Lift, Thrust, and Flight

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1 FORCES AND MOTIONS

Force is the push or pull that acts on an object. That push or pull could cause the object to change in the speed and/or direction of its motion, including the initation of motion from rest. That push and pull can also cause the object to deform. Force ($\boldsymbol{F}$) is a vector quantity with both magnitude and direction. When describing a force, one must specify its magnitude, its direction, and its line of action.

Motion refers to changes in the location of an object. Motion is always observed and measured relative to a frame of reference. An object that is motionless relative to a given frame of reference could be moving relative to infinitely many other reference frames. Thus, the frame of reference is critical when describing forces and motions.

When the speed of an object is much less than the speed of light, Newton's three laws of motion describe quite accurately the relationship between forces, motions, and the frame of reference. Newton's three laws of motion are as follows:

Encyclopedia of Aerospace Engineering.
Edited by Richard Blockley and Wei Shyy
 ISBN: 978-0-470-68665-2

Newton's First Law states that relative to an inertial frame of reference, an object with no net force acting on it will move without change in its velocity. This law is often simply stated as "an object persists in its state of rest or of uniform motion unless acted upon by an external unbalanced force." Therefore, Newton's first law is also referred to as the *law of inertia*.

Newton's Second Law states that, when observed from an inertial reference frame, the net force on an object is equal to the time rate of change of its momentum. This law is also often stated as, "force equals mass times acceleration" (i.e., the net force acting on an object ($\boldsymbol{F}$) is equal to the mass of the object (m) multiplied by its acceleration $\boldsymbol{a}$ or $\boldsymbol{F} = m\boldsymbol{a}$.

Newton's Third Law states that "whenever an object $\boldsymbol{A}$ exerts a force on another object $\boldsymbol{B}$, object $\boldsymbol{B}$ simultaneously exerts a force on object $\boldsymbol{A}$ with the same magnitude in the opposite direction." The strong form of the law further postulates that these two forces act along the same line. This law is often simplified into the sentence, "to every action there is an equal and opposite reaction."

Newton's three laws of motion can be used to explain why an airplane could fly and guide the design of an airplane. As shown in Figure 1, the forces that act on an airplane in flight can be grouped into four categories, and they are lift, drag, thrust, and weight.

Weight is a force due to gravity and is directed towards the center of the earth. The magnitude of weight depends on the mass of all the airplane parts, the fuel, and any payload on board the airplane such as people, baggage, freight, and so on. Though the mass is distributed throughout the airplane, the net force due to gravity can be assumed to act through a single point, called the center of gravity.

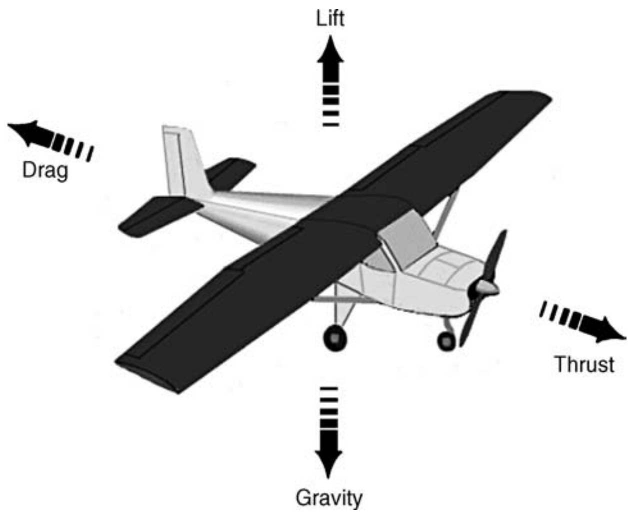

Figure 1. The forces that act on an airplane in flight.

In order for an airplane to fly, it must overcome the force of weight. The airplane accomplishes this by generating an opposing force, called lift. Lift is generated by motion of the airplane through the air and is an aerodynamic force. Lift is directed perpendicular to the flight direction. The magnitude of the lift depends on several factors including the shape, size, and velocity of the airplane. As with weight, each part of the airplane contributes to its lift force. Most of the lift is generated by the wings. Though the aerodynamic pressure forces that lift the airplane is distributed throughout the airplane, the net lift force can be assumed to acts through a single point, called the center of pressure/shear forces. The center of pressure/shear is defined just like the center of gravity, but using the pressure distribution around the body instead of the mass distribution.

