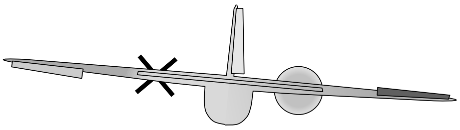

Control and Performance During Asymmetrical Powered Flight

Detailed theoretical paper
in accordance with the JAA Learning Objectives,
US Federal Aviation Regulations and EASA Certification Specifications

for

Multi-engine Rated Pilots
CPL & ATPL

Based on
Airplane Design Methods as taught by Aeronautical Universities
and
Flight Test Techniques as taught by Experimental Test Pilot Schools

January 2012

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Much of the theory is also included in a video on YouTube (ref. [7]). An oral presentation to accompany this paper is available as well.

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[1] (-) denotes nice-to-know; not required in the Learning Objectives for multi-engine rating, yet very relevant.

LIST OF FIGURES

1. INTRODUCTION

Propulsion systems (engines, propellers) are nearly, but never 100% perfect and may occasionally fail during takeoff, go-around, while en-route, and during approach. Multi-engine airplanes are designed to be able to continue to fly safely when an engine fails or is inoperative. Nevertheless, accident investigation reports, published on the Internet, reveal that during the past 25 years more than 400 propulsion system malfunctions of multi-engine airplanes resulted in accidents, during which more than 4,000 people lost their lives. Many more engine failure related accidents must have happened in countries or organizations that do not report on the Internet. Obviously, equipping an airplane with more than one engine does neither guarantee safety immediately following a propulsion system malfunction nor during the remainder of the flight while an engine is inoperative. During the research for writing this paper, the author noticed that most textbooks and Airplane Flight Manuals explain the controllability and performance after engine failure in a different, in some cases even incorrect way as compared to airplane design methods taught by Aeronautical Universities and flight-test methods and conditions as presented in FAA and EASA Flight Test Guides and as taught at formal Test Pilot Schools.

Learning Objectives require multi-engine rated pilots to have knowledge of flight with asymmetrical thrust (ref. [1]). This paper complies with these objectives and presents the theory that formal Test Pilot Schools [2] and Aeronautical Universities teach [3]. It also complies with Federal Aviation Regulations and EU Certification Specifications and equivalent for Part 23 and 25 airplanes and with Flight Test Guides for flight-testing airplanes with an inoperative engine, ref.'s [4], [5], [6].

This paper briefly reviews some of the forces and moments that act on multi-engine airplanes after one of the engines fails and briefly describes the design method used by the tail design engineer for sizing the vertical tail, during which the minimum control speed of the airplane is born and bred. The controllability at low speed while the asymmetrical thrust is high and the (remaining) performance while an engine is inoperative will be explained, as will be most of the factors that have influence on the One Engine Inoperative (OEI) controllability and performance. The experimental flight-tests to determine the minimum control speeds are explained and finally, some aspects of flight operations with an inoperative engine are reviewed, and a few improved and important first steps of engine emergency procedures are introduced.

Pilots, after reading and understanding this paper, will be able to maintain control of their multi-engine airplane after engine failure during takeoff, go-around, approach, or en-route, and return home safely. A supporting video lecture is presented in ref. [7].

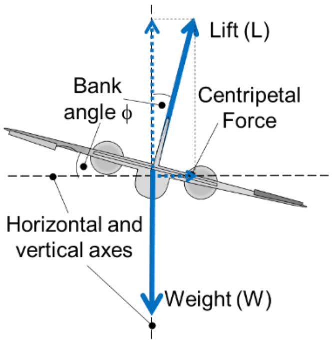

Figure 1. Centripetal force in flat earth referenced coordinate system.

2. FORCES AND MOMENTS

2.1. Body-fixed axes

Pilots are used to explain turning an airplane using the horizontal component of the wing lift L (in the flat Earth coordinate system), also called the centripetal force (Figure 1). When an airplane is banking, a turn is made. But this is not always the case; the rudder and the bank angle play an important role as well. Glider pilots use a bank angle with opposite rudder to increase the rate of descent during approach for a spot landing. And how would a knife-edge maneuver – straight flight while maintaining a bank angle of 90° that fighter airplanes sometimes perform during airshows – be explained? And how the yawing and rolling motions about their axes that occur when an engine fails? For those maneuvers, and for analyzing the controllability before and after engine failure, when the flight is no longer coordinated, the body-fixed coordinate system is used by aeronautical engineers during designing the airplane and by experimental test pilots and flight test engineers to prepare for (engine-out) flight testing. Figure 2 shows the body axes and the most relevant forces and moments that act on the airplane. Body-fixed axes are also called axes of motion.

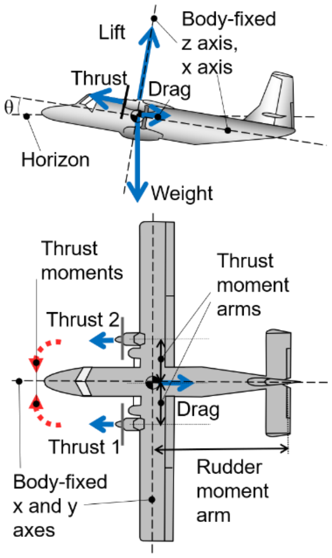

Figure 2. Forces and thrust moments acting on multi-engine airplanes in level flight.

2.2. Forces

A force, or the resultant of several different forces, causes an acceleration in the direction of the force or of the resultant of the forces. The thrust of an engine is a force, as is the drag of an airplane (Figure 2). If the total thrust force is equal to the drag force, then the airplane no longer accelerates or decelerates and maintains the achieved steady airspeed. The aerodynamic airfoils of an airplane, like wings, tail, and control surfaces, all develop forces (lift) that can be calculated with the equation $\frac{1}{2}\rho V^2 S C_{L\alpha}$ in which ρ is the air density, V is the airspeed and S is the surface area of the aerodynamic airfoil, and Lift coefficient $C_{L\alpha}$, which does not only depend on the shape and other characteristics of the aerodynamic airfoil, but also on its angle of attack (α) to the free air stream. The equation does not only apply to 'horizontal' airfoils, but also to the vertical tail with rudder. Notice that airspeed V has a significant (quadratic) influence on the generated lift, and on the sideforce generated by the vertical tail.

The forces most relevant to the control of a multi-engine airplane after engine failure are the thrust of the operative engine opposite of the inoperative engine, the propeller drag of the failed engine, the side forces generated by the fuselage and the vertical tail due to sideslip (weathercock), the sideforce generated by the rudder deflection, and the drag of the airplane. Refer to the blue solid vectors in Figure 3. Another very important sideforce due to banking will be introduced below.

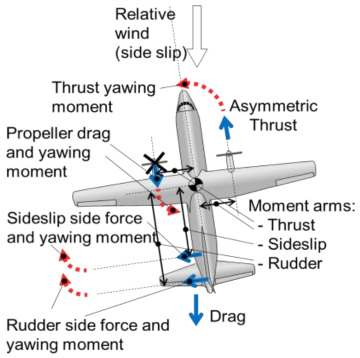

Figure 3. Forces, their moment arms and moments, shortly after engine failure.

2.3. Moments

Forces acting on an airplane also cause moments, which are rotating forces, if the forces do not act in or through the center of gravity of the airplane. A moment is a force times its moment arm; a moment arm is the perpendicular distance from the center of gravity to the line along which the force acts. The moments are shown as red dotted curved vectors in Figure 2 and Figure 3.

The figures presented in this paper do not show all of the forces and moments that act on an airplane; the ones shown are not to scale.

The most important moments, relevant for explaining the controllability of multi-engine airplanes after engine failure, are the thrust yawing moment generated by the wing-mounted operative engine(s), the yawing moments generated by the side forces of the fuselage, by the vertical tail when the sideslip angle is not zero, and by the rudder when deflected. Figure 3 shows the most important forces and moments acting on a multi-engine airplane when engine #1 is inoperative.

The pitching moment change caused by engine failure is usually small; the horizontal stabilizer and elevator are dimensioned to be able to handle the change easily.

When an engine fails, or is inoperative, the corresponding opposite operative engine causes a large yawing moment about the center of gravity that can only be counteracted by the yawing moment generated by the rudder and/ or by the side force that is developed by the fuselage and vertical tail (fin) due to the sideslip. A small bank angle also plays an important role, as will be shown in § 3.4 below.

Required for equilibrium,
for steady flight:

Sum of all forces = 0

and

Sum of all moments = 0

2.4. Straight equilibrium flight with an inoperative engine

For straight equilibrium (trimmed) flight, balance is required of all forces and of all moments that act on an airplane; both the sum of all forces and the sum of all moments need to be equal to zero. This also applies when an engine is inoperative. Any change in forces, such as engine thrust or control deflection will change the sum of forces and moments, resulting in an acceleration in the direction of the resultant of the remaining forces or moments that only ceases when both the sum of all forces and the sum of all moments are again zero. Then a new equilibrium, a new balance of forces and moments, is achieved. If the sum of all forces and the sum of all moments cannot become zero anymore, then the airplane continues to accelerate and/or rotate; the airplane is out of control.

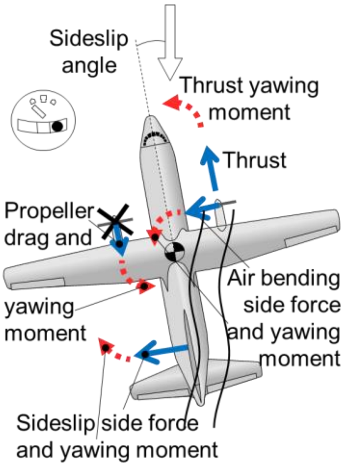

Figure 4. Some of the side forces and yawing moments immediately after engine failure.

3. AIRPLANE CONTROL WHILE AN ENGINE IS INOPERATIVE

3.1. Engine failure

When an engine or, more appropriate, a propulsion system fails and the corresponding opposite engine is generating high thrust, the thrust distribution on the airplane has become asymmetrical causing a large thrust yawing moment resulting in a yaw rate in the direction of the failed engine (Figure 4). Instantaneously, a sideslip develops causing the total drag of the airplane to increase considerably and hence, the Rate of Climb (ROC) or the altitude to decrease. The yaw rate is not always large; if the failing engine is a turbojet/ -fan, the thrust decay might be slow and undetected for some time. If, however, the failing propulsion system includes an automatic feathering propeller, the loss of thrust and, consequently, the buildup of yaw rate, might be very fast.

Yaw rate detection is not easy anymore on modern airplanes, especially at night or while in Instrument Meteorological Conditions (IMC) when the yaw rate is not easily observable on a turn & bank indicator or on the primary flight display. On some airplanes, a yaw rate can only be detected while monitoring the (slow moving) heading scale.

The yawing continues to increase until the thrust yawing moment is balanced by opposite yawing moments, such as the yawing moment due to sideslip (as long as the pilot not yet deflects the rudder). Then the sum of the yawing moments is zero after which the yawing does not increase any further. The sum of the side forces might however not yet equal zero. Equilibrium, i.e. balance of side forces, is not yet achieved. The resultant side force due to sideslip continues to accelerate the airplane sideward (slowly) to the dead engine side until the resulting sideslip side force is balanced by another or some other side force(s). This will again change the sideslip angle as well. Equilibrium of forces and moments is possible, but the remaining sideslip increases the drag and reduces the climb performance or altitude.

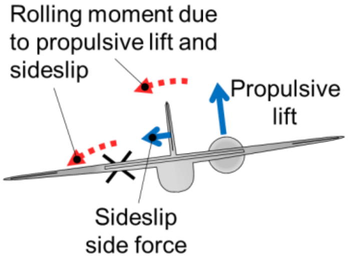

Figure 5. Some of the rolling moments after engine failure – no control inputs yet (in body axes).

