section will give details of the current modelling system used, give a brief description of the processes that are followed when setting up this model, explains how Mathematics is used to model drag and to improve hull designs, and compare the model to any real life testing.

4.1 Background on Modelling Drag on Submarines

Modelling fluid flows around a system as large and as complex as a submarine would be a daunting task if it were not for Computational Fluid Dynamics (CFD) software and Computer Aided Drafting (CAD) programs. Even with the help of a supercomputer with simulation software, it is not an easy task to predict the flow around the body and thus determine the drag forces, but at the moment models are very similar to the actual physical processes taking place. A computer simulation of a submarine hull can substitute time-consuming and costly testing in a water tunnel. Over the past decade or so, a computer code based on the Finite Element Analysis (FEA) method which relies on the velocity-pressure formulation of the incompressible Navier-Stokes equations has been developed.

There are many different types of software currently used by different countries around the world. In the UK, BAE Systems have been using a product called ‘Paramarine’ developed by QinetiQ GRC for over 10 years. Paramarine is the world's only fully integrated Naval Architecture Design and Analysis product that can handle the complexities of submarine design [8]. Paramarine uses a functionally building block approach for submarine design, starting with a handful of blocks, and building up to a complex model of several hundred.

<u>Mathematics behind the model</u>

Paramarine and other programs which incorporate CFD are built upon lines of code and mathematical equations. Although the complexities of the different codes and equations used are beyond the scope of this project, there are some basic formulas which you must be aware of and are used in CFD. The first general equation is known as the ‘drag equation’ and is defined as:

$$F_d = \tfrac{1}{2}\rho v^2 C_d A$$

Where: F_d is the force of drag

ρ is the density of the fluid

v is the relative velocity of the body

C_d is the drag coefficient

A is the reference area

The drag equation is a practical formula used to calculate the force of drag experienced by a body due to movement through a fully enclosing fluid.

The next equation is the 'drag coefficient'. It is a rearrangement of the previous equation and is calculated in the following way:

$$C_d = \frac{F_d}{\frac{1}{2}\rho A V^2}$$

C_d is a dimensionless quantity that is used to quantify the resistance of a body in a fluid environment. It is used in the drag equation, where a lower drag coefficient indicates the body will have less hydrodynamic drag.

Another formula used is the 'ITTC 1957 Model-Ship Correction Line Formula':

$$C_F = \frac{0.075}{\left(Log_{10}\,\mathrm{Re} - 2\right)^2}$$

In addition to these formulas the 'Reynolds Averaged Navier-Stokes (RANS) Equations', and 'Bernoulli's Equation' are also used.

4.2 Method

Although in an in-depth procedure for modelling drag using CFD software is outside of the scope of my project, this section will provide an overview of the methods involved.

To look at separate elements in a high amount of detail, a tetrahedral mesh system is build up around the submarine structure. The more detailed the geometry, the finer the mesh should be to resolve it. Conversely the complexity of the mesh should be reduced in areas of little change such as free stream flow. The flow around the casing is more important to model accurately than flow at the edge of the domain; therefore the mesh will be very fine near the submarine surface and will get coarser as you move away from the body. Fig. 8 shows a constructed mesh over the exterior of a submarine.

For visualisation a colour plot is generated and this can show the pressure distribution around the submarine. As pressure on the casing is related to the forces acting on the body, this can prove useful for determining the drag forces in different places. Fig. 9 shows how this visualisation can show the regions of high and low pressure surrounding a submarine.