As an airplane moves through the air, in addition to the lift force, there is another aerodynamic force generated. That force is called drag, and it results because the air resists the motion of the airplane. Drag is directed along and opposed to the direction of flight. There are many factors that affect the magnitude of the drag force including the shape of the airplane, the "stickiness" of the air, and the velocity of the aircraft. Though the resistance to the airplane's motion is distributed thoughout the aircraft, the net resistance or drag force acts through the airplane's center of pressure/shear.

To overcome drag, an airplane uses a propulsion system to generate a force called thrust. In general, the thrust force is in the direction of flight. However, for some airplanes, the thrust direction can be varied to help the airplane take off in a very short distance. The magnitude of the thrust depends on many factors associated with the propulsion system including the type of engine, the number of engines, and the throttle setting.

The motion of an airplane through air depends on the relative strength and direction of the four forces shown in Figure 1. If all of the four forces are balanced, then the airplane cruises at constant velocity. If the forces are unbalanced, then the airplane either accelerates or decelerates in the direction of the force imbalance.

It should be noted that the purpose of the engine is just to generate the thrust needed to overcome the airplane's drag for cruise, for takeoff, for landing, and for maneuvering, but not to lift the airplane. As an example, a one-million-pound Boeing 747 airliner with its passengers and payload has four engines that only produce about 200 000 pounds of thrust. It is the wings of the Boeing 747 that are doing the lifting, not the engines. In fact, there are some airplanes called gliders that have no engines at all, but fly just fine. For gliders, some external source of power has to be applied to initiate the motion necessary for the wings to produce lift. However, during flight, the weight is opposed by both lift and drag. During reentry and landing, the Space Shuttle is a glider; the rocket engines are used only to launch the Shuttle into space.

2 METHODS OF GENERATING LIFT AND THRUST

There are a number of ways to generate lift and thrust. In this section, an overview is first given on how natural flyers/swimmers such as birds, insects, and fish generate lift and thrust. Understanding how these natural flyers/swimmers fly/swim can provide considerable guidance in the development of micro aerial vehicles. Afterwards, an overview is given on how humans fly through engineered systems such as the airplane.

2.1 How nature does it (birds, insects, and fish)?

Flapping propulsion is one of the most complex yet widespread modes of transportation found in nature. Birds, insects, fish, and cetaceans, such as whales and dolphins, have evolved and used flapping wing/fin systems for thrust and lift production for millions of years. Locomotion of natural flyers/swimmers by flapping wings/fins is a sophisticated realm of propulsion and has intrigued humans for centuries if not since the dawn of human existence. There is a long list of literature by biologists and naturalists describing the kinematics of flapping wing/fin motions of natural fliers/swimmers and the empirical correlations between flapping frequency, weight, wing-span/fin size, and power requirements based on the studies of many different families of birds, bats, insects, and fishes. See Shyy *et al.* (2008) for a review.

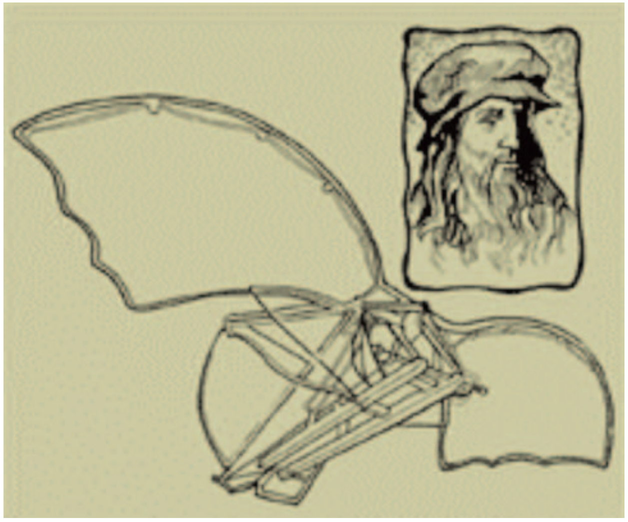

Figure 2. Leonardo da Vinci and his ornithopter.

