Applications of Theoretical Fluid Dynamics on Ship Drag Reduction and Control

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Abstract—Shipping accounted for 3.3% of global CO$_2$ emissions in 2007. A growing consumer dependency on oil and products manufactured in Asia means this figure is rising. A good knowledge of the factors affecting the economy of the shipping industry is therefore important and fluid dynamics dictates one of these factors: drag. The paper concludes with a consideration of the applications and implications of the theory discussed.

Introduction

The improvement of the efficiency of ships has been progressive for thousands of years. In the 18$^{th}$ century Froude gave us reliable laws to calculate resistance on ships, increasing their efficiency further. Further developments in efficiency are still being made.

This paper begins with the fundamental derivation of the parameters relating to drag on a ship. Section II considers the different mechanisms of this drag and section III looks at established and progressive methods of controlling and reducing drag by modification of form, surface type and fluid phase. Section IV discusses similarity and the calculation of the drag on a hull and section V briefly covers the impact of the knowledge gained through sections I-IV.

I. Parameters Relating to Drag

An assumption is made that the resistance to motion $F$, of a floating object such a ship will be dependent upon speed $V$, characteristic length $l$, density of the fluid $\rho$, dynamic viscosity of the fluid $\mu$, and acceleration due to gravity, $g$. The variables consider that drag will be a result of both viscous and gravitational forces. The general solution takes the form

$$ F = f(V, l, \rho, \mu, g). $$

Dimensional analysis via the group method can be used in this case and the Buckingham $\pi$ method can be used to generate a number of dimensionless groups. The number of dimensionless groups formed from $n$ variables in $m$ dimensions is given by $n-m$ and is therefore 3, since $n = 6$ and $m = 3$. There will also exist 3 repeating variables, $V$, $l$ and $\rho$ which will be present in each dimensionless groups. Thus the solution will take the form

$$ \pi_1 = f(\pi_2, \pi_3). $$

Dimensional analysis, the full derivation of which is detailed in Douglas [5, p. 277], yields the dimensionless group expression

$$ \frac{F}{0.5\rho V^2 l^2} = \phi \left( \frac{Vl}{\mu}, \frac{V}{\sqrt{gl}} \right), $$

which is recognisable as the coefficient of drag, Reynolds number and Froude number [5].

II. Drag Mechanisms Acting on a Hull

Different drag mechanisms contribute to the overall drag acting on a submerged body. Skin friction drag, form (pressure) drag, and wave-making resistance are considered in this section. Pressure drag and skin friction depend upon the state of the boundary layer. A qualitative understanding of boundary layer theory is assumed for this section. Schlichting and Gersten’s [12] ‘Boundary Layer Theory, 8th ed.’ is recommended for further reading into this topic.

A. Skin Friction Drag

Skin friction is experienced where there is laminar or turbulent flow across the hull. Blasius is responsible for a set of analytical solutions for detached laminar-flow boundary layers, detailed in Douglas [5, p. 380]. Integrating shear stress at a surface over a length $l$, yields the skin friction force, expressed as

$$ F = 0.5\rho V^2 A C_f, $$

where $V$ is flow velocity, $A$ is area and $C_f$ is the coefficient of drag, which Blasius showed to take the value

$$ C_f(\text{laminar}) = 1.33Re_x^{-0.5} $$

in laminar flows. In practice, the transition from laminar to turbulent flow across the body of a ship occurs abruptly and rather early. Hull roughness, free stream disturbances, vibrations from the engines and curvature all contribute to the initiation of turbulent flow, at which point the skin friction coefficient can be approximated by

$$ C_f(\text{turbulent}) = 0.074Re_x^{-0.2}, $$

for $5 \times 10^5 < Re_x < 10^7$. It is apparent then that laminar flow is preferred for drag reduction. An engineering critical Reynolds number of $Re_{x,cr} = 5 \times 10^5$ is often used as a means by which to determine if the flow is laminar, ie. $Re_x < Re_{x,cr}$ or turbulent $Re_x > Re_{x,cr}$ at a given point $x$ along the body surface. [3] A ship with a smooth hull moving at 10ms$^{-1}$ in
5°C water, of kinematic viscosity $1.519 \times 10^{-6} \text{m}^2\text{s}^{-1}$ will see a transition to turbulent flow after just 75mm, and therefore a ship’s hull is dominated by turbulent flow over most of its length.