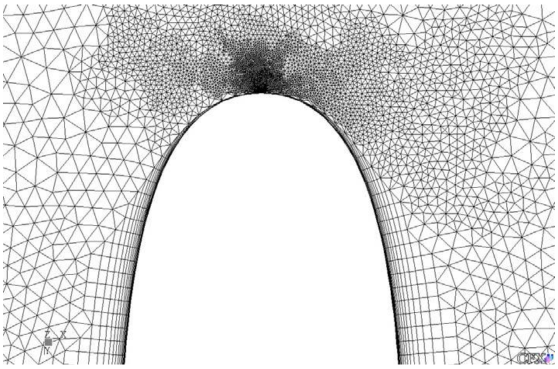


Fig. 8 Finite element mesh consisting of many tetrahedral elements

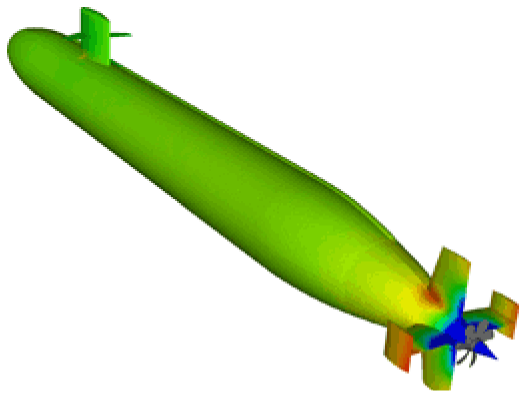


Fig. 9 Pressure distribution around a submarine

5. Design Changes to Reduce Drag

This section will present possible changes to the design of the hull and casing which could be implemented for use in future submarine designs. It will consider the function of current external structures and control surfaces, and suggest how their geometries, and the geometry of the entire casing, could be changed for the purpose of DR. New technologies for reducing drag will be considered and assessed in terms of practicality and ease of development.

5.1 Redesigning of External Structures

The design of the outer structures which come into contact with the water is crucial for DR. In an ideal world the surface of the submarine would be free from any protrusions and as a result would be much more hydrodynamic. However this is just not possible as structures such as the bridge fin, propulsor, arrays, and control surfaces are fundamental features on a submarine, allowing it to navigate and sense other vessels. It is, however, possible to modify the shape and placement of these structures in order to reduce the drag as much as is feasible. This area of study is fascinating and very important because there is no ‘perfect’ design for a submarine which incorporates all of these features yet and therefore there is scope for new designs which compliment the purpose of the submarine.

Current General Structure of a Submarine

As you would expect, naval architects already spend a lot of effort refining the designs of the exterior structures so that DR is maximised. Below are main features found on most current submarines and a brief description of their location and function.

- ***Pressure hull*** – Reinforced cylinder with domed ends designed to withstand the immense underwater sea pressures and maintain normal atmospheric pressure inside, allowing the crew to operate at low depths.
- ***Casing*** – The outer ‘shell’ of the submarine. Built up around the pressure hull, this steel structure is free-flooded and streamlines the submarine as much as possible whilst providing a suitable platform for personnel to walk on. This structure is also covered in acoustic tiling.
- ***Bow*** – The bow houses the bow array sonar for the submarine, which is used to detect noise in the surrounding environment in the front. The underside of the bow is where the passive hydrophones are located.
- ***Control surfaces*** – Hydroplanes (situated at the bow, aft end, and sometimes on the bridge fin) and the rudder (situated at the aft end of the submarine near the propulsion system). These structures are controllable and allow the submarine to manoeuvre.
- ***Bridge fin*** – Tower-like structure found on the upside of the submarine. It houses the conning tower, optronics masts (periscopes), radar and communications masts.
- ***Propulsion system*** – Situated at the back of the submarine. Nuclear-powered submarines include a nuclear reactor coupled with a propulsor. The nuclear reactor generates heat which creates steam to power the generators. Older submarines use diesel electric systems and propellers.
- ***Arrays –*** Located on the bow (bow array), flank (flank array), and can also be towed (towed array). They contain hydrophones and detect signals from outside the submarine creating a full envelope allowing the submarine to detect sound signals coming from any angle.

- ***Pylon*** – Structure on the upside of the submarine used for active sonar.
- ***Ballast Tanks*** – Tanks that can be flooded with water helping the submarine remain neutrally buoyant and allowing it to dive.