The observations of the success of the flapping propulsion of natural fliers/swimmers apparently inspired the designs of flapping-wing aircraft (i.e., ornithopter) that could be pushed or pull with human hands and arms, or pump with legs to flap wings up and down to achieve flapping propulsion for flying since the beginning of aviation history. Indeed, no less great mind than Leonardo da Vinci designed numerous such ornithopters in pre-Wright era of aviation history. One of de Vinci's own ornithopter designs taken from his voluminous notebooks of drawings is given in Figure 2. While numerous human-powered ornithopter have been designed and flight tested, no human-powered ornithopter has ever successfully flown.

The success of the Wright brothers in 1903 with the fixed-wing aircraft concept soon convinced the aeronautical engineering community to regard the flapping-wing aircraft concept as unpromising for further development and, indeed, throughout the whole twentieth century few attempts were made to build flapping-wing vehicles. It wasn't until near the end of the 20th century with the advent of the vision to create a new type of air vehicle of greatly diminished size, the micro aerial vehicles (MAVs), was there a renewed interest on natural flyers and triggered a surge in the re-examination of the flapping-wing flight concept. This renewed interest came about because of the small Reynolds numbers that these MAVs would experience, typically from a few thousand to a few tens of thousands, and the need for better agility and maneuverability requirements for in-door flight applications.

It has long been realized that the mechanisms responsible for lift and drag in steady-state aerodynamics/hydrodynamics involving high Reynolds number flows differ considerably from the mechanisms that generate lift and drag in unsteady low-Reynolds number flows produced by the flapping wing/fin systems employed by natural fliers/swimmers for locomotion. This has prompted extensive studies to uncover the underlying physics and to elucidate fundamental mechanisms employed by the natural fliers/swimmers to produce enough aerodynamic/hydrodynamic forces needed for propulsion and maneuvering. Knoller (1909) and Betz (1912) are among the first to propose a theory to explain why a flapping wing can generate thrust during flapping motion. Their explanation is shown schematically in Figure 3, where an airfoil is depicted which executes harmonic plunge oscillations. As shown in the figure, when the airfoil moves through its mean position in either the up stroke or the down stroke of the flapping cycle, the airfoil "sees" an effective angle of attack, α_{eff}, due to the vectorial superposition of its flight speed, V_∞, and the plunge velocity, $z'(t)$ due to the flapping motion. By neglecting viscous and three-dimensional effects, a resultant

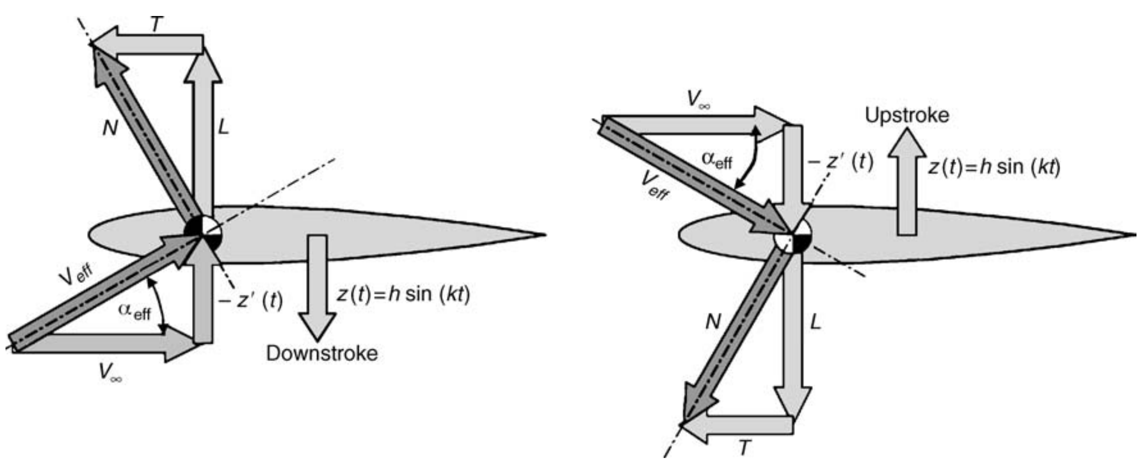

Figure 3. Schematic illustrating thrust production by a plunging airfoil as suggested by Knoller (1909) and Betz (1912). Reproduced from Jones and Platzer (2009) © Springer.

aerodynamic force, *N*, is generated which is always inclined forward. As a result, a harmonically varying force component in the flight direction, *T*, (i.e., thrust) is produced. Since a positive thrust component is generated during both up strokes and down strokes in the flapping motion, a time-averaged positive thrust will be produced as a result of the flapping motion of the airfoil. This is also called Knoller–Betz effect.