B. Form Drag

Flow separation from a body occurs when an adverse pressure gradient produces a flow reversal, as depicted in figure 1. This occurs near the rear of the body and the discontinuity of the solid body and flow separation as a result leads to highly turbulent large scale eddies, as shown in figure 1. Energy is dissipated in this area of turbulence and pressure in the wake reduces, creating a situation whereby the pressure at the front of the body is greater than that at the rear. The pressure difference gives rise to a resultant force which resists motion, form drag.

As skin friction drag is calculated by integrating shear stress over the surface, so is form drag obtained by integrating pressure over the surface of the body. As Douglas [5] notes, whilst both contributions to drag can be theoretically calculated, it is a length endeavour, as the pressure distribution around the entire body must be known.

C. Wave-making Resistance

As a ship moves in water, waves are produced, originating from the bow and the stern of the ship and diverging away from the sides of the hull. The ship must therefore overcome skin friction and form drag as well as the resistance caused in generating waves. As Douglas [5] notes, it is not possible to measure wave making resistance directly and so it is typical to obtain a value of wave-making resistance by subtracting the calculated skin friction value from that of the experimentally discerned total drag.

It will be remembered from section I that dimensional analysis yields a prediction that friction drag will relate to Reynolds number and that the wave making resistance of a ship will depend upon the Froude number. Dimensional analysis, as shown in Douglas [5, p. 403], can provide an expression for the velocity of propagation of surface waves $c$, given by

$$c = \sqrt{gL\phi \left( \frac{d}{L} \frac{h}{L} \right)},$$

where $L$ is the waveform wavelength, $h$ is the height of the waves and $d$ is the depth of the water. For ships, it is expected that the ratio $h/L$ is small and $d >> L$. It can also be shown by experimentation that the velocity of propagating surface waves is equal to the velocity of the ship, thus the equation reduces to

$$v = c = \sqrt{gL \frac{2\pi}{L}}.$$  \hspace{1cm} (8)

Equating the Froude number equation, derived in equation (3) with equation (8), the Froude number can be expressed

$$Fr = 0.4 \sqrt{\frac{L}{L}}.$$  \hspace{1cm} (9)

Therefore the Froude number describes completely the relationship between the ship’s length and the wavelength it produces. For dynamic similarity, the Froude number must be the same for both the model and the full size ship.

III. CONTROLLING DRAG

The logistical network supported by shipping is so vast that international shipping contributed to 3.3% of global CO$_2$ emissions in 2007, with emissions expected to grow 4% each year [1]. It is of extreme importance, then to reduce the energy requirement to drive ships from both an environmental and economic standpoint. Reduction of drag is an effective means by which to do this. This section details a review of methods to achieve drag reduction.

A. Streamlining

Total drag reduction can be achieved by streamlining a body: reducing the flow separation from the body reduces pressure drag. Conversely, however, streamlining has the opposite effect on friction drag forces, owing to the fact that streamlining, in most cases, increases the surface area of the body.

Consider the CFD generated cut plots in figure 2. The bluff body experiences a large pressure difference and thus form or pressure drag effects are large. A significant reduction in pressure drag effects can be observed after streamlining, indicated by the smaller pressure between the front and the rear of the body. Friction forces will, as mentioned, will be enhanced on the streamlined body, however.

In any optimisation study, the reduction of total drag must therefore consider effects of skin friction and form drag and attempt to minimise the sum of the two factors. [3]
B. Modification of surface properties

A widely used method of drag reduction is to modify the physical features of the surface in contact with fluid flow. It has been shown that turbulent flow will be the dominant flow characteristic across the hull of a ship and thus a smoother surface may be used in order to reduce the turbulence of the flow and hence skin friction. An entirely smooth hull has implications for biofouling growth, however.

