Chapter

Introductory Chapter: Propulsion and Movement

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1. Introduction

Almost all animals move around frequently in their surrounding. Their aim is to travel in search of food or to propagate their species. Changing positions is important for survival and also in balancing and improving the environment. As plants cannot move by themselves, they depend on various things transported by animals. For example, the pollen transported by insects is the essential mechanism for plant reproduction. Transportation and movement are important factors for adapting to the change in various environments.

Movement and transport of different things is inevitable part of human life. Without movement or change of place, survival is difficult. Much efforts have been devoted to the development of the means for transportation of larger and heavier materials, and also over a long distance. To understand the movement of any object it is necessary to know the action of forces such as propulsion and drag ones.

In general, propulsions are closely related to the momentum change in the concerned system. We take the simplest case in which an object of mass m is moving with the velocity v. Newton's second law of motion is written as

$$\boldsymbol{F} = \frac{\mathrm{d}(m\boldsymbol{v})}{\mathrm{d}t}, \tag{1}$$

where $\boldsymbol{F}$ is the force acting on the mass. Integration of the above formula between t_1 to t_2 gives the averaged force, $\overline{\boldsymbol{F}}$, given by

$$\overline{\boldsymbol{F}} = \frac{m_2\boldsymbol{v}_2 - m_1\boldsymbol{v}_1}{t_2 - t_1}, \tag{2}$$

where $m_1\boldsymbol{v}_1$ and $m_2\boldsymbol{v}_2$ are the momentum at $t = t_1$ and t_2, respectively. It is well known that the difference between the momentum at two instants produces some kind of forces. The evaluation of the difference determines its magnitude. To determine the magnitude of forces some calculations of the difference is necessary and it is the first step for understanding the origin.

However, there are many cases in which the usual momentum is difficult to estimate. Suppose, for example, a bird is flying in the sky. The fluid around the bird dominates in an infinite space, the integration for the calculations over the whole fluid does not give a finite value. To evaluate the momentum for the movements of insects, birds, or fish, another quantity called as the virtual momentum should be calculated instead of the usual momentum. This topic will be discussed in detail later.

Next we mention the application in engineering field. Let us take an example in aeronautical field. Recently, jet engines with extremely large thrust and high efficiency have been developed, while the extremely loud noise generated by the high speed jet has suppressed largely, i.e., the development of the jet engine has become environment-friendly [1]. A typical example of the high-bypass engine designed on this principle is shown schematically in **Figure 1**. This type of engine produces stronger thrust by blowing out a larger mass rather than at a higher velocity for the change of momentum.

Such research and development are aimed at the improvement for easier movement in our surrounding. Rocket engines using chemical reaction have been developed to travel outside of earth. To travel to the space, other types of rocket engines, for example, the ion-engine has often been used. This type of engine utilizes ionized gases as the propellant. However, it is impossible to travel further in space, because of the problem of inevitable heavy weight of fuel. The journey to the stars is now being discussed [2]. In the discussion, Newton's classical dynamics might fail and will be replaced by that of the general theory of relativity.

Now we go back to the discussion of motion of insects, fish or birds in more detail. These creatures efficiently utilize the unsteadiness [3, 4]. Formation of a coherent structure called the leading edge vortex (LEV) is a typical structure in the generation of unsteady force. Many authors have published studies on this topic and hilighted its importance, experimentally and numerically. The magnitude of the unsteady force cannot be explained by a steady-state approach. In many cases the unsteadiness generates *larger* forces more efficiently than that in the steady state. Experiments have been conducted in three-dimensional space and numerical analyses have been carried out to understand the mechanism of generation of force. These studies explained several aspects of unsteady phenomenon. How does the behavior of vortices affect the generation of force? In particular, how does momentum change depend on the force? We are yet to devise a method to estimate the momentum of a unsteady vortex system that changes in a complex manner. Characteristics such as the magnitude, the rotation direction, and the position play the key role in determining the momentum. Unless we determine their properties, the evaluation of force cannot be made quantitatively.

When an object of a constant circulation Γ moves with a constant speed $\mathrm{d}x_0/\mathrm{d}t$, a fluid force acts perpendicular to the direction of motion. The magnitude is given by $\rho(\mathrm{d}x_0/\mathrm{d}t)\Gamma$ (Kutta-Joukowski theorem) [5]. It should be noted that the magnitude is the derivative of the *virtual momentum* $\rho x_0\Gamma$ with respect to time. Here, ρ is the density of the fluid. This is the simplest application of a well-known law that governs the conservation of momentum. In other words, this is a typical example of the application of the second law of motion to cases including vortices. This simple example is an application to steady motion, however, the estimation of force even