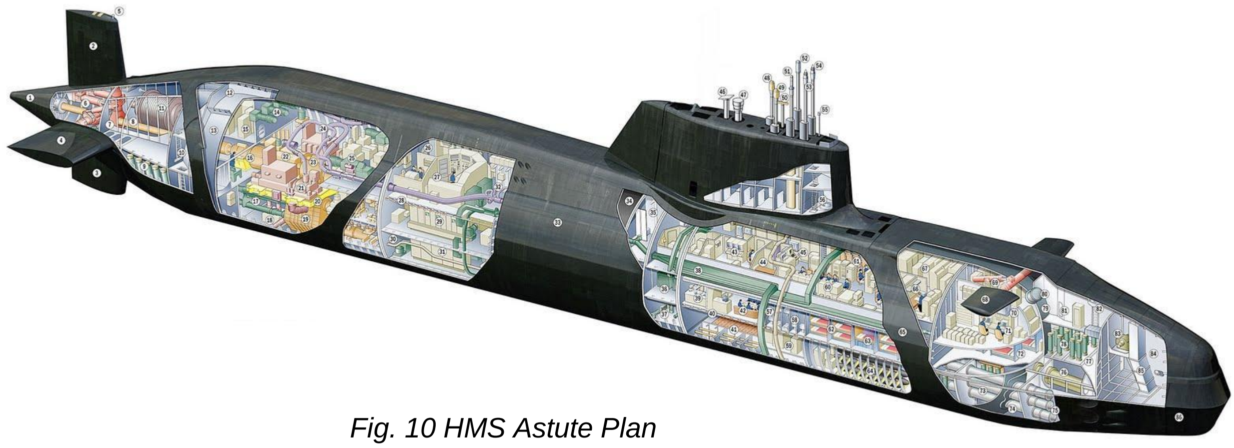


Fig. 10 HMS Astute Plan

<u>Possible Redesigning of External Structures</u>

5.1.1 Bow

The bow geometry is possibly the most important feature to get right when aiming for as much DR as possible. It is the surface which first comes into contact with the free stream and therefore its properties determine the types of flow regime that occur over the leading edge of the submarine.

It is important that the flow over the fore section which houses the bow array be as ideal as possible. The forward sonar must be able to receive clear signals without interference noise from turbulent flow regimes whilst the submarine is moving at speed. Therefore the flow noise must be kept to a minimum, with laminar flow if possible. Although noise is the main driver for a hydrodynamically designed bow, drag will also be reduced if the flow is more laminar.

In terms of the geometry of the bow, it is known that a bow shape with a highly curved forehead over the bow array can cause cavitation when at speed which would mask incoming signals. It is important that the bow shape is designed to encourage low and uniformly distributed local velocities in the vicinity of the hydrophone windows. The shape of the bow should be blunt, which reduces coefficient of friction, but not so blunt that at high velocities the local adverse pressure gradients are large and there is high skin friction.

An asymmetrical bow shape can create a pressure distribution along a line over the casing which is different to a line over the circular cross-section. This can lead to streamlines not flowing symmetrical which can cause vortices to form. The casing cross-section should be like a circular cross-section without a longitudinal valley that would create vortices.

Acoustic tiling is often fitted to submarines to reduce the reflected waves from an incident ping and therefore make the submarine less easily detectable. However if these tiles are fitted to the bow, laminar flow becomes impossible due to the many edges which would create turbulent boundary layer conditions.

To combat this effect it is possible that the bow could be cast in one piece including the acoustic tiling therefore removing any edges which would stimulate turbulent flow.

5.1.2 Control Surfaces

Many vessels use fore and aft hydroplanes and a rudder to control the movement of the submarines. The hydroplanes can be adjusted to control the depth and allow the submarine to maintain neutral buoyancy. For lateral control, the rudder can be adjusted. The bottom blade of the rudder is normally shorter than the top to allow the submarine to rest on the sea bed (bottoming).

However, the problem with these control surfaces is that they create drag, noise, and in the case of fore hydroplanes, may need to be retracted when berthing. They are shaped to cut through the water as smoothly as possible but still can create interference drag and disrupt the flow field around the vessel leading to vortices.

A possible adjustment to the design of the control surfaces would be to introduce an X-plane (or X-rudder) control surface. An X-plane control system would be situated at the back of the vessel and has been used on vessels such as the USS Albacore and the Australian Collins class submarines.

Advantages of X-plane control surfaces	Disadvantages of X-plane control surfaces
Tighter turning circle and better manoeuvrability for small vessels than the conventional cruciform arrangement.	Controlling the planes is a complex task and so would require a computer. In the event of a malfunction, manual control would be more difficult than current control systems.
X-plane submarines can be designed with smaller control surfaces reducing the manufacturing costs.	Building the system would be more complex as it involves 4 independent planes all controlled in a small space.
The size of the planes and the placement at the back means that drag and noise are reduced.	