Katzmayr (1922) provided the first experimental verification of the Knoller–Betz effect by measuring the average thrust acting on the test wing placed a stationary wing into a sinusoidally oscillating wind stream. Katzmayr's experimental work, in turn, stimulated a more detailed analysis by Birnbaum (1924) who applied Prandtl's unsteady thin airfoil theory to study the wake structures and resultant aerodynamic forces acting on oscillating airfoils. Birnbaum (1924) is regarded as the first to give a quantitative prediction of thrust generation due to oscillating airfoils, and he was also able to show that an oscillating airfoil would shed vortices from its trailing edge (an effect not included by Knoller and Betz).

Much progress has been made since then to uncover underlying physics to elucidate fundamental mechanisms of flapping propulsion. It has been found that the wake structures downstream of flapping airfoils can be characterized as drag-producing, neutral, or thrust-producing depending on the flapping frequency and stroke amplitude (Jones and Platzer, (2009)). As shown in Figure 4, drag-producing wakes have velocity profiles that show a momentum deficit when time averaged, typically with von Karman vortex street wake configurations with two alternating vortex rows, clockwise above and anticlockwise below for flow from left to right. Vortex pairs form mushroom-like structures that are tilted upstream. Thrust producing wakes show a momentum increase, similar to a jet superimposed on the momentum-deficit velocity profile in the time-averaged flow, such that the thrust produced is greater than the drag. The wake configuration is typically a reversed von Karman vortex street with two rows of alternating vortices, anticlockwise above, and clockwise below. Thus, vortex pairs form downstream tilted mushrooms. Neutral wakes, where the thrust due to flapping motion balances the inherent drag acting on the airfoil, may show multiple vortices shedding per half-cycle, and vortex pairs are not tilted.

A dimensionless parameter that is widely used to describe the tail or wing kinematics of swimming and flying animals is the Strouhal number, $St = fA/V_\infty$, which divides flapping frequency (*f*) and stroke amplitude (*A*) by the forward flight speed V_∞. Another widely used parameter to characterize the flight performance of many flying animals ranging in size from small insects to albatrosses and kestrels is the reduced frequency, $k = 2\pi fc/V_\infty$, where *c* is the airfoil chord. Since