Besides the yaw rate due to asymmetrical thrust, a roll rate develops as well because of the speed changes of both wings and due to the sideslip (dihedral and wing blanking by the fuselage). On propeller airplanes, an additional rolling moment develops because of the loss of propulsive lift of the wing section behind the failed propulsion system (Figure 5). Turbojet/ -fan airplanes do not have blown wing sections because the engines are mounted below or above the wings, but the sideslip angle reduces the frontal area of the downwind swept wing considerably, increasing the rolling moment.

The asymmetrical slipstream of the propeller will also have effect on the vertical tail as the sideslip angle increases.

When the airspeed is low (during takeoff, approach, or go-around), the control power of the aerodynamic control surfaces rudder and ailerons is small ($\equiv V^2$). The asymmetrical engine thrust however, is the same as at higher speed resulting in larger yaw and roll rates at low speeds.

If the pilot makes no timely control input to counteract the yawing and rolling motions, the airplane will accelerate to and settle in a new equilibrium under the influence of the forces and moments that act on the airplane, or crashes if an equilibrium is not timely established. Pilot action is required to recover, to reduce the drag and to prevent a crash.

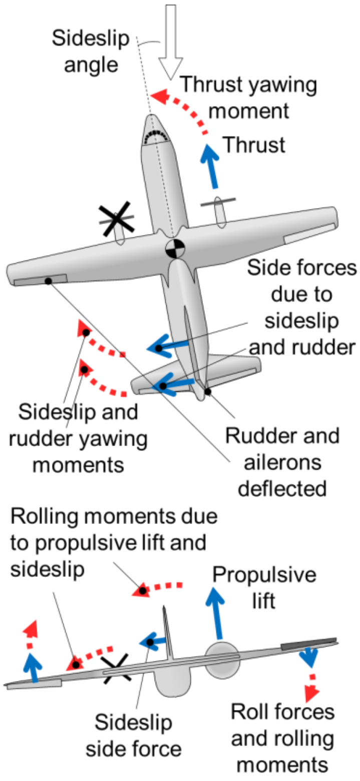

Figure 6. Side forces and yawing moments required for recovery.

3.2. Recovery

To recover to steady straight and controlled flight, first the airplane transient motions must be arrested as soon as possible to prevent an uncontrollable attitude and excessive drag from developing. The controls available to the pilots for recovery are the aerodynamic controls, like rudder, ailerons, and elevator, but also the propulsive directional controls: the throttles or power levers. At low altitude, a pilot will hesitate to (temporarily) reduce the throttle of the corresponding opposite engine (a little) to reduce the asymmetrical thrust yawing moment because of the loss of performance, unless there is enough runway length available to land straight ahead.

A rudder is normally sized – and on big airplanes boosted – to be able to provide adequate aerodynamic control power to counteract the yawing motion generated by asymmetrical engine thrust, down to a certain speed. Ailerons have small control power under low-speed conditions too, but are – on big airplanes – assisted by powerful spoilers. All pilots are aware though, that the downward deflection of an aileron increases the local angle of attack of the wing section in front of that aileron, which – if the airspeed is low – might result in a partial wing stall that causes an uncommanded roll, which only aggravates an already critical situation.

If the asymmetrical thrust is maintained, the moments required for recovery and thereafter maintain straight flight are a yawing moment equal to and opposite of the asymmetrical thrust moment generated by the rudder (Figure 6) and also a rolling moment opposite of the rolling moments due to propulsive lift and sideslip. The rudder is the only aerodynamic control available to the pilot to balance or counteract the thrust yawing moment. The rudder should be smoothly applied proportionate and simultaneously with the thrust decay (up to maximum, if required) to prevent or stop the yawing and maintain the (runway) heading. The rudder-generated side force provides a rudder yawing moment that adds to the sideslip yawing moment (that normally provides the weathercock stability). Provided the airspeed is high enough, the sum of these moments will be large enough to overcome the thrust yawing moments and stop the yaw. The ailerons – on big airplanes assisted by spoilers – are used to reverse the roll rate and thereafter balance the propulsive lift moment and other rolling moments due to sideslip for the sum of the rolling moments to equal zero.

If the aerodynamic control power of the rudder and/ or ailerons is insufficient to recover to and thereafter maintain a safe equilibrium under high asymmetrical thrust conditions, then the airspeed is too low. The airspeed is lower than the minimum speed required for maintaining control of the airplane, which is also called *minimum control speed in the air*, abbreviated V_{MCA}. When the airspeed is as low as V_{MCA} when an engine suddenly fails, the pilot should expect the bank angle to increase to 45° and a heading change of up to 20°, which are the test limits as discussed in § 6.2 below. *V_{MCA} is often inappropriately abbreviated as V_{MC} which is used as minimum control speed in the takeoff configuration, but a minimum control speed applies as soon as and as long as the airplane is in the air, during the whole flight from takeoff to landing. The definitions of V_{MC}, V_{MCA} and other V_{MC}'s are explained in § 5.13 below.*

V_{MC} or V_{MCA}?

Recovery at airspeeds at or below V_{MCA} is still possible though, but only by the already mentioned propulsive directional control, i.e. by reducing the thrust a little, temporarily. This is the only means left when full rudder and/ or ailerons seem not effective enough to counteract the asymmetrical thrust yawing moment. Then the airplane continues to yaw and/ or roll despite the maximum opposite control inputs. If the asymmetrical thrust is reduced temporarily a little, the thrust yawing moment decreases below the aerodynamic yawing moments at the current airspeed. Then rudder and ailerons provide again adequate control power to recover. Once control is re-established, thrust can be increased again (provided another condition is also met, § 5.1).

Following recovery after a sudden engine failure and during subsequent flight with an inoperative engine, many combinations of rudder and aileron deflections are possible that will achieve balance of lateral and directional forces and moments for a safe straight (equilibrium) flight, but there are differences in the remaining control and performance. Two combinations or options, that are most relevant to takeoff and go-around, will be discussed. A third option, straight flight with no or partial rudder input is also included, because this resulted in many accidents.

3.3. Straight flight with wings level

Federal Aviation Requirements (FAR) and EASA Certification Specifications (CS) 23.149 and 25.149 and equivalent require a multi-engine airplane to be capable of maintaining straight flight only when an engine is inoperative, and the thrust of the remaining engine(s) is set to maximum. There is no requirement to be able to maintain control during turns to either side at maximum asymmetrical thrust setting and airspeeds as low as or near V_{MCA}, such as V_{YSE}. A few options exist for a pilot to maintain a safe straight flight for climbing to a safe altitude where shallow turns can be made at a lower thrust setting. These options are subject to (experimental) flight-testing, and will be discussed below.

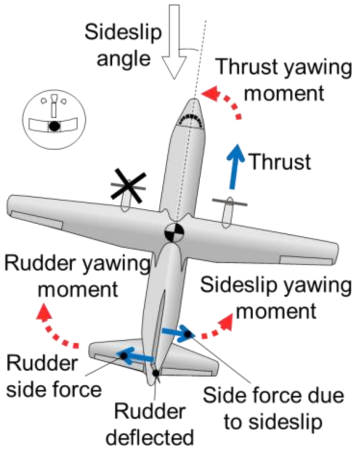

Figure 7. Side forces and yawing moments for maintaining straight, wings level flight.

Following recovery to straight flight after engine failure, the rudder side force remains required to balance the asymmetrical thrust. The rudder side force also causes the airplane to accelerate in the direction of the force causing a sideslip to the left (into the dead engine). This sideslip causes a side force due to sideslip opposite of the rudder side force (Figure 7) which continues to increase until the side force generated by the sideslip is equal to the rudder side force. Then the sum of the side forces equals zero; a balance of side forces is established. The yawing moment due to the sideslip side force however, adds to the asymmetrical thrust yawing moment. Therefore, the rudder deflection needs to be increased to counteract this additional yawing moment as well, or a higher airspeed is required if the rudder control power is not adequate. The sideward acceleration continues until eventually a balance of side forces is established; the rudder will still have to be deflected to maintain a zero yaw rate. A sideslip cannot be avoided; the sideslip angle and hence the drag, depend very much on the airspeed and on the asymmetrical thrust level.

If the airspeed is low or is decreasing, the rudder generated side force decreases because the control power of the vertical tail with the deflected rudder decreases ($\equiv V^2$, § 2.1). An increased rudder deflection is required to increase the rudder side force and achieve and maintain a balance of side forces and yawing moments for straight flight with – in this case – the wings level. The airspeed can be decreased until the rudder deflection is maximum. Below this airspeed, yawing cannot be avoided any more by using the rudder, meaning that straight flight can no longer be maintained; control of the airplane will be lost. Therefore, the airspeed at which straight flight can only just be maintained while keeping the wings level and with maximum rudder or aileron deflection and maximum asymmetrical thrust is called the *wings-level minimum control speed*. A sideslip is required, i.e. cannot be avoided, for straight flight with the wings kept level, although the ball of the slip indicator is in the middle. Under asymmetrical thrust, this is an indication of no residual side forces (Figure 7) and not of zero sideslip.

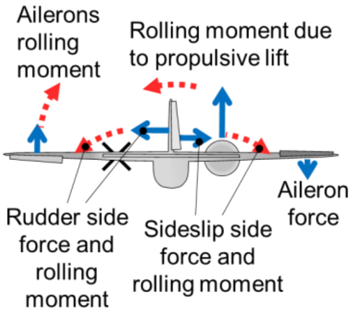

Figure 8. Forces and rolling moments for maintaining straight, wings level flight.

Figure 8 shows the control and sideslip forces and rolling moments in a rear view. The wings can be kept level if the sum of the rolling moments can be made zero.

On some airplanes, maximum aileron deflection is reached before maximum rudder deflection at low airspeed. In that case, the ailerons and not the rudder determine the (*wings-level) minimum control speed*.

Conclusion. A wings-level attitude is easy to fly, but the consequence of keeping the wings level is a sideslip that generates additional drag and therewith decreases the (n-1) climb performance. Some small two-engine airplanes at high takeoff weight do not have a positive rate of climb anymore when the wings are kept level while an engine is inoperative and the corresponding opposite engine set at maximum thrust.

Therefore, another option is urgently needed to reduce the drag, i.e. to reduce the sideslip as much as possible, which is discussed next.

3.4. Straight flight with zero sideslip

If the sideslip is zero, there will obviously be no side force due to sideslip. As explained in the previous paragraph, besides rudder and aileron deflection to balance the asymmetrical thrust yawing and rolling moments, another side force is definitely required to balance the rudder side force (that remains required to counteract the asymmetrical thrust) and to reduce the sideslip, hence drag. This side force can easily be generated; the airplane design engineer already used it at the drawing board for sizing the vertical tail.

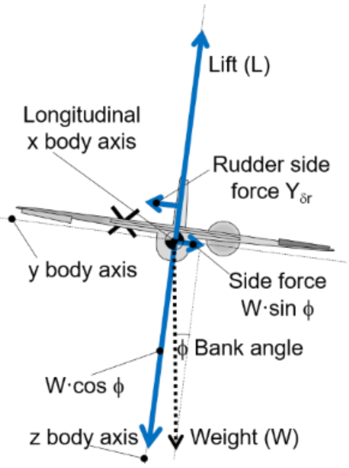

Figure 9. Side forces produced by bank angle and rudder (in body y axes – steady straight flight).

One of the Learning Objectives [1] is the effect of weight and bank angle on airplane control after engine failure. Weight vector W always points to the center of the earth. When an airplane is banking with bank angle ϕ, a component of the weight vector (W·sin ϕ) acts as side force in the center of gravity in the y body axis of the airplane, parallel to the wings (Figure 9). Refer to § 2.1 for a description of the body axes.

