Fluid mechanics theory involved in helicopter flight engineering essay

The rotor of a helicopter provides four basic functions which are hovering, axial climbing, axial descent and forward flight.

In general, the thrust of helicopter is generated by its rotor blades. In hovering, the helicopter will remains stationary at the ground which means the thrust has the equal force with the total weight of helicopter. In axial climbing, additional thrust is generated to move the helicopter upward. Besides that, axial descent is another flight regime which will have opposite direction with climbing. This flight regime is more complicated because of the presence of both upward and downward flow in the rotor disk which can induce significant blade vibration. In the forward flight, the rotor disk is tilted in the flight direction to create a thrust component in desired direction. The component of the thrust in the forward flight direction must overcome the drag. Sometimes, the helicopter operation needs combination of two or more flight regime. For example, landing operation is a combination of forward flight and vertical descent.

The ideal situation for a helicopter is to achieve a constant lift throughout the rotor cycle. However, since the rotor blades rotate in a single direction, in forward flight there will be a force and moment imbalance. As the rotor blade moves in the same direction as the forward flight speed, the velocity near the blade is large and since the lift is proportional to the velocity, the angle of attack need not be large to achieve sufficient lift. On the other hand, as the blade moves in a direction opposite to the direction of flight, the relative velocity is smaller and the angle of attack must thus be larger to achieve the same total lift. Thus, without a moment-balancing mechanism, the helicopter would tend to roll. To balance the forces and moments, we can use the rotor-tail helicopter is used.

2. 0 FLUID MECHANICS THEORY INVOLVED

The helicopter must operate in a variety of flight regimes, for example, the hover, climb, descent, or forward flight. Besides that, helicopter may comprise of a combination of these few basic flight regimes in order to complete their flight. Usually, helicopters use their blades to control the flight regimes such as make some angle difference on their blades.

2. 1 Hovering

Hovering is one of the helicopter flight regimes and it is considered as a very unique flight condition because there has no forward speed as well as no vertical speed for helicopter.

Generally, in hovering, the lift force on helicopter is produced by the rotor of helicopter. In this case, rotor of the helicopter acts as a centrifugal axial pump, which is one of the turbomachinery applications, and causes the pressure difference between the top and the bottom of the blade. This pressure difference will produce a lift force and make the helicopter flight upward.

In order to do the analysis for the hovering of helicopter, we may do some assumptions:

The flow through the rotor is incompressible

Flow properties at a point do not change with time

Flow is one dimensional

Inviscid flow or the flow of a fluid that is assumed to have no viscosity.

In our assumption, flow is one dimensional which means that the fluid properties across any plane parallel to the rotor plane are constant. However it will change only with axial (vertical) position relative to the rotor. Besides that, we can consider an ideal fluid which no viscous shear between shear elements. As a result, the losses in the fluid resulting from the action of viscosity can be assumed as negligible.

Figure 1: Flow model used for analysis of a rotor in hovering flight. Data source: Leishman (2000).

Figure 1 shows that the helicopter’s rotor in an axial climb with velocity Vc , for which the hovering condition is obtained in the limit as Vc is closed to 0. The general equation of fluid mass, momentum, and energy conservation can be applied to the analysis of hovering rotor. This corresponds to the condition Vc 0 shown in Figure 1.

According to Figure 1, cross section 0 represent the plane far upstream of the rotor, where in the hovering case the fluid is quiescent (Vc V0 0). Cross section 1 and 2 are the planes just above and below the rotor. Whereas slipstream or downstream of the rotor is represented by cross section ∞ shown in Figure 1. At the plane of rotor, we can assume that the induced velocity in the control volume at the rotor disc is Vi.. The velocity at the slipstream is represented by w and finally the area of rotor disc is A.