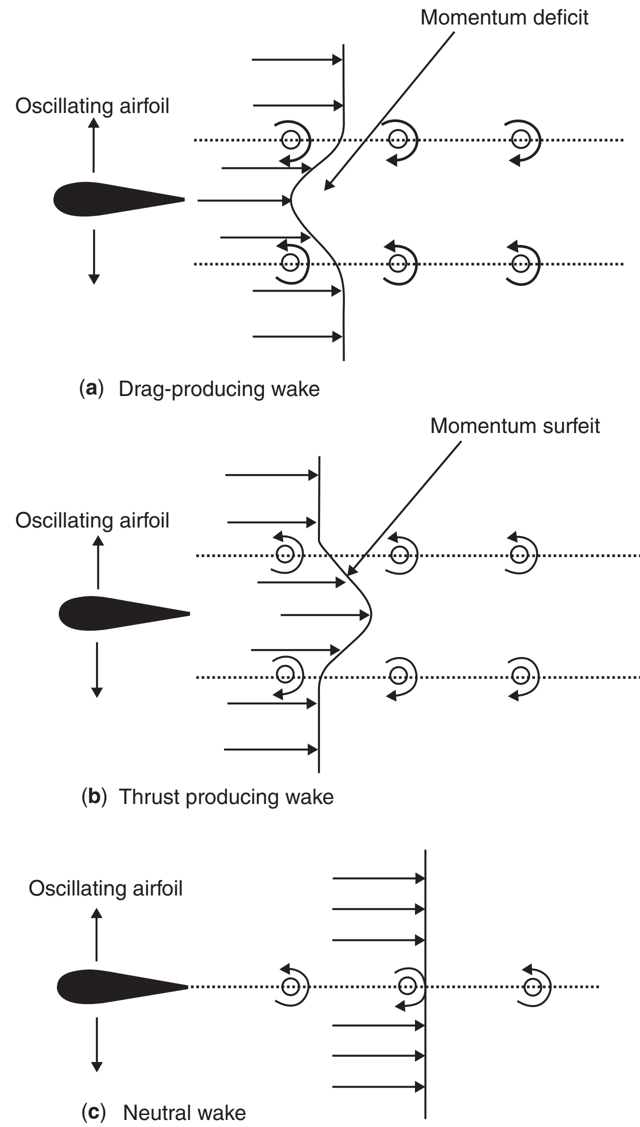

Figure 4. Wake structures of an oscillating airfoil.

the product *f* and *c* is a measure of the flapping velocity, hence reduced frequency, *k*, is a measure of the flapping velocity relative to the flight/swim speed. By using non-dimensional flapping amplitude, $h = A/c$, the relationship between the product *kh* and the Strouhal number *St* can be written as $kh = 2\pi St$.

Extensive experimental studies with isolated pitching or heaving airfoils have revealed that high peak propulsive efficiencies (defined as the ratio of aerodynamic/hydrodynamics power output to mechanical power input) would be achieved within the range of $0.2 < St < 0.4$. Measured propulsive efficiency usually peaks when the flapping kinematics result in maximum amplification of the shed vortices in the wake and an average velocity profile equivalent to a jet as shown in

Figure 4(b). It has been reported that the propulsive efficiency of flapping propulsion can be as high as 70%∼80% (Anderson *et al*., (1998); Read, Hover and Triantafyllou, (2003)). Optimal *St* is found to depend subtly on kinematic parameters including geometric angle of attack, amplitude-to-chord ratio, airfoil section and phase of motion but, for any given motion, efficiency is usually high over a range narrower than $0.2 < St < 0.4$. It has also been found that natural selection is likely to tune fishes and animals to swim or fly in the range of $0.2 < St < 0.4$ for high propulsive efficiency. For example, Taylor, Nudds and Thomas (2003) analyzed the flapping frequencies and amplitudes of 42 species of birds, bats, and insects in cruise flight and found that these flying animals operate within a narrow range of Strouhal number with $0.2 < St < 0.4$. Similar results were also found to be true for dolphins, sharks and bony fish, which swim at $0.2 < Sr < 0.4$ (Triantafyllou, Triantafyllou and Grosenbaugh, (1993); Rohr *et al*., (1998)).

2.2 How humankind does it (engines attached to an airframe with propellers or nozzles)?

For human flight, because of our size and weight and because of our needs on speed, range of travel, and payload, what works for natural flyers/swimmers such as birds and insects may not work for us. Both fixed and rotary wing vehicles have been developed. Here, we focus on the fix wing airplane to illustrate the basic concepts of lift and thrust. For fixed wing airplanes, the wings are used to generate the lift, and propulsion systems are needed to generate thrust to overcome the aerodynamic drag for sustained and controlled flight. An airplane's propulsion system must satisfy two requirements. First, the thrust from the propulsion system must balance the drag of the airplane when the airplane is cruising. Second, the thrust from the propulsion system must exceed the drag of the airplane for the airplane to accelerate. In fact, the greater the difference between the thrust and the drag, called the excess thrust, the faster the airplane will accelerate.

So far, four principal propulsion systems have been used for aircraft propulsion, and these are as follows: the propellers driven by piston or rotary engines, the gas turbines (or jet engines), the ramjets, and the rockets. Different propulsion systems generate thrust in different ways.

Since the first flight of the Wright brothers, propellers driven by internal combustion (IC) engines have been widely used to generate thrust to power airplanes. Today, most general aviation or private airplanes are still using propellers driven by internal combustion engines for propulsion (Figure 5). Much like an automotive engine, the IC engine takes air from the surroundings, mixes it with fuel, burns the fuel to release the energy in the fuel, and uses the heated and pressurized gas to move a piston, which is attached to a crankshaft. In the automobile, the shaft is used to turn the wheels of the car. In an airplane, the shaft is connected to a propeller to generate thrust to power the airplane. While propellers are usually used to power aircraft flying with relatively low speed in subsonic regime, they are found to have the best fuel efficiency among the four kinds of aircraft propulsion systems, at least in the power range of interest to general aviation aircraft.