Table 1. Advantages and Disadvantages of the X-plane system of control

5.1.3 Bridge fin

The bridge fin (or sail) is generally the largest exterior structure on a submarine. In the past, the location of the bridge fin has been determined by through-hull penetration masts such as periscopes which could only be located in specific areas of the submarine [9]. However due to the replacement of the periscope with the photonics system and new technology allowing non hull-penetrating masts to become a possibility, this is no longer the case. Therefore the placement of the bridge fin can become a factor in DR design.

The drag of a large structure such as the bridge fin may be between 15-30% of the bare hull drag, however simply reducing the size of the fin would not be an option due to the loss of important masts. It is suggested that the bridge fin would suffer less interference drag if it is placed on the fore part of the main body, in front of the maximum diameter.

As well as placement, the height and the width of the sail should also be considered. A thinner bridge fin would be beneficial because of the reduced risk of flow separation. Additionally a shorter shape is favoured because a tall fin will affect the centre of mass of the submarine and could cause it to roll.

A further feature of the design to be considered is the shape of the bridge fin where it meets the casing. Any sharp discontinuities should be avoided and the fin should merge slowly into the casing so that no adverse pressure gradients can build up and result in a vortex being generated.

5.1.4 Flank array

The flank array is essentially a rectangular box containing hydrophones situated on the side of the vessel, and due to its length can contribute to the total drag. It protrudes from the side of the submarine but is tapered at every edge so that form drag is reduced. This design is effective, however future designers may want to consider implanting the flank array inside of the casing so that it does not protrude from the submarine surface at all.

5.1.5 Pylon

The pylon is the site for active sonar transmission and on submarines such as HMS Astute is found in front of the bridge fin. At present, the shape of the pylon is optimised and would not require many adjustments. However if it could be designed to be retractable, this would lower the interference drag when the active sonar is not required.

5.1.6 Body Curvature

A fusiform shape, tapered at both ends, is common on most modern submarines. However, if in the future a design similar to the ideal teardrop shape could become practicable, DR would benefit as a consequence. A problem with this sort of design is that the strongest shape for the pressure hull, which allows long decks to be constructed, is cylindrical. This mismatch between the pressure hull shape and the casing shape often results in a compromise where the casing is made to fit around the inner hull whilst retaining an elongated teardrop shape. If a strong pressure hull tending more towards the shape of a teardrop could be manufactured easily, then drag could be lowered.

5.1.7 Reducing the Drag Effect of Gaps in Submarine Casing

With a structure as complex as a submarine, gaps and ridges in the submarine casing are inevitable. Although they may be small, the sheer number of them and distribution over a large part of the surface means they can contribute significantly to the total skin friction.

To combat this effect, fluctuations in the casing before the gap could be manufactured to encourage the flow around these gaps and therefore reduce the chance of turbulent transition. The water could be guided around the gaps so that there is a reduced risk of drag from the exposed ridge or gap.

5.2 Drag Reduction Technologies

There are many radical new DR technologies being developed and some may prove useable for future vessels. Inspiration for techniques often comes from observing nature since sea creatures such as sharks, dolphins and fast swimming fish have been evolving, perfecting their designs, for millions of years. New ideas have also come from the development and understanding of man-made chemicals and scientific methods for manipulating flow. Over the past few decades extensive research has been conducted to develop DR techniques to use on submarines. However, due to the secret nature of the work there are few detailed resources in the public domain.

The main current technologies will be described and I will evaluate their likely effectiveness in reducing drag and the feasibility of using them, including any practical problems or detrimental effects they may have on a submarine's performance.

5.2.1 Polymer Addition

Pumping diluted polymer solutions around the surface of a submarine seems at the moment one of the most promising areas of study for DR. In testing it has been shown to achieve up to 80% DR with only a few parts per million of polymer [10]. Some typical polymer drag reducing solutions are shown in Table 2.