By using the principle of conservation of mass and the assumption of flow properties in the flow is constant with time, we known that the mass flow rate, , must be constant within the boundary of the rotor wake (control volume). Wake is the region of re-circulating flow immediately behind or below a moving solid body. Besides that, from one dimensional incompressible flow assumption we can write down:

Mass passing through element in unit time, =

……………………………………………………………………… (1)

By using the principle of conservation of fluid momentum, we found the relationship between the rotor thrust, T and the rate of change of momentum out of the control volume (Newton’s second law). The rotor thrust is equal and opposite the force on the fluid, which is given by

Since in hovering flight the velocity well upstream of the rotor is quiescent, the second term of the right-hand side of above equation can be consider as zero(Hence, for the rotor thrust can be written as the equation:

……………………………………………………………………………………… (2)

From the principle of conservation of energy, the work done on the rotor is equal to the gain in energy of the fluid per unit time. The work done per unit time, or the power consumed by the rotor is TVi and this result in the equation

Power = TVi = gain in energy of the fluid per unit time

Again, in hover, the second term on the right-hand side of the above equation is zero so that:

……………………………………………………………………………………. (3)

From the Equation (2) and (3), we will have

……………………………………………………………………………………………. (4)

Therefore, we already have the relationship between the induced velocity in the plane of rotor and the slipstream velocity. From this relationship, we have known that the flow velocity increases in the wake below the rotor, continuity consideration require that the area of the slipstream must decrease. This is followed from the conservation of fluid mass between the rotor and from continuity of flow we have,

Mass of fluid entering per unit time

=

Mass of fluid leaving per unit time

+

Increase of mass of fluid in the control volume per unit time

Since the fluid flow around the control volume of rotor is assumed as steady flow, hence,

Mass of fluid entering per unit time = Mass of fluid leaving per unit time

Therefore another equation is formed:

From the Equation (4) we have,

So that in hover, the ratio of the cross-sectional area of the fully developed far wake to the area of the rotor disk is

……………………………………………………………………………………… (5)

In the other word, based on ideal fluid flow assumption, the vena contracta is an area that is exactly half of the rotor disk area. Vena contracta is an area in a fluid stream where the diameter of the stream is the least, for example, when the fluid come out from a nozzle or orifice. Alternatively, by considering the radius of the far rotor wake r∞, relative to that of the rotor, R,

Since A = 2pr2

……………………………………………………………………………………… (6)

Therefore, the ratio of the radius of the wake to the radius of the rotor is = 0. 0707. This is called the wake contraction ratio. In practice, it has been found experimentally that the wake contraction ratio is not as much as the theoretical value given by the momentum theory. However, it is only about 0. 78 compared to 0. 0707. This is because of some reason like a consequence of the viscosity of the fluid, the reality that a non-uniform inflow will be produced over the disk and a small swirl component of velocity in the rotor wake induced by spinning rotor blades. These effects serve to reduce change of the fluid momentum in the vertical direction, and they decrease the rotor thrust for a given shaft torque which is power supplied. In the other word, it will reduce the efficiency of the helicopter.

It has been shown previously using Equation (2) that conservation of momentum theory can be used to relate the rotor thrust to the induced velocity at the rotor disk by using the equation

…………………………………………………………………………………. (7)

Rearranging this equation and solving for the induced velocity at the plane of the rotor disk, Vh gives

……………………………………………………………………………. (8)

In order to find the power required to hover, we can use

……………………………………………………………………………………. (9)

This power is also called ideal power, from the Equation (9), we known that the higher rotor power will produce more thrust and bigger area of the blade of helicopter will produce the higher thrust if the rotor power is constant.

We also can find the relationship between the induced velocity and the rotor power by using P = Tvi and also Equation (4):

…………………………………………………………………………………. (10)

From Equation (10), it is shown that the power required to hover will increase with the cube of the induced velocity (or inflow) at the disk. Obviously, to make a rotor hover at a given thrust with minimum induced power, the induced velocity at the disk must be small. Therefore, the mass flow through the disk must be large and this consequently requires a large rotor disk area. This is a fundamental design feature of all helicopters.

2. 1. 1 Pressure Variation in Hovering

The pressure variation through the rotor flow field in the hover state can be found from the application of Bernoulli’s equation along a streamline above the rotor disc. Since there is a pressure jump across the disc, and this will produce addition energy by the rotor, so that Bernoulli’s equation cannot be applied between points in the flow across the disk. However, the pressure jump is uniform over the rotor disk so the Bernoulli’s equation can be applied to all streamline contained within the control volume instead of the energy equation. For incompressible flow, the Bernoulli’s equation is an alternative to the energy equation. Applying Bernoulli’s equation up to the disk between section 0 and 1 in Figure 1 produces

………………………………………………………………………… (11)

Below the disk, between section 2 and ∞ in Figure 1, the application of Bernoulli’s equation gives:

……………………………………………………………………… (12)

Since the pressure difference is uniform, as a result, the value must be equal to the disk loading T/A. Hence,

and

……………………………………………………………………………………… (13)

It is seen that the rotor disk loading is equal to the dynamic pressure in the rotor slipstream. One can also determine the pressure just above the disk and just below the disk in term of the disk loading. Then, we use the Bernoulli’s equation:

Above the disk

………………………………………………………………………………….. (14)

Below the disk

…………………………………………………………………………………. (15)

Therefore, the static pressure is reduced by ¼ (T/A) above the rotor disk and increase by ¾ (T/A) below the disk. As a result, this lift force (thrust) will be produced because of the pressure difference between the above and below the disk will make a change in flow direction namely from the higher pressure (below the disk) to lower pressure (above the disk).

2. 2 Axial Climb

Climbing flight performance is an important operation because sufficient power must be design to the rotor blade helicopter to perform this type operation.

In climbing fight, we can use the same assumption as well as apply the three conservation laws in hovering. In contrast to the hover case, the relative velocity far upstream relative to the rotor now will be Vc. At the plane of the rotor, the velocity will be , and the slipstream (vena contracta) velocity is . By the conservation of mass, the mass flow rate is constant within the boundaries of the wake and so

By the principle of conservation of momentum and

……………………………………………………………………………. (16)

This equation is same as Equation (2) which obtains for the rotor thrust in the hovering.

However, the work done by the climbing rotor thrust is now

…………………………………………………………. (17)

From Equation (16) and (17), we can get the relationship between the w and Vi :

W= 2Vi

From Equation (16):

Hence, from Equation (8),

……………………………………………………………. (18)

Equation (18) is a quadratic equation in, and this equation has the solution of

Since the value of must be positive hence,

……………………………………………………………… (19)

The Equation (19) shows that when the climb velocity increases, the induced velocity at the rotor will decrease.

2. 3 Axial Descent

The hover and climb model cannot be used for descent because the Vc is directly upward and so the slipstream will be above the rotor. In addition, the magnitude for the Vc must be twice of the average induced velocity at the disk or we can write mathematically the range of Vc :

Figure 2: The assumed flow model and control volume surrounding of descending rotor. Data source: Leishman (2000).

Form Figure 2, we found that the slipsteam will always exist above the rotor and encompassing the rotor disk. The velocity at the far upstream the rotor is equal to Vc . In order to make thing easier, we assumed that Vc is positive when the direction is downward.

By conservation of mass, the fluid mass flow rate through the disk is,

By conservation of fluid momentum give in this case

……………………………………………………………………………. (20)

In the Equation (20), the negative sign arising because the flow direction is opposite to the climb case. In steady descent, the velocity far upstream of the rotor must be finite.

The work done by the rotor in descending is

……………………………………………………………….. (21)

The Equation (21) shows the negative value. This shows that the rotor is now extracting power from the airstream and this operation condition is known as windmill state. By using equation (20) and (21), we can get the relationship between the w and Vi:

w= 2Vi

Since the net velocity in the slipstream is less than Vc and so from the continuity considerations the wake boundary expands above the descending rotor disk. For the descending rotor

Hence, from Equation (8),

……………………………………………………… (21)

Equation (21) is a quadratic equation in, and this equation has the solution of

Since the value of must be more than 1 hence,

………………………………………………………. (22)

The Equation (22) is only valid for, and this equation shows that when the descent velocity increases, the induced velocity at the rotor will decreases asymptotes smoothly to zero at high descent rate.

3. 0 ANTI TORQUE DEVICE

The vast majority of helicopters in production are of the single main rotor with tail rotor configuration. The primary purpose of the tail rotor is twofold. First, the tail rotor provides an anti-torque force to counter the torque reaction of the main rotor on the fuselage. Second, the tail rotor gives yaw stability and provides the pilot with directional control about the yaw axis. The aerodynamics of the tail rotor provides the helicopter with significant weathercock stability. For example, if the aircraft is yawed nose-left, then the tail rotor will experience an effective climb. If the collective pitch is held constant, then this will result in a decrease of thrust (a result of higher inflow) and restoring moment about the yawing axis. Similarly, if the helicopter yaws nose-right, the tail rotor experience an effective descent, with an increase in thrust, and again, a restoring moment is produced. The weathercock stability is a useful characteristic, but it can also make helicopters less maneuverable.