Figure 5. An Allison V-1710-115 IC engine-powered propeller.

Gas turbine engine (Figure 6) was first developed independently in Germany and in England during World War II. Gas turbine engines are also called jet engines. Early gas-turbine engines worked much like a rocket engine creating a hot exhaust gas, which was passed through a nozzle to produce thrust. However, unlike the rocket engine, which must carry its oxygen for combustion, turbine engines get its oxygen from the surrounding air. For a gas-turbine engine, the accelerated gas, or working fluid, is the jet exhaust. Most of the mass of the jet exhaust comes from the air surrounding the airplane and its engines. Most modern, high-speed, passenger and military airplanes are powered by gas-turbine engines. Compared with propeller-based propulsion systems, gas turbine engines can generate much more thrust for aircraft flying with much higher speed such as in transonic or supersonic regime. To increase efficiency, turboprops and turbofan

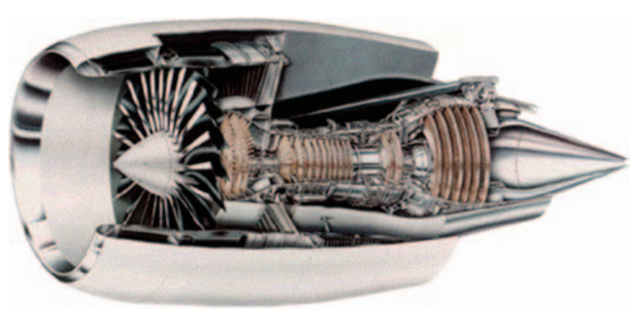

Figure 6. An GE90-115B gas-turbine engine.

Figure 7. A ramjet engine on SR-71 spy plane.

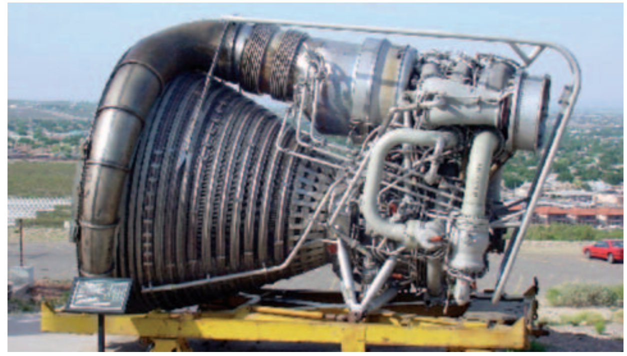

Figure 8. An F-1 rocket engine.

engines are developed by combing propeller or fan with a gas turbine to strike a balance between thrust generation and fuel efficiency for aircraft propulsion.

Some of the original ideas concerning ramjet propulsion systems were first developed in Europe in the early 1900s. For a ramjet propulsion system (Figure 7), thrust is produced by passing the hot exhaust from the combustion of a fuel through a nozzle. The nozzle accelerates the flow, and the reaction to this acceleration produces thrust. To maintain the flow through the nozzle, the combustion must occur at a pressure that is higher than the pressure at the nozzle exit. In a ramjet engine, the needed high pressure is produced by "ramming" external air into the combustor by using the forward speed of the vehicle. The external air that is brought into the propulsion system becomes the working fluid, much like a turbojet engine. In a turbojet engine, the high pressure in the combustor is generated by a compressor, but there are no compressors in a ramjet engine. Therefore, ramjets are lighter and simpler than a turbojet engine. Ramjets produce thrust only when the vehicle is already moving fast enough; ramjets cannot produce thrust when the engine is stationary or static. Therefore, some other propulsion system must be used to accelerate the vehicle to a speed, where the ramjet begins to produce thrust. The higher the speed of the vehicle, the better a ramjet works until aerodynamic losses become a dominant factor.

The combustion that produces thrust in the ramjet occurs at a subsonic speed in the combustor. For a vehicle traveling supersonically, the air entering the engine must be slowed to subsonic speeds by the engine inlet. Shock waves present in the inlet cause performance losses for the propulsion system. With the flying speed above Mach number of 5.0, ramjet propulsion usually becomes very inefficient. The new supersonic combustion ramjet, or scramjet, solves this problem by performing the combustion supersonically in the burner.