Water-soluble polymers	**Solvent-soluble polymers**
Poly(ethylene oxide)	Polyisobutylene
Polyacrylamide	Polystyrene
Guar gum	Poly(methyl methacrylate)
Xanthan gum	Polydimethylsiloxane
Carboxymethyl cellulose Hydroxyethyl cellulose	Poly(cis-isoprene)

Table 2. Drag reducing polymer solutions Source: DSTO

Experiments have shown that polymers with a molecular weight below 100,000 seem to be ineffective in reducing drag. The longer the polymer chain, the more chance of interaction with the flow and the greater the DR therefore polymers with a long linear structure, such as poly(ethylene oxide) and polyacrylamide, are beneficial. Biopolymers and polysaccharides produced by living organisms can be effective for DR and not harmful to the marine environment.

There are many different theories explaining how the polymers interact with the flow to reduce drag. One such theory seems to suggest that the polymer hydrodynamic structure disrupts the eddies and micro-vortices that are characteristic of turbulent flow leading to a more laminar flow regime. It is possible that there is many different DR processes happening and more research into this area is needed to provide a more definitive theory. This method is also believed to reduce the radiated noise generated by the propulsor.

<u>Method for distribution</u>

The best way this technology can be used on a submarine is to eject the polymer at or near the area of minimum pressure in the bow section of the submarine. This could be achieved by pumping polymers from a chamber through a system of pipes and then out through radially spaced ports on the casing in order to distribute the solution at the area of minimum pressure where the fluid is reaching its maximum velocity. The ejection of the polymer as the submarine travels through the water causes it to stream along the surface of the submarine which has a salutary effect on the quiet running of the vessel [10].

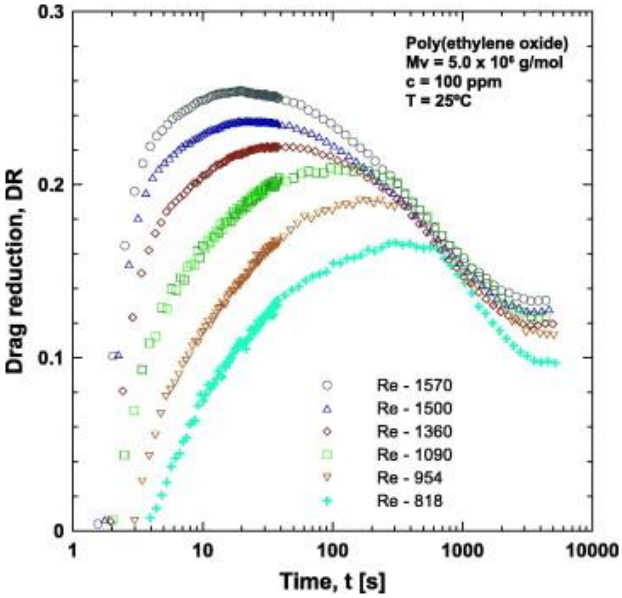


Fig. 11 Effect of changing Reynolds numbers for poly(ethylene oxide) on DR

Details such as the amount of polymer required to be carried and the effect of the substance on marine life would have to be considered for a method such as this. Limited space inside the casing might mean that lower volumes of polymer would need to be carried. A pressurised mixing chamber would also be required and the sound produced by this method would have to be taken into account. However research showing that very small amounts of polymer would be needed to produce a respectable DR is promising for the development and use of this technology in the future.

5.2.2 Micro-bubbles

The ejection of micro-bubbles from an upstream position on a submarine to delay the transition from laminar to turbulent flow is a very similar process to polymer ejection. The main difference is that gas, not a liquid, would be pumped out around the vessel and so detrimental effects on marine life would be lowered. As well as being non-pollutant, micro-bubbles would also be a cheaper option for DR. Although a layer of air next to the surface in water reduces turbulent skin friction, it is important to get the angle of trajectory right. One downside to micro-bubble injection is that they may cause cavitation if not properly introduced.

The size of the bubbles is obviously an important parameter in this technology. Measurements of bubble sizes show that size decreases when free stream velocity is increased but this has very little dependence on the injection procedure. Research from Merkle and Deutsch showed that the bubble sizes (500-1200μm) are best for interaction with the boundary layer [9].Possibilities for controlling the size and trajectories of micro-bubbles remains an important topic and in need of further research.