As the Lift is acting in the z-body axis, it has no lateral component in the y-axis and generates no side force because the z-axis is perpendicular to the y-axis. Components of the Lift (and Weight) do appear in a side view of the airplane, in the x-z plane, which is not of relevance for lateral-directional control.

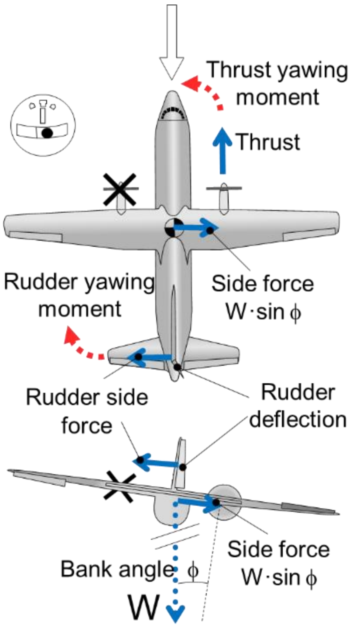

Figure 10. Forces and moments during straight flight with zero sideslip; small bank angle required.

Side force W·sin ϕ can be used to replace the side force due to sideslip of the previous case (§ 3.3, Figure 7) for balancing the side force due to rudder deflection when an engine is inoperative (Figure 10). So, by banking, a balance of side forces can be achieved with zero sideslip, i.e. with minimum drag (hence maximum rate of climb). Rudder deflection remains required though, for counteracting the asymmetrical thrust yawing moment. Side force W·sin ϕ generates no rolling or yawing moments because it acts in the center of gravity; its moment arm is zero. Side force W·sin ϕ varies obviously with weight (W) and bank angle (ϕ) and acts in the direction of banking. The effect of weight and bank angle will be discussed in detail in § 5.1 below.

In this zero sideslip or lowest drag case, the rudder side force only has to generate a yawing moment for balancing the asymmetrical thrust moment and does not have to overcome side forces due to sideslip anymore (as shown in Figure 7), so less rudder deflection for the same airspeed is required as compared to straight flight with wings level as discussed in the previous § 3.3. Therefore, the airspeed can be between 8 (small twin) and 30 knots (4-engine airplane) lower until either the rudder and/ or aileron limits are again reached, depending on size and engine configuration of the airplane. The airspeed at which this occurs is the *minimum control speed* for straight flight with zero sideslip, i.e. with a small bank angle. The ball of the slip indicator is in this case about half a ball width into the good engine, because the wings are banked a few degrees, for the side forces to be balanced.

The engineer designing the vertical tail dimensioned the vertical tail using a small bank angle of maximum 5° away from the inoperative engine as allowed by

Regulations FAR/ CS 23.149 and 25.149 (ref. [4], [9]). These design considerations are briefly explained in § 4 below. The sideslip for the given tail size is zero only at a certain bank angle, which varies with airspeed. The higher the airspeed, the less rudder deflection is required to balance the asymmetrical thrust and the smaller the bank angle (W·sin ϕ) can be to balance the rudder side force.

Conclusion. In this zero-sideslip case, a rudder generated side force remains required for balancing the asymmetrical thrust. Banking a few degrees towards the operative engine (live engine low; to the same side as rudder pressure) generates a side force opposite of the rudder generated side force, therewith reducing the sideslip and hence the drag to a minimum, leaving maximum possible climb performance. The actual *minimum control speed* for small twins is ≈ 8 kt lower than when keeping the wings level.

For takeoff or go-around after engine failure or while an engine is inoperative, it is of vital importance that the remaining climb performance is maximum. This requires the drag to be minimal, which will be the case only if the sideslip is zero, which in turn will only be the case if a small bank angle, usually between 3° and 5°, as the manufacturer should have published in the Airplane Flight Manual (AFM), is attained and maintained away from the inoperative engine. For most small twin engine airplanes, this zero-sideslip option is the only option for maintaining control and achieving some climb performance while an engine is inoperative and the corresponding opposite engine is producing maximum thrust. Hence, the pilot controls the drag, i.e. the remaining ROC, using ailerons and rudder.
Accidents have learned though, that pilots do not always use maximum or adequate rudder to counteract the yawing. This is the subject of the next paragraph.

3.5. Straight flight with zero or only partial rudder

This case should be of academic interest only, but is included to show the consequences of using the rudder only partial or not at all for counteracting the asymmetrical thrust. Many accident investigation reports show that pilots used no or only partial rudder before they lost control of their airplane and crashed.

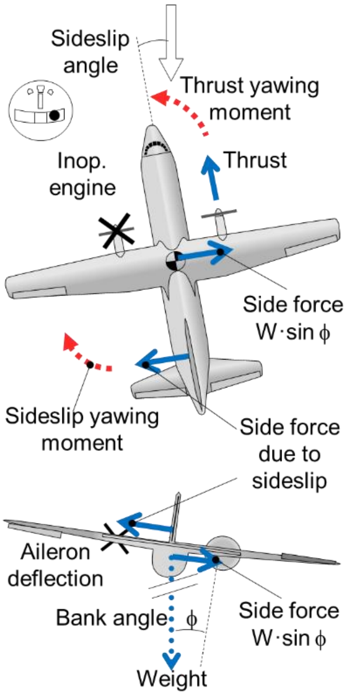

Figure 11. Forces and moments during straight flight with zero rudder.

If, after engine failure, the rudder is not deflected at all to stop the yawing, only the yawing moment generated by the sideslip side force can balance the asymmetrical thrust yawing moment. The drag will be huge, the ROC will most probably be small or negative. To achieve a more favorable balance of side forces with no or partial rudder, the side force due to banking (W·sin ϕ), that was explained in the previous paragraph, can also be used here (Figure 11). Side force W·sin ϕ acts in the center of gravity and does not influence the yawing moments. In this no-rudder case, the required bank angle for maintaining straight flight will exceed the maximum approved 5° at low airspeeds (in FAR/CS 23.149, 25.149). The resulting remaining sideslip increases the horizontal angle of attack of the vertical tail, the fin, which might result in a fin stall and therewith in a certain loss of control. The drag in this no rudder case will be high, the climb performance most certainly negative. A higher airspeed will be required to reduce the sideslip angle and decrease the required bank angle for equilibrium straight flight: the actual *minimum control speed* with zero rudder is higher.

If, after engine failure or while an engine is inoperative, the rudder is only deflected partially, the vertical tail with rudder cannot develop as much side force as with full deflection. Therefore, as the side force varies with V^2, the airspeed needs to be higher than with maximum rudder deflection to be able to counteract the still high asymmetrical thrust and maintain the heading. Hence, the *actual minimum control speed* with partial rudder is higher, the drag not as low as possible and hence, the climb performance not maximal.

The fatal accident with a Saab SF-340B, analyzed in ref. [12], was caused by inappropriate use of the rudder during a go-around with one idling engine of which the propeller was not feathered. This increased the thrust yawing moment, and the *actual* minimum control speed, which increased above the actual airspeed and rendered the airplane out of control. The rudder is often not adequately used.

Conclusion. When the rudder is not or only partial deflected after engine failure while the power setting is high and the airspeed low, the airplane will yaw and start sideslipping; the drag will increase and the climb performance decrease. A bank angle in excess of the maximum approved 5 degrees is required for balancing the side forces, resulting in a large sideslip angle that might result in a fin stall. Not only the performance is affected, the minimum speed for maintaining control is higher as well. This option is not thoroughly flight-tested and not recommended to fly.

3.6. Control during turns

As mentioned above, FAR and CS do only require a V_{MCA} to be determined for straight flight while an engine is inoperative, and the asymmetrical thrust is maximal. As already analyzed above, there is a relation between bank angle and minimum control speed; V_{MCA}, while banking 5° away from the inoperative engine, is lower than V_{MCA} with the wings level. During a turn, there still must be a net side force that counteracts the asymmetrical thrust yawing moment, requiring rudder and/ or sideslip. So, the question needs to be answered what the effect of bank angles other than 0° and 5° is on V_{MCA}, i.e. during turns to either side. These effects are analyzed in § 5 below and in a YouTube video, ref. [7]. Pilots must read this or view if they want to survive an engine failure.

3.7. Engine-out Trainer – University of North Dakota

In the introduction of this paper, the references presented were the USAF Test Pilot School [2], the US Naval Test Pilot School [3] and the University of Kansas [8]. The Test Pilot School courses on engine-out flying qualities can be downloaded from the US National Archives. A very interesting and easily accessible reference for pilots who really want to understand the principals of airplane control after engine failure is an Engine-Out Trainer presented on-line by the University of North Dakota. This trainer allows several variables to be changed to learn about their effects on minimum control speed (V_{MCA}), on the sideslip (drag), on the rate of climb, etc. Open the trainer by clicking or copying the full URL to your browser, see ref. [11].

3.8. Conclusion best balance

After discussing three cases for maintaining straight flight equilibrium after engine failure or while an engine is inoperative, the following conclusion can be drawn. In case the airspeed is low while the power setting is high, the only option for maintaining control of the airplane and for a positive or maximum rate of climb is to deflect the rudder as much as required for maintaining the heading and to apply a small 3° – 5° favorable bank angle away from the inoperative engine. Maintain straight flight only. Any other bank angle or less rudder deflection than required for maintaining zero yaw rate, will result in a less favorable balance of side forces and yawing and rolling moments which results in increased drag and in less or no climb performance at all, or in the complete loss of control.

4. V_{MCA} AND TAIL SIZE

The vertical tail with rudder of multi-engine airplanes is the only aerodynamic control surface that can provide for the required side force (and hence, rudder yawing moment) to counteract the asymmetrical thrust yawing moment down to a minimum speed for maintaining straight flight after engine failure, the *minimum control speed*. The smaller the vertical tail, the higher the *minimum control speed* will be for generating the required yawing moment (which is proportional to the area S of the tail, and to V^2) for counteracting the thrust yawing moment.

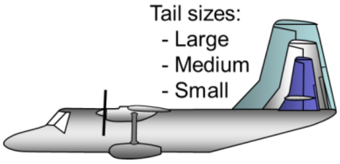

Figure 12. Sizing the vertical tail.

Operators prefer a minimum control speed that is as low as possible, because that results in a low takeoff speed, which is usually 5% above the *minimum control speed* V_{MCA}. A low takeoff speed allows operations from shorter runways, or with higher payload from longer runways. A low takeoff speed would mean having to put a large tail on the airplane, though (Figure 12). A large tail lowers the *minimum control speed* but is heavier and more expensive. Therefore, the design engineer rather designs a small vertical tail, but there is a limit to minimum size.

The smallest possible size of the tail is constrained by Regulations (ref. [4], [9]). These Regulations do not allow the vertical tail to be made so small that the *minimum control speed* exceeds 1.2 times the (lowest) stall speed (V_S) for Part 23 airplanes (§ 23.149 b) and 1.13 times the reference V_S for Part 25 airplanes (§ 25.149 c).

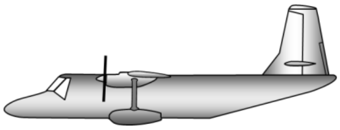

Figure 13. Selected tail size; requires bank angle after engine failure when thrust high and speed low.

As was explained in § 3.4 above, banking only a few degrees away from the inoperative engine reduces the minimum speed for maintaining balance of forces and moments, and reduces the sideslip to zero therewith maximizing the remaining climb performance. For this purpose, the Regulations allow the engineer to size the vertical tail using a bank angle of maximum 5 degrees. The bank angle that the design engineer selects is the bank angle for zero sideslip (Figure 15 below). By using a bank angle smaller than or equal to 5° away from the inoperative engine, the engineer designs the smallest and therewith the lightest in weight and cheapest possible vertical tail that is still adequate for maintaining control after engine failure and that complies with the Regulations (Figure 13 and Refs [4], [9]).

