Communication Skills I

GROUP PRESENTATION:
THE PHYSICS BEHIND BOATS AND PLANES

Gomà, Pol - Pacheco, Rafael - Pérez, Magdalena

Introduction

The goal of this presentation is to give a brief explanation on the physical principles that allow planes to fly and boats to float. Planes and ships seem to have utterly different physics, but yet they rely on similar principles or field. This so-called field is what may be called fluid mechanics.

The physics of a regular ship are explained within fluid statics (hydrostatics). This presentation will develop the concept of stability and how it is achieved. Instead, aircrafts are governed by the laws of fluid dynamics (aerodynamics). The aerodynamic force that allows a plane to fly is called lift, a simple introduction to how is computed and the parameters that affect lift will be given.

Ships statics

The two main forces involved in the physics behind a boat are the weight and the buoyancy. The explanation of why a ship stays afloat relays in the equilibrium between weight and buoyancy forces. The weight of a boat is obtained by means of integrating the density of the material over the volume. On the other hand, the buoyancy force is the force which the fluid exercise on the ship. It is computed by integrating the density of the water over the volume displaced by the ship.

Computed that way, both forces are magnitudes. In order to obtain the application point, a lever of masses is applied. Thus, the centre of gravity (CoG) and buoyancy (B) are obtained. "CoG" and "B" have to be in the same vertical, otherwise the boat would have an initial angle of tilt (roll or trim).

However, this is only a partial explanation. A barrel may float and still not be functional, as it can easily spin. Thus, another important concept is derived, namely, stability. The stability is a concept needed to be fulfilled for any naval architect. Otherwise, the boat may tilt, sink and will no longer be afloat.

Until this point there were two characteristic points considered: centre of gravity and centre of buoyancy. But the calculus of stability involves a third point called metacentre. The metacentre is said to be a point, which at any given angle of roll or pitch, will be the intersection between the vertical line from the initial centre of buoyancy (roll and pitch angle equal to 0Âž) and the vertical line from the centre of buoyancy of the given angle.

Thus from the previous presentation, an expression was derived:

$$GM \gg 0 \qquad when V_{lost} = V_{gained} and \frac{\partial(G)}{\partial\theta} = 0 \tag{0.1}$$

which means that GM must be a large and positive distance. This theory is based on the fact that the volume of water which is lost when rolling is similar to the one that has been gained and that the centre of gravity does not move, because if it had moved the distance GM would not be constant.

A ship is not stable if its righting arm once it starts rolling or pitching is negative and this happens only if M<0 . In other words, the moment generated is negative and helps the ship to keep rolling. If the distance GM is positive, then the righting arm is positive and therefore the ship tends to recover its initial position.

A fourth point arises, which is called Z. This new point is the righting arm and it is defined as:

$$RM = GZ \cdot \Delta where \Delta = displacement \tag{0.2}$$

Considering small angles theory, GZ can be approximated as $GZ = GMsin\theta$.

This leads to consider what will happen if the angle of roll or pitch is bigger than 15Âž. In reality, for conventional ships angles of such magnitude are very uncommon and therefore this stability method has been used during many decades.

However, with the advance of computer technology new techniques have been introduced. Since the calculations that can be perfomed in a computer are much larger and complex, considering extreme situations that involve more computations is no longer a troublesome task to be undertaken.

To summarise, the old fashion method relies on the fact that the shape should be like a square, since the volume equilibrium when rolling is hold and that gravity centre stay relatively still. The new techniques allow to re-calculate G,B in each angle possible for any range of shapes.

Aircrafts dynamics

The force that keeps an airplane in the air is called lift. A body facing an upcoming flow of velocity V_∞ will generate lift by changing the velocity of this upcoming flow. Considering potential flow and applying Bernoulli's equation, a change in velocity can be translated into a change in pressure. If this change in pressure, generated all around the body, is integrated along the body's surface it will give a resultant force, the so called lift.

A simplified theory for computing the lift generated by a 2D thin airfoil was developed in the XX century. This theory neglects the thickness of the airfoil (thus making it only valid for very thin profiles) and models it as a mean-line. The airfoil is then considered as a distribution of vortices along the mean line that generate a certain circulation γ. Considering the Kutta-Zhukowski theorem, the lift is proportional to the circulation such that $L = \rho V_\infty \gamma$. Thus, if the circulation can be estimated, then the lifting force can be computed.