<u>Hybrid Method</u>

Another possibility is a hybrid method combining both micro-bubble and polymer technology. There is a suggestion that bubbles may promote the elongation of polymer chains or that polymers increase the concentration of small bubbles next to the wall. Polymers can also prevent bubbles coalescing and increasing in size. The synergy of these two techniques may produce DR exceeding that of only air or only polymer injections.

5.2.3 Supercavitation

Supercavitation is a topic mainly associated with the development of faster torpedoes through DR, but could possibly be implemented into submarine design.

How it works:

Supercavitation is the use of cavitation effects to create a bubble of gas inside a liquid large enough to encompass an object travelling through the liquid. Whereas normal cavitation is avoided on submarines, supercavitation greatly reduces the skin friction drag on the object and therefore the maximum velocity can be increased. When the nose of the object is shaped correctly it creates a lot of drag but also accelerates the water through very fast speeds. This causes a loss in pressure and the water vaporises into bubbles which surround the object. This technology has already been shown to work on underwater weapons such as the Barracuda or VA-111 Shkval rocket.

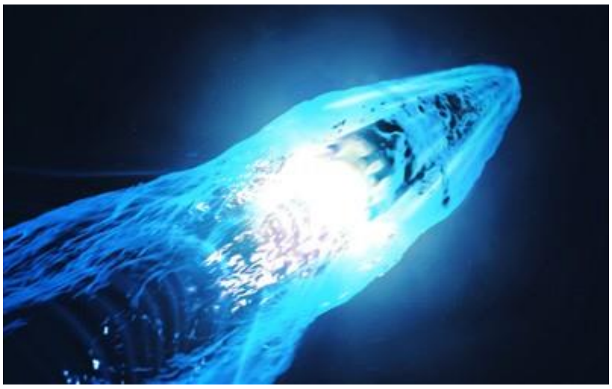


Fig. 12 Supercavitation

<u>Application to submarines</u>

By purposely vaporising as much water as possible a submarine could potentially create a bubble so large that it encompasses the whole structure and massively reduces drag, allowing the submarine to travel up to speeds of 100 knots. The main downside to this technology is that it creates a lot of noise and therefore may only be suitable in situations where stealth is not essential. Also, in order to create the bubble the submarine would need to first be propelled to quite a high speed. Therefore this technology could be implemented for fast escapes rather than constant use. Designs for the bow would be inherently drag producing, and so could possibly be combined with a changeable casing for when the submarine was cruising at normal speeds.

One other problem is that whilst supercavitating it may be hard to navigate and therefore further research must be done into this field before the technology could become a possibility. However, supercavitation is considered a serious enough possibility for DARPA to launch a research study entitled 'Underwater Express program' looking into the use for transporting small groups of navy personnel at high speed. DARPA announced in 2009 that a current one quarter scale model is being trialled and if successful they will commence building a full scale prototype.

Fig. 13 Super fast supercavitating submarines of the distant future

5.2.4 Flexible/Changeable Outer Casing

Just as dolphins wrinkle their skin to allow them to glide through the water, submarines could also be fitted with an undulating surface to reduce drag.

Dolphins induce their skin to wrinkle so that water does not stick to them. If this can be applied to submarines, the active skin must assume the shape of the ideal ordered surface wave it is trying to create, something that changes at different velocities [12]. Although this is a technically demanding task to get right, it could pay off with up to 50% reduction in drag.

One way to produce this effect would be to use ‘piezoceramic legs’ just beneath the surface which could be manipulated under the influence of an electromagnetic field. It may be hard to implement this onto the entire surface but even a small amount of strategically placed corrugated skin could yield a worthwhile amount of DR.

5.2.5 Electromagnetic Turbulence Control (EMTC)

The US navy are conducting research on EMTC for use on future nuclear-powered attack submarines. EMTC is based on the principle of creating electromagnetic forces due to an electromagnetic field. This force acts on the conducting fluid (sea water) to produce a DR effect.

EMTC panels or fabrics could be placed on the surface of the submarine to prevent the start of turbulent conditions. At the moment, research into this field is at an early stage, but it proves to be a promising technology for reducing drag when becomes fully understood.