Superhydrophobic surface treatment, resulting in a surface that cannot be wetted, has been shown to be effective for drag reduction, interestingly, particularly for turbulent flows. [11]

Biomimicry is yet another area of interest in drag reduction research. Some animals skin exhibits remarkably low skin friction characteristics. Some species of sharks feature small ‘riblets’ on their skin, as seen in figure 3, which have been researched for commercial applications.

According to Dean and Bhushan [4], drag reduction is achieved by the riblets due to the impedance of cross stream vortices in the viscous sublayer. Reducing cross stream vortices reduces the shear force necessary to overcome the momentum transfer between the moving body and the fluid. Shark skin replicas, as shown in figure 4, have been used to achieve a drag reduction of 10%. Interestingly, in addition to the physical characteristics, it has been shown that further drag reductions can be achieved by mimicking the superhydrophobic effects of mucus present on the skin of sharks and other aquatic animals [7]. Blade shaped riblets, like those shown in figure 4 appear to have the best drag reducing properties, however their fragile nature makes them commercially an unviable option, as noted by Dean and Bhushan [4].

C. Reducing Marine Life effects

A smooth hull will initially exhibit low skin friction properties, but the effects of Marine biofouling can alter the surface geometry over time. Marine biofouling on ships is a result of algae and barnacles adhering to the ship, increasing surface roughness and skin friction drag. Callow and Callow note that the effects of biofouling cost the US Navy approximately one billion USD each year. [2]

D. Modification of fluid properties

An alternative method of drag reduction involves modifying the liquid properties themselves. This can be achieved by adding chemicals or air to the water, ultimately changing the fluid phase. Work carried out by Japan’s National Maritime Research Institute has shown that drag reduction can be achieved by injecting a layer of bubbles into the water, creating a blanket of liquid around the hull which has a reduced viscosity due to the inclusion of small 2 millimetre pockets of air. The research, carried out by Yoshiaki Kodama, necessitated the use of ribs running parallel to fluid flow in order to prevent the bubbles rising upwards between blow holes. [9]

In scale tests, skin friction drag was reduced by up to 40%. In full scale tests, involving a 120 metre ship, a 10% energy saving was achieved, which equates to a net saving of 5% when the energy required to generate the bubbles is factored in. [6]

IV. ESTIMATING POWER REQUIREMENTS OF MODERN TANKERS

Tankers are responsible for 30% of shipping [14], so make an excellent area of study. This section considers the
calculation of drag through model based experimentation and computational fluid dynamics. Even though super-computers are commonplace in research institutes, calculating $C_f$ by solving a complex set of Navier-Stokes equations is still challenging and is not always possible. Scale model experiments are still necessary for this reason.

A. A Problem of Similarity

We know from section I that a ships resistance is dependent on Reynolds number $Re$, and Froude number $Fr$. Two geometrically identical hulls with the same $Re$ and $Fr$ will have the same coefficient of drag $C_d$. Subscripts $m$ and $p$ refer to model and prototype (i.e. full size ship) respectively. To achieve similarity for the hull of a ship

$$Re_p = Re_m \text{ or } \frac{V_m}{V_p} = \frac{\rho_p l_p h_m}{\rho_m l_m p_p}, \quad (10)$$

and

$$Fr_p = Fr_m \text{ or } \frac{V_m}{V_p} = \left(\frac{g_m}{\rho_p}\right)^{0.5} \left(\frac{l_m}{l_p}\right)^{0.5}. \quad (11)$$

Consider a prototype to model ratio of 64 : 1. Equations (10) and (11) require

$$\frac{V_m}{V_p} = 64 \rho_2 h_m \rho_1 \mu_p \mu_m \quad \text{and} \quad \frac{V_m}{V_p} = \frac{1}{8} \left(\frac{g_m}{\rho_p}\right)^{0.5}. \quad (12)$$

In order to satisfy the requirements of both equations, it is necessary to either perform experiments in an adjustable gravity field, or to compose a fluid with model to prototype kinematic viscosity ratio of 1:512.