A number of rocket-powered airplanes were built during and following World War II to explore high-speed flight. In a rocket engine (Figure 8), fuel and a source of oxygen, called an oxidizer, are mixed and exploded in a combustion chamber. The combustion produces hot exhaust, which is passed through a nozzle to accelerate the flow and produce thrust. For a rocket, the accelerated gas, or working fluid, is the hot exhaust produced during combustion. This is a different working fluid than those in a turbojet engine, scramjet, or a propeller-powered aircraft. Turbojet engines, scramjet, and propellers use air from the atmosphere as the working fluid (i.e., they are air breathing engines), but rockets do not use air or the oxidizer in air to generate thrust (i.e., they are not air-breathing). This is why rockets work so well in space, where there is no air, and why gas turbines, ramjets, scramjets, or a propeller do not work there.

There are two main categories of rocket engines, liquid rockets, and solid rockets. In a liquid rocket, the fuel and the oxidizer are stored separately as liquids and are pumped into the combustion chamber, where burning occurs. In a solid rocket, the fuel and the oxidizer are mixed together and packed into a solid propellant. Under normal temperature conditions, the solid propellants do not burn. They will start to burn only when exposed to sufficient heat such as that provided by an igniter. Once the burning starts, it proceeds until all the propellant is exhausted. Thus, there is no control on the thrust unless the propellants are designed and packed differently in different parts of the rocket's long circular cylinder. With a liquid rocket, thrust can be controlled by adjusting the flow of the fuel and oxidizer into the combustion chamber. Liquid rockets tend to be heavier and more complex because of the pumps and storage tanks. For liquid rockets, the liquid fuel and oxidizer are loaded into the rocket just before launch. A solid rocket is much easier to handle and can sit for years before firing.

Different missions will place different requirements on the airplanes' propulsion systems. Some airplanes, like commercial airliners and cargo planes, spend most of their lives in a cruise condition. For these airplanes, excess thrust is not as important as high engine efficiency and low fuel usage during cruise. Since it is more efficient to accelerate a "large" quantity of mass by a small amount than to accelerate a "small" quantity of mass by a large amount to achieve the same change in momentum, high bypass fans, and turboprops are usually used on cargo planes and airliners. Some aircraft, like military fighter planes or experimental high-speed aircraft, requires very high excess thrust to accelerate quickly and to overcome the high drag associated with high speeds. For these airplanes, engine efficiency is not as important as very high thrust. Modern military aircraft typically employ afterburners on a low bypass turbofan core to provide tremendous thrust for faster acceleration to achieve better maneuverability with less concern on fuel efficiency. Future hypersonic aircraft will employ some type of scramjet with a rocket engine for propulsion.

3 BASIC EQUATIONS ON THRUST

The thrust generated by a propulsion system of an airplane can be explained by using Newton's laws of motion. Figure 9 shows the stream tube of the flow entering and exiting a generic propulsive device from left to right, where the reference frame is placed on the propulsion device moving at constant speed of V_i. This device may be a propeller, a jet engine, or a ramjet operating under steady-state conditions. The function of the propulsive device is to produce thrust T, acting to the left, as sketched in the figure. No matter what kind of propulsive device is used, the thrust is exerted on the device via the net resultant of pressure and shear forces distributions acting on the exposed surface areas, internal and/or external, at each point where air contacts any part of the propulsive device. According to Newton's third law, for every action, there is an equal and opposite reaction – the propulsion device will exert on the air an equal and opposite force T' acting to the right, as shown in the Figure.