The tail rotor has to operate in a relatively complex aerodynamic environment and must produce thrust with the relative flow coming from essentially any direction. For example, the tail rotor must operate properly in side winds and during yaw maneuvers. In a yawing maneuver, the tail rotor operates either in an effective climb mode or in descent, depending on the yaw direction. The yawing direction that produces an effective descending condition is the most critical because it is possible for the tail rotor to enter the vortex ring state. This can result in a loss of tail rotor authority, and perhaps even loss of control under the wrong combination of conditions. These effects are carefully examined during certification of the helicopter to ensure that there is a minimal chance that the machine will inadvertently exhibit undesirable flight characteristic.

As describe previously, the tail rotor is also mounted in proximity to a vertical fin or other empennage assembly, and the aerodynamic interactions will effect tail rotor operation. In addition, the operation of the tail rotor will be affected by turbulent separated flow generated by the main rotor hub a fuselage wakes and the energetic main rotor wake itself. This adverse environment means that the aerodynamic design requirements for the tail rotor are different in some respects from those of the main rotor. For these reasons, it is known to be difficult to design a tail rotor that will meet all the aerodynamic, control, stability, weight, and structural requirements.

The primary purpose of the tail rotor is to provide a sideward force in a direction and of sufficient magnitude to counter the main rotor torque reaction. The tail rotor also provides yaw control. Roughly, the tail rotor consumes up to about 10% of the total aircraft power. This is power that is completely lost, because unless the tail rotor is canted, as on the UH-60 Blackhawk, it provides no useful lifting force. The purpose of the canted tail design is to widen the allowable center gravity of the aircraft. This, however, introduces an adverse coupling between yaw and pitch, but this effect can be minimized by a flight control system.

The direction of the anti-torque force depends on the direction of the rotation of the main rotor. For a rotor turning in the conventional direction (counterclockwise direction when viewed from above), the tail rotor thrust is to the right (starboard). The magnitude of this thrust as well as the power consumption depends on the location of the tail rotor from the center of gravity (i. e., the moment arm). The main rotor torque reaction effect,, is cancelled when the tail rotor moment is equal to the yaw reaction torque, that is, , where is the yaw acceleration and is the mass moment of inertia about the yaw axis.

The tail rotor thrust is controlled by the pilot’s feet by pushing on a set of floor mounted pedals. For example, for a rotor turning in the conventional direction, pushing on the left pedal increases tail rotor thrust (positive to starboard) and the helicopter will yaw nose left. The tail rotor must also provide the specified yaw acceleration in the maximum specified crosswind conditions, taking into consideration possible losses on efficiency because of aerodynamics interference effects between the tail rotor and the vertical fin. Keep in mind that when the main rotor thrust or power is increased, for example to climb, the reaction torque, , on the fuselage is increased. This means that the tail rotor thrust must also increase to balance this torque reaction, therefore, when the pilot increases the collective to climb, he or she must also apple foot pressure to the appropriate pedal to keep the nose pointed straight in the direction of the flight.

4. 0 CONCLUSION

The main considerations in designing a helicopter are the ability to operate efficiently for long periods of time in hover, high cruising efficiency and speed, range, and payload. All of these considerations are influenced greatly by the aerodynamics of the rotor blades and by other interactions between various components. Unlike fixed-wing aircraft, the helicopter often operates in an unsteady environment; whether in hover or in forward flight, the helicopter operates in, or very nears, its own wake which is three-dimensional and highly unsteady.

In hover, theoretically, trim and flap are not required to balance forces on an isolated rotor. However, non-uniformities and the presence of the fuselage make them necessary. In addition, rotor blades are twisted and often tapered. A twisted blade is one in which the local geometric pitch angle varies along the span. To provide trim capability and for aeroelastic stress relief, helicopter rotors are often hinged in the sense that the rotor blades must be permitted to bend out of the rotor disk plane as well as pitch to satisfy trim requirements. Rotor blades have a large span-to-chord ratio and thus severe stresses can be communicated to the hub if the blades are not permitted to flap. However, if the blades are aeroelastically soft, then hub stresses can be kept to a minimum and hinges can be eliminated. In such cases, the rotor is said to be hingeless.