5.2.6 Rotating Submarine

A very extreme change to the current submarine design would be a rotating submarine. If somehow the bow and aft sections of the vessel could rotate, with grooves cut in the flank, whilst the middle section housing the bridge fin and hydroplanes could remain stationary, the vessel may be able to propel itself using a ‘corkscrew’ motion. At present I have not come across any designs for this type of structure but it is a possibility and it is worth considering if the design would be feasible.

6. Summary

6.1 Evaluations

There are many methods for reducing drag mentioned in this report; however there are some to which more consideration should be given. A change to the bow geometry is certainly an area to look at in more detail, since it is important to get the right flow conditions over the bow sonar. Ideas such as; casting the entire bow section in one piece, containing the acoustic material, in order to provide a surface free from joins, are definitely worth considering. The move towards an X-plane control system is an idea that would increase manoeuvrability and reduce drag if the complexities in setup and manual control can be managed. Future design plans should emphasise the need to streamline exterior structures such as the bridge fin and flank array, merging them seamlessly into the casing, in order to reduce interference drag. Small structures which protrude should be made retractable if possible and the drag effect of any gaps or ridges could be minimised by placement of structures in front to distort the flow.

In terms of new technology, polymer and micro-bubble addition appear to be very useful in reducing not only the drag, but the acoustic signature of the submarine. How this technology could work on the large scale needs further research. Whilst polymers are capable of large DR, their storage on the submarine, the method of ejection and effect on marine life are all considerations which must be addressed. The cheaper and non-pollutant method similar to polymer addition is micro-bubble addition. Micro-bubble addition, however still presents problems which need to be addressed – primarily getting the size and trajectory perfect without causing any cavitation. A more radical, but nonetheless possible, solution to DR is supercavitation, which has already been shown to be effective on torpedoes. If supercavitation can be utilised for use on submarines then it would reduce drag enormously but at the cost of a very loud signature being emitted. Changeable casings and EMTC are promising ideas which, with a bit more testing, could soon be contenders for DR techniques used on new vessels.

Many of these new technologies may seem impractical now but in 15-30 years, when the next class of submarines are being designed, problems with the design could be easily overcome due to advances in science and engineering.

6.2 Conclusion

Drag reduction is a crucial factor to consider in submarine hull design, primarily to reduce costs associated with powering the submarine and also to improve manoeuvrability. A number of ideas have been discussed to modify the hull geometry, such as evolving the design of the hull closer to that of a tear drop shape, and also the introduction of X-planes. In addition, new technologies such as polymer and micro-bubble injection have been identified as potential systems to reduce drag.

6.3 Further Research

There are some techniques for reducing drag which I have not had enough time to go into detail in when writing this report. But further research on the following topics may prove helpful when designing a submarine that has a minimal drag profile;

Riblets and Scales: Sharks have small riblets like projections on their skin allowing them to reduce drag. These grooves have already proven useful in DR in swimsuit and boat technology and should be utilised for submarines.

Metamaterial Mesh: A mesh that can be placed on the aft section of the submarine and calibrated to manipulate the flow field so that no wake is produced. This could potentially make the submarine invisible and reduce drag at the same time.

Surfactants: Compounds similar to polymers which reduce the surface tension of the water which could reduce drag.

Dimples: A coating of shell constructed to be dimpled (similar to the dimples on a golf ball) and discourage turbulent flow in the boundary layer.

7. Acknowledgements

I would like to thank the following people and organisations for their help in making this research project possible:

The Nuffield Foundation and Judith Wardlaw for their help in guiding me through the application process and securing me a placement.

Edward Stamp, Colin Utting and Nicholas Thomas of BAE Systems Maritime - Submarines in Weymouth, for being the project providers and mentoring me throughout my time working on the project.

John Salisbury, Mike Biddell, and the people at the Advanced Technology Centre in Filton, for discussing aspects of my project with me and giving me insight into topics related to drag from an expert's perspective.

Mandy Samuel, Andy Holmes-Evans, Scott Wilson, and all other employees at BAE Systems Maritime - Submarines, for welcoming me to the site and answering any questions I might have had.

Without their effort, the completion of the project would not have been possible.