As indicted in the figure, air will enter the control volume bonded by the dash line at inlet (left boundary) and leave the control volume at outlet (right boundary). The reacting

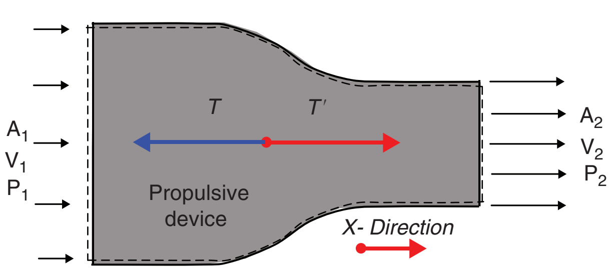

Figure 9. Thrust generation by a propulsive device.

force T′ that the propulsion device exerts on the air can be determined based on Newton's second law, which can be expressed as follows:

$$\sum \boldsymbol{F} = \frac{\partial}{\partial t}\int_{C.V.} \boldsymbol{V}\,\rho\,\mathrm{d} + \int_{C.S.} (\boldsymbol{V}\,\rho\,\boldsymbol{V})\cdot\mathrm{d}\boldsymbol{A} \tag{1}$$

Along the X direction, the above equation can be simplified with the assumption of steady flow condition inside the propulsion device and ignoring the effects of the pressure and shear stresses acting on the side "walls" of the stream tube. By invoking these assumptions, equation (1) becomes

$$T' + P_1A_1 - P_2A_2 = \dot{m}_2V_2 - \dot{m}_1V_1 \tag{2}$$

where $\dot{m}$, P, V, and A denote, respectively, the mass flow rate, pressure, fluid velocity, and cross sectional area at the inlet and outlet sections of the stream tube.

For a propulsion system like a gas turbine, a scramjet or a propeller, it uses air from the atmosphere as the working fluid for thrust generation. According to the conservation of mass principle, the mass flow rate at the outlet is equal to the mass flow rate of the air entering the inlet plus the fuel added. However, as a first approximation, the fuel flow rate can be neglected because it is relatively low when compared to the air-flow rate so that $\dot{m} = \dot{m}_1 \approx \dot{m}_2$. Therefore, the thrust force produced by the propulsive device reduces to

$$T' = \dot{m}\,(V_2 - V_1) + P_2A_2 - P_1A_1 \tag{3}$$

The term of $\dot{m}(V_2 - V_1)$ on the right side of the equation (3) indicates the time rate of the change of the air momentum as it flows through the propulsive device. For a propulsion device like a gas turbine, a scramjet or a propeller, air will be accelerated as it flows through the propulsion device (i.e., $V_2 > V_1$), which result in a net positive thrust. The air pressure at the inlet section is usually lower than ambient air pressure, while the air pressure at the exit section is almost equal to ambient air pressure. Therefore, the pressure terms in the equation (3) will also result a net positive thrust to power the aircraft.

For propulsion systems like rocket engines, air never enters so that the air mass flow rate at the inlet section ($\dot{m}_1$) will be zero (i.e., $\dot{m}_1 = 0$). Thus, the thrust force produced by a rocket is

$$T' = \dot{m}_2V_2 + P_2A_2 - P_1A_1 \tag{4}$$

The thrust given by equations (3) and (4) indicate that the amount of thrust generated by an airplane propulsion system depends primarily on how momentum of the mass entering the device is increased by the propulsion device. High thrust can be generated by accelerating a large mass of gas by a small amount as is done by propellers and turbofans or by accelerating a small mass of gas by a large amount like a turbojet, ram jet, or rocket.

It should be re-emphasized that the thrust equations given above are based on the assumption that the effects of the additional forces exert by the pressure and shear forces acting on the side "walls" of the stream tube were neglected. More detailed and comprehensive derivations of the thrust equations that do not make these simplifying assumptions can be found in Anderson (1998) and Farokhi (2008).

4 SUMMARY

An introduction is given on the forces that affect flight, namely, how weight must be overcome by lift and how drag must be overcome by thrust. On lift and thrust, natural flyers/swimmers, by virtue of their low weight and their low-Reynolds number flight regimes, achieve flight through flapping wings/fins that generate lift and thrust through unsteady means. For human flight, there is a wide spectrum of needs in terms of payload, speed, and range of flight, and this produces a spectrum of airframes to generate lift with minimum drag and engines to provide the thrust. Propellers and turbofans generate thrust by accelerating a large quantity of gas by a small amount, and are ideally suited for flights that involve mostly cruise at subsonic speeds because it can operate efficiently under these conditions. Turbojets, ramjets, scramjets, and rockets generate thrust by accelerating a small quantity of gas by a large amount, and are ideally suited for military aircraft that require fast acceleration at high speeds.

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