Since the ratio of lengths is much greater than 1, Re scaling becomes impractical because, assuming all else being equal, velocity $V$ has to be scaled by a large factor. Froude number scaling is more practical. Attaining a value of coefficient of resistance for the model $(C_R)_p$ from measurements of $(C_R)_m$ is desired. $(C_R)$ is function of Fr and $Re$ numbers, however Froude’s hypothesis alleviates this issue, the full derivation of which is available in Molland et al.[10]. The Froude hypothesis states

$$C_R(Re, Fr) = C_F(Re) + C_w(Fr) + C_{form} \quad (13)$$

where $C_F$ is the frictional coefficient, which is said to be a function of $Re$ only, $C_w$ is waving making resistance coefficient, which is a function of $Fr$, and $C_{form}$ is the form drag, which is said to be independent of $Re$ and $Fr$ is constant and is similar for geosims.

B. Calculating the drag on a large tanker

The originally named Seawise Giant is the largest oil tanker ever built, with a length of over 458m and a cruising speed of 18mph or 8.05ms$^{-1}$. This ship will be the subject of analysis in this section.

The ship has a wetted area of approximately 43000m$^2$, and skin friction forces dominate, so wave making resistance and form drag can have not been considered. Consider the following expression for $C_f$, discussed in section II-A,

$$C_f = 0.074Re^{-0.2}. \quad (14)$$

At full speed the ship experiences a $Re \approx 3.5 \times 10^6$ and therefore the $C_f \approx 0.0014$. Inputting this value of $C_f$; 43000m$^2$ as area A; 8.05ms$^{-1}$ as velocity $V$; and 1027kgm$^{-3}$ as the density of salt water $\rho$, into equation (4) yields a drag value of $2.0 \times 10^9$N. Assuming that only skin friction drag is present, the ships power requirement can be calculated using $P = FV$ which, at a speed of 8.05ms$^{-1}$, yields a requirement of 16,000KW or 21,600SHP.

V. THE ECONOMICAL AND ENVIRONMENTAL IMPACT

Consider that in 2014 world wide CO$_2$ emissions 36.1 billion tonnes, of which shipping contributed approximately 1.2 billion tonnes. The worlds 90,000 ships consumed 7.3 million barrels of oil. Understanding the effects of drag on these ships, and implementing systems to reduce drag, like those discussed in section III can have a large economic and environmental impact. A system such as that discussed in section III-D, which injects bubbles into the water can result in an 5% reduction in drag, reducing the fuel consumption of the ship by a similar amount. Implemented globally, this drag reduction system could reduce global CO$_2$ emissions by 60 million Tonnes and save the shipping industry the financial equivalent of 365,000 barrels of oil.

REFERENCES


NOMENCLATURE

CFD Computational Fluid Dynamics
SEM Scanning Electron Microscope
SHP Shaft Horse Power

$V$ Velocity ($ms^{-1}$)
$l$ Characteristic Length ($m$)
$\rho$ Density ($Kgm^{-1}$)
$\mu$ Dynamic Viscosity ($Kgm^{-1}s^{-1}$)
$\nu$ Kinematic Viscosity ($m^2s^{-1}$)
$A$ Surface Area ($m^2$)
$g$ Acceleration due to Gravity ($ms^{-2}$)
$C_f$ Coefficient of Friction ($\frac{1}{\rho}$)
$Re$ Reynolds Number ($\frac{1}{\nu}$)
$Fr$ Froude Number ($\frac{1}{\nu}$)
$h$ Wave Height ($m$)
$d$ Depth of Water ($m$)
$c$ Rate of Propagation of Surface Waves ($ms^{-1}$)