Bank angle and maximum asymmetrical thrust however, are not the only variables that have influence on the minimum control speed and therewith on the required size of the vertical tail plus rudder. The minimum control speed varies with many more variables than bank angle and thrust, a few of which will be described in § 5 below. It is also a fact that there are many minimum control speeds, one for each combination of variables; three of which were discussed in § 3 above. To avoid a too complex use of many different minimum control speeds, the applicable Regulations allow using a *standardized minimum control speed* that will be safe whatever the values of the variables that have influence on the *minimum control speed* are. This means that the worst cases of the factors that have influence on the minimum control speed are used during the tail design process. The use of these worst-case factors results in the highest minimum control speed for any value of these factors, which is safest. The even more important factors that the design engineer considers, but that are controlled by the pilot are: maximum thrust level on the operative engine(s), maximum rudder deflection to maintain straight flight (constant heading), and ailerons to maintain a small bank angle (maximum 5 degrees) away from the inoperative engine for zero sideslip (lowest drag). This design method results in the smallest possible vertical tail and hence, in a *standardized minimum control speed in the air*, called V_{MCA} or sometimes inappropriately V_{MC} in Flight Manuals and textbooks as already mentioned above. This V_{MCA}, that was born at the designer's drawing board, will be verified, and accurately determined during experimental flight-testing a prototype of the airplane (§ 6.1) and published in Airplane Flight Manuals.

CAUTION
FROM THE AIRPLANE DESIGNERS DRAWING BOARD

The published and indicated standardized V_{MCA} is valid only while maintaining a small bank angle away from the inoperative engine, i.e. during straight flight only, definitely not during turns.

A significant conclusion for flight operations can be drawn from this design method for making the smallest possible tail. Pilots need to be made aware that the size of the vertical tail is only adequate to maintain straight flight when an engine is inoperative and only while banking the same bank angle that was used to design the vertical tail. This in fact means that the V_{MCA}, that was used to size the vertical tail and that is published in Airplane Flight Manuals, is valid only if a small bank angle is being maintained while an engine is inoperative, the asymmetrical thrust is maximal and the rudder is deflected up to maximum to stop the yawing and maintain straight flight. The saved hardware weight for a minimum sized vertical tail has to be replaced by a quite heavy 'software' condition (a **CAUTION**) with V_{MCA} in Airplane Flight Manuals. The manufacturer should specify the exact bank angle (number of degrees), that was used to design the vertical tail and that was confirmed during experimental flight-testing, with the V_{MCA} data. These flight-tests will be discussed in § 6.2 below.

5. VARIABLE FACTORS THAT INFLUENCE V_{MCA}

As already mentioned above, many variable factors have influence on the magnitude of the *minimum control speed* in the air, or airborne (V_{MCA}). Already discussed were the influence of thrust, bank angle (through side force $W \cdot \sin \phi$) and rudder deflection, all of which are under pilot control. Any other factor that influences the thrust or drag asymmetry about the yaw and/ or roll axes and that requires a change of rudder or aileron deflection to compensate for will have effect on the magnitude of the *minimum control speed* and will change the standardized, the Flight Manual published value of V_{MCA} to some actual value, also called the *actual* V_{MCA} . If for instance the asymmetrical thrust is not maximal, the thrust yawing moment is smaller, the rudder deflection to counteract this moment can be smaller, and/ or the airspeed lower until the rudder is maximal again; the *actual* V_{MCA} is then lower than the standardized V_{MCA} that was determined using maximum asymmetrical thrust.

In the paragraphs below, most of the variable factors that have influence on V_{MCA} will be discussed. As was mentioned before, the worst-case values of these variable factors were used during designing the vertical tail and will also be used during experimental flight-testing to verify/ determine V_{MCA} in-flight; these values will also be presented. The Learning Objectives, ref. [1], do not require knowledge of all of the factors. The nice-to-know factors are marked with a (-) in the paragraph title. This paragraph applies to all multi-engine airplanes.

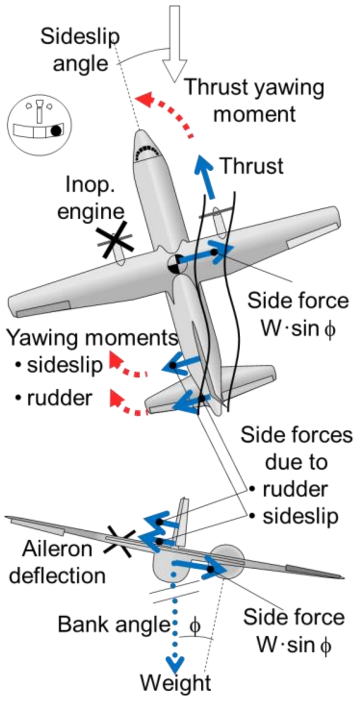

Figure 14. Forces and moments after banking more than 5 degrees away from the inoperative engine.

5.1. Effect of bank angle and weight on V_{MCA}

Effect of Bank Angle. The pilot controls the bank angle, as long as roll control power is adequate. Therefore, it is very important for pilots to understand the effect of bank angle on V_{MCA}.

As was already explained in § 3.4 above, a small favorable bank angle away from the inoperative engine decreases the *actual* V_{MCA} to a lower value than when the wings are kept level. The airplane manufacturer – i.e. the tail design engineer – determined the small bank angle (usually between 3 and 5 degrees) for which the sideslip is zero, because that was used for sizing the vertical tail. Regulations allow a favorable bank angle of maximal 5 degrees. The V_{MCA} that is published in Airplane Flight Manuals, and that is to be used by pilots, is the V_{MCA} with the small so called favorable bank angle applied. Below, the effect of both a change of bank angle away from the favorable bank angle to either side, and the effect of weight on the standardized V_{MCA} will be discussed in greater detail.

A bank angle (ϕ) of more than 5 degrees away from the inoperative engine (Figure 14) increases side force W·sin ϕ, which (in this example and with unchanged rudder side force) causes an increasing sideslip to the right. Consequently, a side force due to sideslip develops to the left, reducing the rudder requirement for straight flight. Since the rudder is not fully deflected anymore, the airspeed can be further decreased until the rudder deflection is again maximum. Hence, the result of maintaining a bank angle more than 5° away from the inoperative engine is that the *actual* V_{MCA} would decrease. However, because the sideslip angle increases, the (horizontal) angle of attack of the vertical tail increases, which might cause flow separation off the vertical tail (fin) and eventually cause the vertical tail to stall. In addition, the sideslip might cause the slipstream of the operative engine to influence the airflow around the vertical tail.

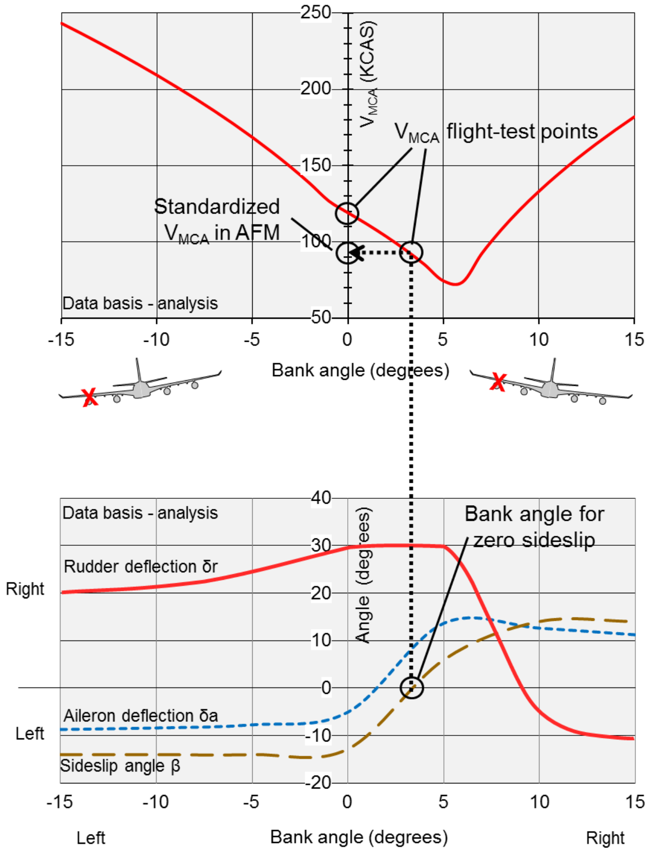

Figure 15. The effect of bank angle on the actual V_{MCA} and the accompanying control deflections and sideslip angle.

Although the *actual* V_{MCA} might be lower if bank angle ϕ is larger than 5 degrees away from the inoperative engine (which in itself is safer), using a bank angle in excess of 5 degrees away from the inoperative engine is not recommended because of the increasing sideslip and risk of fin stall. In addition, the increased sideslip increases the drag and hence, decreases performance. These must be the real reasons that this 5-degree limitation exists in the Regulations FAR/ CS 25.149.

Figure 15, that was calculated using the stability derivatives and lateral-directional equations of motion, ref. [10], of this sample airplane, shows the change of V_{MCA} with increasing bank angle for a sample 4-engine swept wing airplane with one outboard engine (#1) inoperative, and while the opposite engine (#4) is producing maximum available takeoff thrust. The other engines do not affect the thrust yawing moments if their thrust is equal, but only the remaining (climb) performance.

For this sample airplane, as for any multi-engine airplane, V_{MCA} increases when the bank angle increases above 6 degrees away from the inoperative engine because a maximum approved sideslip angle of 14° was defined during the analysis to prevent the vertical tail from stalling. Nevertheless, a bank angle of 10 degrees could be safe to maintain control, provided a much higher airspeed (135 kt) is maintained. The bottom graph of Figure 15 shows the increasing sideslip angle with increased bank angles, which reduces the climb performance. The lowest drag, i.e. zero sideslip, is at or near the bank angle used for sizing the vertical tail and for determining the standardized V_{MCA}, for this sample 4-engine airplane just 3 degrees. This bank angle for zero sideslip varies a little with airplane weight; at higher weight, the favorable bank angle might have to be only 2 degrees. Both a small bank angle and high asymmetrical thrust at low speed have great effect on controllability and performance.

Figure 15 also shows that the rudder deflection needs to be reduced and even reversed from into the good engine to into the dead engine, when the bank angle increases above 6 degrees because of the increasing side force due to sideslip and $W \cdot \sin \phi$. The question is whether the pilot can detect the increasing sideslip and will reverse the rudder to prevent the loss of control. It is often said that turning into the good engine is better than into the dead engine, but that is only the case at small bank angles, as Figure 15 shows; *actual* V_{MCA} decreases below the standardized V_{MCA}, but only between 3 and 6 degrees of bank (for this airplane).

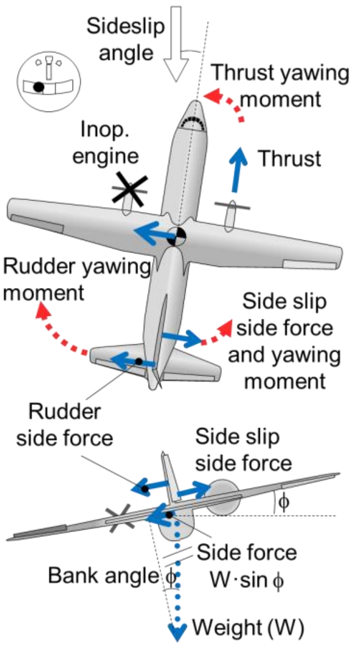

Figure 16. Forces and moments after banking into the inoperative engine.