Assuming a certain distribution for the circulation (Taylor's expansion), considering changes in velocity the horizontal direction negligible when compared to changes in the vertical direction and setting a boundary condition that allows no circulation normal to the airfoil's surface, the circulation can be computed and the lift can be obtained.

A usual manner of representing the lift for comparison and analysis purposes is as a nondimensional coefficient called the *lift coefficient* C_L, defined as:

$$C_L = \frac{Lift}{\frac{1}{2}\rho V_\infty^2 c} \tag{0.3}$$

where c is the characteristic length of the object if in 2D, or the area in the 3D case.

There are many factors that affect the lift force. We can group these factors into 3 categories:

1. Those associated with the **object**. The geometry of the wing has a large effect on the amount of lift that is generated. Thus, the airfoil shape and wing size play an important role, and so does the ratio of the wing span to the wing area.
2. Those associated with the **motion of the object** through the air. Lift depends on the velocity of the air and how the object is inclined to the flow.
3. Those associated with the **air** itself. Lift depends on the mass of the flow, and it also depends in a complex way on the air's viscosity and compressibility.

All of this information on the factors that affect lift are gathered in the previously stated equation for the lift coefficient (0.3), that can be rearranged as (0.4) . With this equation it is possible to predict how much lift force will be generated by a given body moving at a given speed, where the body's lift coefficient is usually measured experimentally.

$$L = \frac{1}{2}\rho V^2 A C_L \tag{0.4}$$

Velocity effects on the lift

Lift depends on the square of the velocity. The velocity used in the lift equation is the relative velocity between the object and the flow. Since the lift depends on the square of the velocity, doubling the velocity will quadruple the lift.

Density effects on the lift

Lift depends linearly on the density of the fluid and, consequently, halving the density halves the lift. The fluid density depends on the type of fluid and the depth of the fluid, and in the atmosphere, air density decreases as altitude increases. This explains why airplanes have a flight ceiling, an altitude above which they cannot fly. As an airplane ascends, a point is eventually reached where there just isn't enough air mass to generate enough lift to overcome the airplane's weight.

Shape effects on the lift

The amount of lift generated by an object depends on how much the flow is turned, which depends on the shape of the object. In general, the lift is a very complex function of the shape. Aerodynamicists model the shape effect by a lift coefficient C_L which is normally determined through wind tunnel testing. However, for some simple shapes, mathematical equations can be developed in order to determine the lift coefficient. A result of the analysis shows that the greater the flow turning, the greater the lift generated by an airfoil.

Using the lift coefficient is a good way to deal with complex dependencies, since the dependence is characterized by a single variable. This allows to collect all the effects, simple and complex, into a single equation. For given air conditions, shape, and inclination of the object, we have to determine a value for C_L to determine the lift.

The lift force depends on the shape of the airfoil, especially the amount of camber (curvature such that the upper surface is more convex than the lower surface). Increasing the camber generally increases lift. Cambered airfoils will generate lift at zero angle of attack, whereas symmetric airfoils will not.

Size effects on the lift

The amount of lift generated by an object depends on its size. Lift is an aerodynamic force and therefore depends on the pressure variation of the air around the body as it moves through the air. Since the lift is directly proportional to the area of the object, doubling the area doubles the lift.

Inclination effects on the lift

As a wing moves through the air, it is inclined with respect to the flight direction at some angle. The angle between the chord line and the flight direction is called the angle of attack, and it has a large effect on the lift generated by a wing. For thin airfoils, the lift is directly proportional to the angle of attack for small angles (within $\pm 10°$). For higher angles, however, the dependence is quite complex.

This way, lift depends on the density of the air, the square of the velocity, the air's viscosity and compressibility, the surface area over which the air flows, the shape of the body, and the body's inclination to the flow. In general, the dependence on body shape, inclination, air viscosity, and compressibility is very complex.

References

s6.aeromech.usyd.edu.au/
www.grc.nasa.gov/