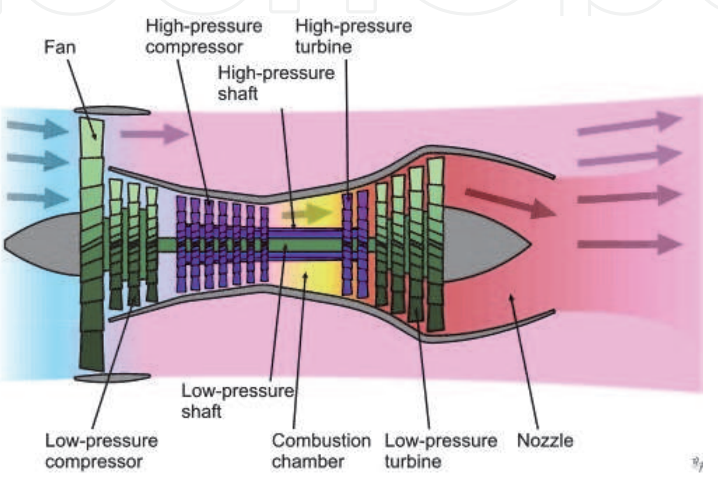

Figure 1.
An example of the cross-section of the jet engine of high-bypass ratio implemented in modern aircrafts [1].

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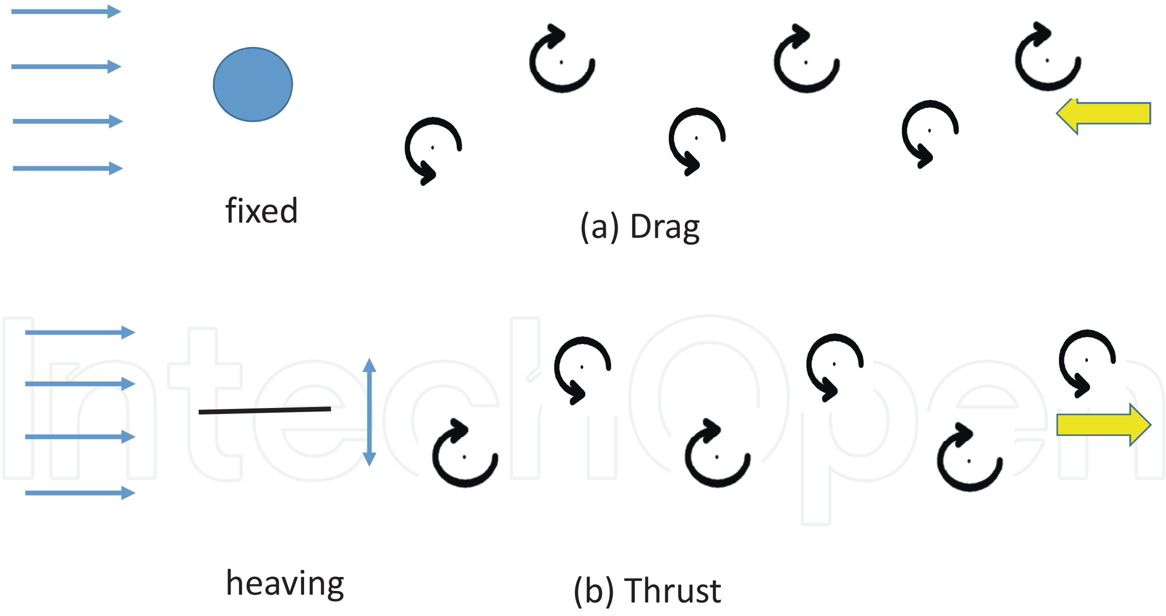

Figure 2.
Vortex street and an object in the stream. (a) An object fixed in the free stream; (b) a thin aerofoil heaving vertically. Two thick arrows denote the direction of momentum increase resulting from the induced velocities due to the vortices.

for such unsteady flow is easy by knowing the virtual momentum. As illustrated above, the virtual momentum is important for the generation of force even for unsteady flows. Among many examples, the application to a heaving motion of a thin plate is the simplest. The importance of the virtual momentum is evident from the discussions about a thin plate. Another importance is that the motion has an analytical solution in the limit as the heaving amplitude becomes smaller.

As an example, let us consider the relation between the force acting on a body fixed in a stream and free vortices flowing down behind it. It is known that a drag acts on a still body set in the stream. We can see two vortex rows, also known as the Kármán vortex street (see **Figure 2a**).

On the other hand, a similar vortex street can be seen behind flying birds and swimming fish. However, the direction of rotation of vortices is quite opposite to the above case. In the case of the Kármán street, there appears to be momentum defect in the street, while the momentum seems to increase behind the birds and fish. In the latter case, a thrust acts on the object to move forward due to the momentum rise. We illustrate the vortex streets appearing in heaving motion (see **Figure 2b**). In the figure the thick arrows represent the direction of the increased momentum. Two typical examples mentioned above are ideal examples for explaining the function of the virtual momentum.

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