A bank angle less than 5 degrees away from the inoperative engine or into the inoperative engine (as will be the case during a turn as shown in Figure 16) decreases and reverses the direction of side force $W \cdot \sin \phi$. This will cause a sideslip to the left and a side force due to sideslip to develop to the right, increasing the total yawing moment into the inoperative engine. To counteract this increased yawing moment, the rudder yawing moment needs to be increased by increasing the rudder deflection. However, if the airspeed is as low as (standardized) V_{MCA}, and hence the rudder is already (almost) fully deflected, the required increase of the rudder yawing moment is not possible unless the airspeed is increased first, because the control power of aerodynamic surfaces is a quadratic function of the airspeed ($\equiv V^2$, § 2.1). This required increase of airspeed with this bank angle change means that the *actual* V_{MCA} during banking away from the favorable 3° – 5° bank angle will be higher than the standardized published V_{MCA}.

In other words, if the airspeed is as low as the published, standardized V_{MCA} (at which speed straight flight equilibrium can just be maintained using full rudder and maximum thrust), a wings level attitude or a banking maneuver in the direction of the inoperative engine causes the airplane to start sideslipping to that side. Both the sideslip angle and the drag increase; climb performance decreases. If either the rudder or aileron deflections were maximum before banking (as was required for straight flight when the airspeed is V_{MCA}), it might not be possible to reverse the bank angle to end the turn unless either the airspeed is increased first to a value well above V_{MCA}, or the thrust asymmetry is reduced by closing the throttle of the corresponding opposite engine temporarily a little (§ 3.3). If the altitude is low, the required increase of airspeed might not be possible at all; the airplane is already out of control and disaster is imminent. Therefore, if rudder and/or aileron deflections are (near) maximum, the airspeed must be close to the *actual* V_{MCA}. Then do not bank away from the favorable 3 to 5-degree bank angle that was determined by the manufacturer; the rudder (and ailerons) are not sized large enough to return to straight flight, to end the turn.

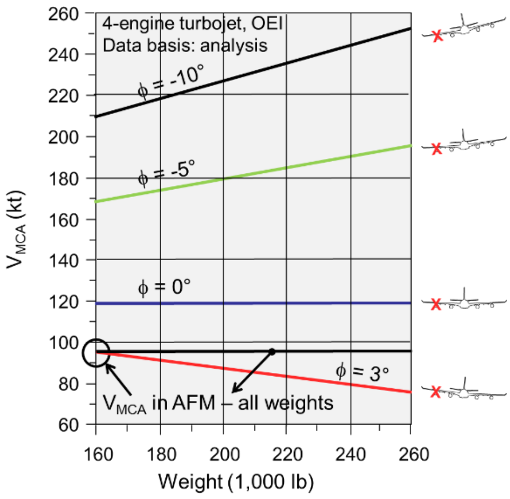

Figure 17. Effect of weight and bank angle ϕ on the actual V_{MCA}.

Effect of Weight. Figure 17 shows the effect of bank angle and weight on the *actual* V_{MCA} (through side force $W \cdot \sin \phi$) for the same sample 4-engine swept wing airplane with one outboard engine (#1) inoperative and the opposite engine (#4) is producing maximum available takeoff thrust. The thrust level of the inboard engines, provided these are the same, do not contribute to the asymmetrical thrust yawing moments, only to performance. The data basis is the same as used for Figure 15, is the result of the analysis of the stability derivatives of this sample airplane while the thrust is asymmetrical, ref. [10].

C-130 pilots know this figure because it looks very similar to the corresponding figure in the Performance Manual of the Lockheed C-130 Hercules (SMP777, page 3-18). The airspeeds at the given four bank angles for lowest weight correspond with the data in Figure 15, because V_{MCA} is determined with the airplane at the lowest weight possible, the worst-case weight for (a standardized) V_{MCA}.

In this case, the manufacturer opted for a favorable bank angle of 3 degrees away from the inoperative engine for determining the standardized V_{MCA} ($\phi = 3°$ line in Figure 17) because this bank angle results in zero sideslip and hence, lowest drag (refer also to Figure 15) at V_{MCA}, and maximum thrust on the operative engine(s). The V_{MCA} of the airplane for this configuration and bank angle would be 95 knots at the lowest possible weight and would decrease to a lower, safer actual value with increasing weight (side force W·sin ϕ increases). This decrease is also very common for straight wing multi-engine airplanes with 5 degrees of bank. Low weight results in the highest V_{MCA} and is therefore used as the worst-case weight for tail design and during flight-testing for determining V_{MCA} and, hence, for publishing (standardized) V_{MCA} in Airplane Flight Manuals. Any higher weight, while maintaining the favorable bank angle, reduces the *actual* V_{MCA} to a value lower than the published, standardized V_{MCA}; the safety margin to the indicated airspeed increases.

Things change dramatically for this and other multi-engine airplanes if a bank angle is not maintained away from the inoperative engine. If the wings are kept level, the analysis shows (and flight tests prove) that the *actual* V_{MCA} for this sample airplane, in this configuration, will have become 119 kt at all gross weights (side force W·sin ϕ = 0), 24 kt (!) higher than the published, standardized $V_{MCA.}$ At or below an airspeed of 119 kt, straight flight cannot be maintained following the failure of an outboard engine while the wings are kept level and the corresponding opposite engine is at maximum available thrust setting, and also provided the other factors that have influence on V_{MCA} are at their worst-case values.

Actual V_{MCA} will be even higher and increases with weight if the bank angle is only 5 degrees into the failed or inoperative engine (ϕ = -5°). The 10 degrees bank angle line (ϕ = -10°) is presented as well and speaks for itself. The increase of *actual* V_{MCA} with weight on straight wing airplanes will be smaller, but still a factor to consider.

The powerful adverse effect of side force W·sin ϕ, if bank angle ϕ is not equal to the favorable small bank angle away from the inoperative engine, can be observed in both Figure 15 and Figure 17. Of course, the AFM-published V_{MCA} is the minimum speed for maintaining straight flight (equilibrium) only, which an intentional turn is not, but the control power of rudder and ailerons might be insufficient to be able to end the turn and return to the favorable bank angle, between 3 and 5 degrees, away from the inoperative engine for a safe control margin and lowest drag. The remaining control power at an airspeed as low as V_{MCA} and at bank angles other than the favorable bank angle is not subject of flight-testing and may therefore not be counted on.

The (standardized) V_{MCA} that is published in flight manuals is always determined using the lowest possible gross weight **and** a small bank angle away from the inoperative engine, as (should have been) specified together with the V_{MCA} data by the manufacturer, and with the other factors that have influence on V_{MCA} at their worst-case values. This in fact means that the published, standardized V_{MCA} is only valid and safe for all gross weights, on the condition that the bank angle is a few degrees, as specified by the manufacturer (usually between 3 and 5 degrees), away from the inoperative engine. Weight increases the *actual* V_{MCA} while banking into the inoperative engine.

Maintaining a small favorable bank angle is therefore essential for the takeoff and in-flight safety after engine failure or while an engine is inoperative, not only for this sample airplane but for all multi-engine airplanes, during takeoff, approach and even during a long straight-in approach for landing (if high thrust settings might become necessary).

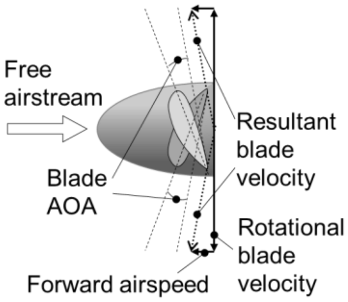

Figure 18. Propeller blades angles of attack, high speed level flight.

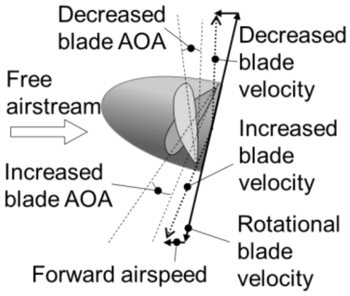

Figure 19. Propeller blades angles of attack, low speed level flight.

5.2. Critical engine

At high-speed flight, the angle of attack (AOA) of the wings of an airplane is small. The relative wind not only runs into the lift-producing wings, but also into the propeller blades. Figure 18 shows the up and down-going propeller blades of a two-blade propeller on the same engine in a side view, both at the instant they are horizontal. The resultant blade velocity of each of the blades (dotted vector) is the resultant of the rotational blade velocity (Prop RPM) and the forward airspeed. In this case, the AOA's of both blades are nearly equal, so is the thrust developed by each blade.

If the airspeed of the airplane decreases or is low (during takeoff or go-around), the AOA of the wings of the airplane has to increase to maintain the required lift or to climb. Not only the AOA of the wings increases, but also the AOA of the down-going propeller blade, increasing the thrust of this blade, as Figure 19 shows. The AOA of the opposite up-going blade decreases, decreasing the thrust generated by that blade. In addition, the resultant velocity of the down-going blade increases, increasing its thrust even more, because the forward airspeed vector is in the direction of the free airstream. The resultant velocity of the up-going blade decreases. Remember this by

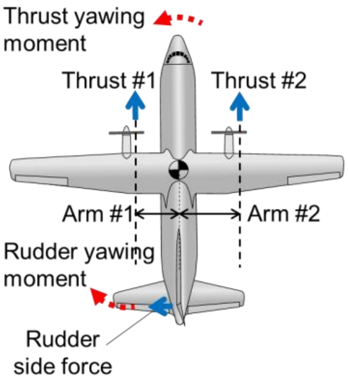

Figure 20. P-vector, also called P-factor.

thinking of a helicopter rotor; the airspeed of the forward going blade is higher than of the aft going blade, if not hovering.

Therefore, at low speed when the AOA is higher, the thrust vector of the whole propeller disc shifts in the direction of the down-going or descending propeller blade. This asymmetrical loading of the propeller disc is called Propulsion or P-vector, also called P-factor, see Figure 20.

If both propellers of a twin-engine airplane rotate clockwise, an increasing AOA shifts the thrust vectors of both engines to the right. The moment arm of the propeller thrust on the left wing (thrust #1) decreases and the moment arm of the propeller thrust on the right wing (thrust #2) increases. Then the yawing moment of engine #2 (thrust #2 × arm #2) is larger than the yawing moment of engine #1 (thrust #1 × arm #1). This effect is also noticeable during normal all-engines-operative operations at low speed (at high AOA), when a rudder input will be required to counteract the difference in thrust yawing moments for maintaining the heading, even for single engine airplanes.

If engine #1 fails, the total remaining thrust yawing moment (in this case generated by engine #2) is larger than the remaining thrust yawing moment if engine #2 would fail. A larger asymmetrical thrust moment requires larger rudder deflection to counteract or – if the rudder is at its limit as required for determining V_{MCA} – a higher airspeed. Consequently, V_{MCA} after failure of engine #1 will be higher than V_{MCA} after failure of engine #2. The engine that, after failure, leads to the highest V_{MCA} is called the *critical engine*. In this example, both propellers rotate clockwise; the left engine (#1) is the critical engine.

If the airplane is equipped with *counter-rotating propellers* or with *turbofans*, there is no difference between the thrust yawing moments with increasing AOA while a left- or a right-hand engine is inoperative, provided the gyroscopic effects of rotating engines and propellers are negligible. The opposite engines are equally critical; the *actual* V_{MCA} is the same after failure of #1 or #2. If a rudder boosting system is powered by only one of the engines, that engine might be the critical engine (§ 5.8).

On *four or more engine airplanes*, the thrust yawing moments and hence the *actual* V_{MCA}'s differ for the inboard and outboard engines. The outboard engines are most critical because of the longest moment arm. If equipped with four propellers that turn clockwise, engine #1 is the most critical engine. Not a civil requirement anymore, but still a military requirement for four or more engine airplanes is the determination of V_{MCA2}, the minimum control speed if two engines on the same wing are inoperative (n-2). V_{MCA2} is usually at least 30 kt higher than V_{MCA} (n-1), which on four or more engine airplanes is also called V_{MCA1}.

Slipstream effects might also determine which engine is the critical engine; refer to the applicable paragraphs below (§ 5.5). The yaw rate after failure of the critical engine might be a little higher than after failure of any other engine.

The failure of the critical engine results in the highest, the worst case V_{MCA} that is valid as long as the bank angle is the same as was used for sizing the vertical tail and for V_{MCA} testing, while the thrust is maximal. Airplane Flight Manuals present the V_{MCA} that is determined after failure of the critical engine. The *actual* V_{MCA} after failure of any other engine is a few knots lower – which is safer.

The adjective 'critical' is only of use to airplane design engineers and experimental test pilots to make sure they use and determine the highest V_{MCA} after failure of any of the engines. Airline pilots should not have to worry whether a failing engine is critical or not; they should not even have to learn about the criticality of an engine. Just a single V_{MCA}, that is a safe minimum control speed in anticipation of, and after failure of anyone of the engines, applies. Maintaining the small favorable bank angle away from the inoperative engine(s) however, is a vital condition for obtaining the lowest, safest possible *actual* V_{MCA}, whether the inoperative engine is critical or not.

Therefore, pilots do not have to remember which of the engines is the critical engine; there is only one engine emergency procedure in the checklist or QRH, and only one V_{MCA} published in the AFM. The use of "critical" in V_{MCA} definitions in an AFM is inappropriate. V_{MCA} applies after failure of either engine. The difference is the direction of rudder and aileron inputs. V_{MCA} training and/or demo should be conducted with alternating the inoperative engine (or set at the thrust for zero drag).

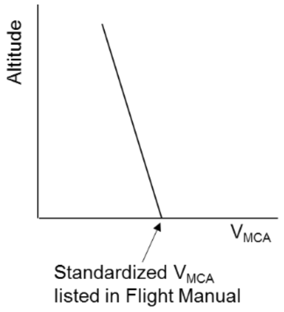

Figure 21. Change of (actual) V_{MCA} with altitude.

5.3. Engine thrust; altitude and temperature

The thrust setting used on the engine(s) opposite of the inoperative engine for determining V_{MCA} is the maximum thrust that the engine develops, which might be higher than the thrust the manufacturer guarantees in the engine specification.

The thrust of most engines depends on air density (altitude) and temperature; increasing altitude and higher temperatures (at sea level) decrease the thrust. Following an engine failure at high altitude, the asymmetrical thrust will be lower, as will be the requirement for rudder control power after engine failure. The *actual* V_{MCA} will be lower than the standardized, AFM-published V_{MCA} (provided the favorable bank angle is being maintained, see Figure 21).

If the outside air temperature increases, engine thrust decreases and hence, the *actual* V_{MCA} decreases. A large variation of engine thrust with density and temperature leads to a large variation of *actual* V_{MCA}'s. This is the reason that (turboprop) airplane manufacturers provide V_{MCA} charts or tables in their AFM with more realistic and lower V_{MCA}'s for hot and high operations, rather than listing the higher standardized, worst case, sea level, ISA temperature V_{MCA} only. These more accurate V_{MCA} data enable hot and high operations at lower takeoff speeds, which are 1.05 V_{MCA} for Part 23 and ≥ 1.13 V_{MCA} for Part 25 airplanes.

Older engines might not develop as much thrust anymore as new engines; the *actual* V_{MCA} will then be a bit lower, safer, than V_{MCA} with new engines.

On four- or more engine airplanes, the thrust yawing moment can be reduced by decreasing the thrust of the engine opposite of the failed or inoperative engine and, if required for performance, increasing the thrust of the symmetrical operating engines. This way, maximum performance is available, while keeping *actual* V_{MCA} to a lower, safer value for maneuvering.

5.4. Control deflection (-)[1]

The V_{MCA} of a multi-engine airplane is determined when the rudder and/ or ailerons are either fully deflected or when reaching a Regulation-determined rudder or aileron control travel or force limit, whichever occurs first during the test (§ 6.2 below). If, for instance, the rudder is not fully deflected (while the asymmetrical thrust is maximal) then the rudder generated side force is smaller than with full rudder, as was also mentioned in § 3.5 above. This smaller aerodynamic side force can be increased only by increasing the airspeed. Therefore, the airspeed for the vertical tail with the not fully deflected rudder to generate a side force large enough to counteract the – still unchanged – high asymmetrical thrust will have to be higher than the Flight Manual-published standardized V_{MCA}, that was determined using maximum rudder. The *actual* V_{MCA} with partial rudder is higher. If the rudder deflection is partial and the indicated airspeed is equal to, or decreases below this *actual* V_{MCA}, the pilot will definitely notice a controllability problem. Do not forget to apply as much rudder as required to maintain heading, i.e. a zero yaw rate. Figure 15 above shows control deflections and sideslip angle.

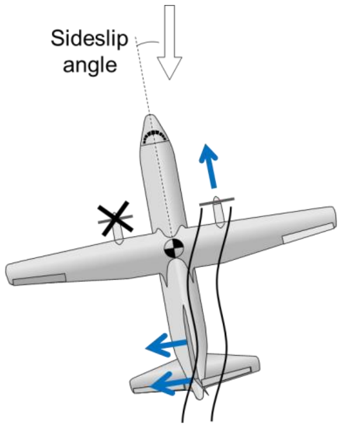

Figure 22. Slipstream effects due to sideslip.

5.5. Slipstream effects

Asymmetrical and spiraling slipstream effects might influence the recovery after engine failure, as well as the magnitude of V_{MCA}, if the slipstream affects the air stream around the horizontal as well as the vertical tail at larger sideslip angles (Figure 22 below). Some airplanes have vortex inducers on the vertical tail to prevent an early fin stall when the sideslip angle increases during equilibrium flight with an inoperative engine. Slipstream effects might have influence on the magnitude of both the static and dynamic V_{MCA}'s (§ 6.2 below) and, if the effects are dominant, the slipstream might even determine which of the engines is the critical engine. During flight-testing V_{MCA}, slipstream effects, if any, will have effect during the determination of V_{MCA}, for the sideslip and bank angles tested. However, if during flight with an inoperative engine a bank angle is allowed that leads to an increased sideslip angle, the slipstream effects might increase *actual* V_{MCA} to a value higher than the standardized, published V_{MCA} or to an early fin stall. In some cases, adverse slipstream effects, encountered during flight-testing, resulted in a tail re-design.

5.6. Propellers; wind milling, feathering

After an engine failure, the airflow will start driving a not-feathered propeller (wind milling) causing the drag of the propeller to increase significantly. The yawing moment generated by this drag increases the asymmetrical yawing moment of the opposite operative engine (Figure 4), which – during takeoff or go-around – is at maximum available takeoff thrust setting to attain the maximum available climb performance. The lower the propeller drag, the smaller the asymmetrical yawing moment and the less rudder deflection is required to maintain straight flight at any given airspeed. Most propellers are equipped with a feathering system that automatically feathers the propeller blades after engine failure, unless disabled or not armed. Feathering a propeller will decrease its drag considerably. V_{MCA} of propeller airplanes is determined while the propeller blades are in the position they automatically assume after engine failure. Small twin-engine airplanes might not be equipped with a feathering system; the propeller of the inoperative engine might continue to windmill, causing high propeller drag. The V_{MCA} of such small twin-engine airplanes is determined with this high propeller drag and will therefore be high enough for maintaining control, provided the bank angle is between 3 and 5 degrees, as specified by the manufacturer, away from the failed engine.

Propellers will only auto-feather after engine failure if the feathering system is enabled or armed, which is normally set prior to both takeoff and landing (in anticipation of an engine failure during go-around). If feathering was used to determine V_{MCA}, the asymmetrical thrust yawing moment without feathering is (much) larger and hence, a larger rudder deflection is required for straight flight or a higher speed if the rudder deflection is maximum: the *actual* V_{MCA} is higher. This has a consequence for training too. A realistic V_{MCA} cannot be demonstrated by just idling one engine. This is the reason that airplane manufacturers provide a (number of) thrust or torque setting(s) to be set on the simulated inoperative engine for the drag of the not-feathered propeller to match the drag of a feathered propeller (thrust for zero drag).

A suspected failed engine should never be left idling as a 'standby source of thrust'; the engine should be shut down or set to provide zero thrust in order for the *actual* V_{MCA} to be as low as, or below the published V_{MCA}. If a propeller is not feathered (because the engine is kept idling) or if the feathering system fails (or is not armed), the drag and, hence, *actual* V_{MCA} is much higher than the published (and indicated) V_{MCA}. Loss of control will occur as soon as (asymmetrical) thrust is increased (during approach or go-around).

Torque and gyroscopic effects due to rotating propellers are mostly neglected in the V_{MCA} analysis. These effects, as well as the rapidness of the automatic feathering process, if any, play their role in determining the dynamic V_{MCA} or during transient effects testing. These effects will be included in the Flight Manual-published V_{MCA}.

5.7. Effect of center of gravity on V_{MCA}

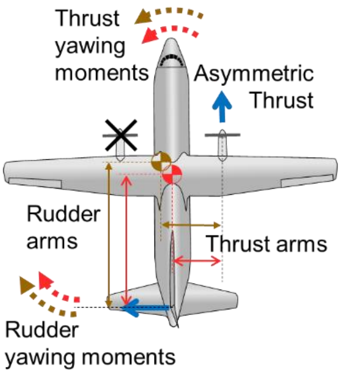

Figure 23. Center of gravity shift, longitudinal and lateral.

Longitudinal shift of center of gravity. The yawing moment generated by the rudder, is the multiplication of the moment arm or distance from the center of gravity to the aerodynamic force developed by the rudder. If the center of gravity is at its approved aft limit, the yawing moment generated by the vertical tail and rudder deflection is smallest. If the center of gravity is more forward, the moment arm to the rudder force is longer and rudder deflection can be smaller to counteract the same asymmetrical thrust yawing moment (Figure 23). Then the airspeed could be further decreased until rudder deflection is again maximum: the *actual* V_{MCA} with a forward center of gravity is lower.

Lateral shift of center of gravity. A lateral shift of the center of gravity also affects V_{MCA}. A lateral shift into the inoperative engine, for instance caused by trapped fuel in wing tanks, increases the asymmetrical thrust yawing moment of the operative engine(s) (longer moment arm) and requires a higher counteracting force: larger rudder and aileron deflections are required or, if these are maximum already, a higher airspeed: *actual* V_{MCA} increases. Therefore, Airplane Flight Manuals present a maximum allowable wing-fuel imbalance or asymmetry to avoid controllability problems after

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[1] (-) denotes nice-to-know; not required in the Learning Objectives for a multi-engine rating, yet very relevant.

engine failure due to the lateral shift of the center of gravity. It is favorable to maintain a (lateral) cg into the good engine, by cross feeding or transferring fuel, and/ or to ask the passenger(s) to take a seat on the good engine side, while observing the limits. The loss of a propeller or engine also affects the center of gravity and controllability.

Worst case center of gravity. Considering all possible centers of gravity for determining the V_{MCA} would be excessively complicated. The standardized V_{MCA} is therefore determined with the center of gravity at the maximum approved lateral position into the critical engine and longitudinally most aft, both representing the worst case, because this returns the highest V_{MCA} due to center of gravity shift (at the favorable bank angle, § 5.1). During normal operations, the *actual* V_{MCA} will not increase above the published value due to any center of gravity shift within the approved envelope. Airline pilots therefore do not have to worry whether the center of gravity is forward or aft, left or right. The published V_{MCA} is valid for any center of gravity, as long as the small favorable 3° – 5° bank angle, which should be specified by the manufacturer, is maintained away from the inoperative engine when the thrust is set to maximum.

5.8. **Rudder boosting (-)**

On some airplanes, the rudder is boosted by a hydraulic system to increase the rudder deflection per pound (or Newton) of pedal force, for maintaining control under asymmetrical thrust conditions. The boost system will only be available at low airspeeds to avoid damage to the vertical tail at high speeds and might be automatically switched on as flaps are selected down in stages of one or more different boost pressure levels. If a hydraulic pump that powers the boost system happens to be driven by the inoperative engine, the boost pressure might be lower than required, or not be available at all; *actual* V_{MCA} will be higher. If the airplane is equipped with only one hydraulic pump driven by one of the engines, that engine might have to be defined as the critical engine.

If the flap handle is not selected above a certain setting, rudder boosting might not be switched on and *actual* V_{MCA} will be much higher than anticipated. The boost system has a very powerful effect on the magnitude of V_{MCA}. If not switched on, an *actual* V_{MCA} increase of 23 knots is not exceptional on four-engine C-130 type airplanes. Refer to the Airplane Flight Manual to find out whether flap handle position affects V_{MCA} of your airplane.

5.9. **Landing gear, flaps, slats, and spoilers (-)**

The drag of the landing gear is normally symmetrical about the center of gravity, provided the pilot maintains straight flight with no sideslip. Then, the extended landing gear might have no influence on V_{MCA}. The total drag is of course higher, on some airplanes just a little, on other airplane types more. If, however, the sideslip is not zero, for instance during wings-level flight while an engine is inoperative (§ 3.3), the extended landing gear has some influence on the balance of lateral forces and moments. Because the moment arms of the main landing gears to the center of gravity are small, the yawing moments due to gear drag will not be large; furthermore, the drag induced forces act behind the center of gravity (for nose gear airplanes). It depends on the direction of the sideslip, whether these forces are in the same direction or opposite of the rudder generated side force.

The side force generated by the nose gear on big airplanes due to a sideslip angle has a much longer moment arm to the center of gravity. If the pilot allows a sideslip to build up by keeping the wings level after engine failure, the nose gear will generate a side force due to drag and hence an additional yawing moment that requires a change of rudder deflection: *actual* V_{MCA} will either increase or decrease.

An extended landing gear has no asymmetrical effects if the sideslip is zero. Zero sideslip can be achieved with a small 3-to-5-degree bank angle, as was explained in § 3.4 and § 5.1. In addition, as long as the landing gear is down, its drag of course decreases the rate of climb, but retracting the gear might temporarily decrease the available rudder boost pressure (§ 5.8), therewith temporarily reducing the rudder deflection and increasing *actual* V_{MCA}. The opening of gear doors could also increase drag temporarily. Check your Airplane Flight Manual whether gear retraction should be delayed until reaching a safer speed and/ or altitude.

Flaps and slats, after extension, might have an effect on the airflow striking the tail and therewith affect V_{MCA}. Also, the flaps extension might influence the pitch angle and the angle of attack of the airplane, and therewith the P-factor and hence, the thrust yawing moment and V_{MCA}. In addition, on propeller airplanes, the flaps might result in a roll rate due to reduced asymmetrical propulsive lift of the wing section behind the inoperative propeller. The flap handle might also be mechanized to switch on or increase the rudder boost pressure system, so the position of the flap selector handle has influence on the rudder control force and on V_{MCA} (§ 5.8). On some airplanes, V_{MCA} with flaps up is more than 10 kt higher than with takeoff flaps. If boosting would be off or low – as might be the case with the flap handle at zero – V_{MCA} would be much higher. This increase of V_{MCA} is indeed a factor to consider while returning to base when an engine is inoperative.

V_{MCA} is to be determined with gear up and flaps in takeoff position, but not with gear and flaps in transition. Refer to the Airplane Flight Manual to find out whether transitioning or retracted flaps affect V_{MCA}. This would be 'nice' to know for a safe return to base following the failure of an engine.

Spoilers affect the lift distribution on, and the drag of the wings. When flight spoilers kick-in asymmetrically if the control wheel is rotated more than for instance 7 degrees to assist roll control during the early phases of takeoff, they not only affect V_{MCA} because of the increased yawing moment due to asymmetrical drag, but also decrease the already reduced climb performance.

5.10. Ground effect (-)

An airplane is in ground effect if the altitude is less than about half a wingspan above the ground. On some airplanes, V_{MCA} might be influenced by the ground effect, because the control power of the aerodynamic control surfaces might change while the airplane is close to the ground. On other airplanes, the pitot-static air data system measurements might be influenced by the ground effect. Then, V_{MCA} out of ground effect might differ a few knots from V_{MCA} in ground effect. The highest V_{MCA} of in and out of ground effect should be used for takeoff. This V_{MCA} will be published in the Airplane Flight Manual.

5.11. Stall speed (-)

Some multi-engine airplanes with the engines mounted close to the fuselage, like DC-9 and F100, or airplanes with counter-rotating propellers might have a V_{MCA} that is lower than the stall speed V_S. In this case, the Flight Manual lists either no V_{MCA} at all or states that 'the airplane is controllable down to the stall', which is of course the preferable and most safe situation. However, as was explained in § 5.1, this will only be the case if the pilot (after engine failure) actually maintains the bank angle that was used to determine V_{MCA}, in most cases 5° away from the inoperative engine. If the bank angle differs from this favorable bank angle, the *actual* V_{MCA} might increase to a value higher than V_S and a controllability problem might arise despite of the statement in the flight manual. Refer to Figure 15.

5.12. Configuration changes (-)

Any configuration change, modification or alteration that changes the location of the lateral center of gravity or changes the asymmetrical thrust or drag, and/ or affects the required rudder and aileron deflections after failure of an engine, will affect V_{MCA}. For instance, the installation of external (camera) wing pods, antennas, or other external equipment on one of the wings, as well as weight changes in wing-engine nacelles or inside the cabin that influence the position of the lateral center of gravity, or engine or propeller upgrades, etc. could require a change of the standardized Flight Manual-published V_{MCA}. Such changes require a change in the Type Certificate Data Sheet and at least also flight-testing to determine V_{MCA}.

If a cowl flap is left open, a cargo hatch accidently opens in flight, or a de-icing boot comes loose from the leading edge of a wing, the drag increases asymmetrically and might result in an increase of the *actual* V_{MCA}, even if all engines are operative.

5.13. Conclusions factors that have influence on V_{MCA}

Many factors have influence on V_{MCA}. Being able to find the applicable V_{MCA} for any situation or configuration would require many tables with data in an AFM, which would not be workable and prone to errors. Therefore, FAR and CS require only one V_{MCA}, for straight flight while maintaining a small favorable bank angle of 3° – 5° as opted by the manufacturer, that is measured with maximum asymmetrical thrust, and the other affecting variables at their worst-case values. All pilots are aware of the increase of the stall speed of their airplane with bank angle and weight. Pilots should also be made aware and never forget that:

- The V_{MCA} published in flight manuals is a standardized V_{MCA}, a constant value, that is determined during straight flight while maintaining a small bank angle of 3° – 5° away from the failed engine, maximum rudder, and maximum asymmetrical thrust, with the airplane in the certificated configuration.
- A*ctual* V_{MCA} varies considerable with bank angle, weight, thrust setting and rudder deflection; *actual* V_{MCA} is definitely not a constant (low) airspeed.
- *Actual* V_{MCA} increases as much as 25 knots above the Flight Manual published V_{MCA} (at high power settings) if the wings are kept level, instead of banking 3 – 5 degrees away from the inoperative engine. On small straight wing twin-engine airplanes, the increase will be smaller (approximately 8 – 10 knots).
- *Actual* V_{MCA} increases when banking more than 5° into the good engine to avoid the fin to stall. In addition, the rudder needs to be reversed to reduce the sideslip.
- *Actual* V_{MCA} increases into even more while maneuvering into the inoperative engine side. If the actual V_{MCA} increases (unnoticed) above the calibrated (indicated) airspeed due to a change of bank angle or due to the increase of asymmetrical thrust, control will be lost right away if high thrust setting is maintained.
- A V_{MCA} applies during the whole flight, not only during takeoff. The standardized V_{MCA} that is published in Airplane Flight Manuals is a minimum speed for maintaining straight flight only while an engine is inoperative, on the conditions that a small bank angle is maintained away from the inoperative engine while the other engine(s) produce maximum thrust and the rudder is deflected up to maximum to maintain straight flight. V_{MCA} is definitely not a minimum speed for maneuvering the airplane while the asymmetrical thrust is set to maximum. Never ever increase the (asymmetrical) thrust to maximum while in a turn.

6. MINIMUM CONTROL SPEEDS – DEFINITIONS AND TESTING

6.1. Seven defined minimum control speeds

Airplane Flight Manuals of two-engine Part 23 airplanes present two different minimum control speeds (V_{MC}); four or more engine airplanes have five defined V_{MC}'s. As illustrated in Figure 24, the defined V_{MC}'s for all Part 23 and 25 airplanes are: Minimum Control speed – Ground (V_{MCG}) and Minimum Control speed – Airborne, or in the Air (V_{MCA}). In addition, Part 25 airplanes have a Minimum Control speed – Approach and Landing (V_{MCL}). The Minimum Control speed – Airborne (V_{MCA}) is often inappropriately abbreviated as V_{MC} (which applies to takeoff).

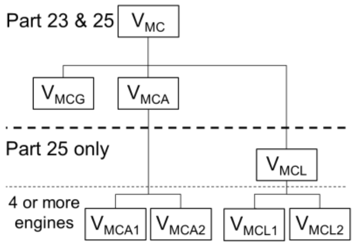

Figure 24. Schematic diagram with all Regulation-defined V_{MC}'s.

Four or more engine airplanes (Part 25) not only have a V_{MCA}, but also a V_{MCA2} and a V_{MCL2}, both with two engines inoperative (n-2, same wing). V_{MCA1} and V_{MCL1} are the same as V_{MCA} and V_{MCL} respectively, both with one engine inoperative (n-1). Contrary to military regulations, civil regulations (FAR, CS) do require a V_{MCL2}, but not a V_{MCA2} to be determined during flight-testing and published in Airplane Flight Manuals anymore. Still, a V_{MCA2} is the acting minimum control speed when one of the engines is already inoperative, in anticipation of another engine failure. The decision to delete V_{MCA2} from civil regulations and introduce $V_{MCL(2)}$ is incomprehensible, also given several dual engine failures that occurred in the past.

V_{MCA} is the most important minimum control speed of all V_{MC}'s and was already discussed in greater detail in this paper (§ 3). Below, the definitions of all V_{MC}'s and the flight test techniques for determining the V_{MC}'s are included for a better understanding of these important minimum control speeds.

Figure 24 shows the Regulation-defined V_{MC}'s of which the standardized values are determined during flight-testing and published in the limitations section of Airplane Flight Manuals. As was explained in § 3.3, 3.4 and 3.5 and shown in Figure 15 and Figure 17, there are many more *actual* V_{MCA}'s, that differ from the Flight Manual-published standardized V_{MC}'s, because the configuration, thrust setting, weight, bank angle and control inputs are not the same as used during tail design and flight-testing.

WARNING

V_{MC} testing is dangerous! Experimental Test Pilots and Flight Test Engineers prepare these tests thoroughly using in-depth theoretical analysis and simulators.

6.2. V_{MCA} testing

During the flight-test to determine V_{MCA}, the airplane is in the same configuration that was used to design the vertical tail (§ 4 above), of which the most important factors are the lowest possible weight (smallest side force $W \cdot \sin \phi$), an aft center of gravity (smallest rudder moment arm), maximum takeoff power setting on the engine opposite of the inoperative critical engine (max. thrust yawing moment) and a feathered propeller, if automatic (§ 3 and § 5). This configuration leads to the 'worst case' V_{MCA}, a V_{MCA} that is always safe, whatever the configuration of the airplane is (provided the pilot maintains the small favorable bank angle away from the inoperative engine and deflects the rudder to stop yawing). Two types of V_{MCA} are determined, the *static* V_{MCA} and the *dynamic* V_{MCA}. The tests are conducted at safe altitudes; the data are reduced and extrapolated to sea level standard atmosphere.

The *static V_{MCA}* is of vital importance for continuing the flight safely while an engine is inoperative. The airspeed is slowly reduced (while keeping the wings level) until the heading no longer can be maintained using maximum rudder or aileron deflection, or up to the Regulations-defined maximum control force limits (150 lb for rudder pedal, 25 lb for roll control, refs [4], [9]). This first test point is the wings-level V_{MCA} (Figure 15 on page 13). Then, while applying the same bank angle that was used to design the vertical tail (between 3 and 5 degrees away from the inoperative engine), the airspeed is (and can be) further decreased until again the heading can no longer be maintained. This airspeed is the *static V_{MCA}* of the airplane. This V_{MCA} is usually between 8 (small twin) and 25 knots (B707 type) lower than the wings-level V_{MCA} as illustrated in Figure 15. Refer to § 3.3 and § 3.4 for an explanation of forces and moments at these test points.

If a three or more-engine airplane still climbs while n-1, the thrust of the centerline engine or of the symmetrical engines may be reduced for maintaining the test altitude. This symmetrical thrust reduction does not affect the total thrust asymmetry.

Static V_{MCA} applies during the entire flight while an engine is inoperative and is obviously only valid during straight flight as long as the small favorable bank angle is being maintained, and definitely not during turns (at high power setting); then the *actual* V_{MCA} is much higher (§ 5).

The *dynamic V_{MCA}* is important for regaining control immediately following the sudden failure of an engine during the resulting dynamics. The dynamic V_{MCA} is determined by cutting the fuel flow to the critical engine at several speed points down to the airspeed at which the heading change is maximum 20 degrees, the bank angle does not exceed 45 degrees, no dangerous attitudes occur and no exceptional piloting skill is required. This airspeed is the *dynamic V_{MCA}* of the airplane.

Test data. The highest of static and dynamic V_{MCA} is usually published in the Airplane Flight Manual as the V_{MCA} of the airplane. In case the dynamic V_{MCA} (sudden engine failure) exceeds the static V_{MCA} (flight with an inoperative engine), both the dynamic and the static V_{MCA} might be published in the Airplane Flight Manual, because the static V_{MCA} applies during the remainder of the flight with an inoperative engine.

On four or more engine airplanes, these tests are repeated while two engines (n-2) are inoperative; the critical outboard engine and the engine next to it on the same wing. These tests provide V_{MCA2}, the minimum control speed while two engines are inoperative. V_{MCA2} can be 40 – 50% higher than the V_{MCA} or V_{MCA1} (both n-1) of the airplane.

Qualitative evaluation. Following determining the static and dynamic V_{MCA} of a multi-engine airplane, the flight test crew qualitatively evaluates an n-1 approach, landing and go-around, first at a safe altitude of 5000 ft AGL. The Flight Manual of a small twin might recommend a flap setting of 10° max. and an airspeed of V_{MCA} + 35 kt to be able to maintain control during the shallow turns in the traffic pattern.

6.3. Definition of V_{MCA} for pilots

The V_{MCA} definition in an Airplane Flight Manual is often: "*Minimum control speed is the minimum flight speed at which the airplane is controllable with a bank angle of not more than 5 degrees when the critical engine suddenly becomes inoperative and the remaining engine is operating at takeoff power*". This line is copied inappropriately out of an Aviation Regulation (ref. [4] or [9]) that is intended to be used by airplane design engineers for designing airplanes (including sizing the vertical tail) and for flight-testing and certification of the airplane. Once the airplane is in operational use, for which the Airplane Flight Manual applies, pilots should definitely not keep the wings level to within 5 degrees of bank, left or right, as the definition suggests. On the contrary, in order to ensure that control of their airplane after engine failure can be maintained, whatever the configuration and center of gravity are, and that the drag is minimal (for a positive remaining climb performance), pilots need to maintain straight flight with the same bank angle that was used to design the vertical tail and that was also used to determine the published V_{MCA} during flight testing, which is usually between 3 and 5 degrees away from the inoperative engine. Any other bank angle, including a bank angle to the other side, will disturb the balance of side forces and yawing moments and will result in lateral accelerations and yawing moments that cannot guaranteed be balanced by the aerodynamic controls, simply because the vertical tail with rudder (and the ailerons) were not sized large enough to do so.

The highest of static and dynamic (sudden failure) V_{MCA} is published as the standardized V_{MCA} in an Airplane Flight Manual.

V_{MCA} also applies when a non-critical engine fails, or is inoperative during the remainder of the flight. In addition, V_{MCA} is also the minimum speed in anticipation of an engine failure – it already applies before engine failure. V_{MCA} applies always, even during the approach when any engine already failed during takeoff or en-route.

Therefore, the words 'critical' and 'suddenly' in the V_{MCA} definition in an Airplane Flight Manual do not make sense at all, are misleading. The above quoted definition of V_{MCA} is definitely deficient. A suggestion for an improved definition is:

Definition of V_{MCA} for pilots: V_{MCA} is the minimum speed for maintaining straight flight only when an engine fails or is inoperative and the corresponding opposite engine is set to provide maximum thrust, provided a bank angle is being maintained of 3 – 5 degrees (exact number to be provided by the manufacturer) away from the inoperative engine.

It is strongly recommended to include the following warning:

Warning. Do not initiate a turn away from this bank angle while the thrust is maximal, or the rudder or aileron are (near) maximum. Not only the loss of control is imminent, climb performance might be lost as well. V_{MCA} is not a safe minimum airspeed for turning, only for straight flight. V_{MCA} increases considerable during turns.

For Part 25 airplanes, V_{MCA} might be defined and published, but not displayed. V_{MCA} of these airplanes is used to calculate rotation speed V_R and takeoff safety speed $_{V2MIN}$, refs [4], [9]. See also § 8.1 below. The *Warning* applies as well.

6.4. Minimum control speed – ground (V_{MCG})

When an engine fails during the takeoff ground roll, the thrust yawing moment will force a displacement of the airplane on the runway. If the airspeed is not high enough and hence, the rudder generated side force is not powerful enough, the airplane deviates from the runway centerline and might even veer off the runway if the asymmetrical power setting is maintained. The airspeed at which, after engine failure, the lateral deviation on the runway is less than or equal to 9.1 m (30 ft), despite using maximum rudder, but with the nose wheel free to caster (without the use of nose wheel steering, the tiller), is called the Minimum Control Speed on the Ground (V_{MCG}). The propeller, if applicable, is in the position is automatically achieves after engine failure.

During the acceleration for takeoff, the propellers are not (much) tilted; the moment arms of the P-vectors (§ 5.2) of the left or right propellers, and therewith the thrust yawing moments, are about equal and do not change with increasing speed (until rotation). Hence, the engines are equally critical when on the ground and in zero crosswind conditions, unless rudder boost is powered by only one of the engines (§ 5.8). The effect of crosswind is discussed in § 6.7 below.

The V_{MCG} presented in Airplane Flight Manuals is, like V_{MCA}, a worst-case minimum control speed. The *actual* V_{MCG} is usually a bit lower, safer, whatever the configuration of the airplane is. Nevertheless, when one or more of the engines fail at airspeeds below V_{MCG}, the takeoff must be aborted immediately, all throttles should be closed at once, in order to prevent the airplane from veering off the runway.

6.5. V_{MCG} testing

The airplane will be in the test configuration, i.e. takeoff configuration, most unfavorable center of gravity (aft), trimmed for takeoff and at the most unfavorable weight in the range of takeoff weights (civil: highest weight, ref. [6]; military: lowest weight, because of the lowest nose landing gear tire friction – worst case). First, the airplane will be accelerated to an airspeed well above the predicted V_{MCG}, while kept on the ground. Then the fuel to the critical engine is cut after which the test pilot will try to keep the airplane on the runway centerline using the rudder only while maintaining maximum takeoff thrust on the corresponding opposite engine for maintaining the maximum asymmetrical thrust forces and moments. During the test, a pilot reaction time of one second will be added. For the next test points, the airspeed for cutting the fuel is gradually decreased until the lateral deviation on the runway is (not exceeding) 9.1 m (30 ft) with maximum rudder deflection or 150 lb foot pressure. That airspeed is V_{MCG}. In addition, at every test point, the transient response and handling qualities are subject to testing. This test is also dangerous!

When one engine of a high-performance twin-engine airplane fails, the airplane might still accelerate because of the high thrust of the remaining engine. Therefore, it will not be possible to perform the deceleration V_{MCG} test technique on such twins, but an acceleration test method has to be used. On three or more engine airplanes, the thrust of the centerline or symmetrical inboard engine(s) may be reduced to prevent acceleration because then these engines do not contribute to the yawing moments.

6.6. Definition of V_{MCG} for pilots

- V_{MCG} is the lowest speed at which the takeoff may be safely continued following an engine failure during the takeoff run, or
- V_{MCG} is the lowest speed at which directional control can be maintained on the runway following an engine failure while the thrust is maximal.

For Part 25 airplanes, V_{MCG} might be defined and published, but not displayed. V_{MCG} of these airplanes is used to calculate decision speed V_1. V_1 is V_{MCG} + the speed gained until the (test) pilot reacts to the engine failure, usually one second, refs [4], [9].

6.7. Effect of crosswind and runway condition on V_{MCG}

When a crosswind takeoff is made, some rudder deflection may be required to keep the airplane on the runway centerline. When the (or an) upwind engine fails, the rudder deflection needs to be increased to counteract the thrust yawing moment as well. Because the rudder is already deflected against the crosswind, the pilot may not have as much rudder travel available as is required to keep the airplane on the runway. The *actual* V_{MCG} will be higher. The critical engine for V_{MCG} with crosswind might be the, or an, upwind engine and not the same as the in-flight critical engine.

Runway condition is relevant to V_{MCG} as well, because of the friction of the nose landing gear tires on the runway surface. A contaminated runway leads to higher *actual* V_{MCG}'s.

There are no requirements for crosswind and runway conditions during V_{MCG} testing; check the Flight Manual for conditions that might apply to V_{MCG} or to the derived decision speed V_1 for the subject airplane.

6.8. Minimum control speed – landing (V_{MCL})

The minimum control speed during approach and landing (V_{MCL}) is similar to V_{MCA}, but the airplane configuration is different (§ 6.9 below). V_{MCL} is defined for Part 25 airplanes only in civil Regulations, refs [4], [9].

During a normal stable approach, the required thrust of the engines, even if one of the engines is inoperative, will not have to be at maximum setting. V_{MCL} will therefore be no factor until the thrust has to be increased to maximum, for instance during severe turbulence or after initiating a go-around.

In addition to V_{MCL}, a V_{MCL2} exists for airplanes with four or more engines. V_{MCL} for these airplanes is sometimes published as V_{MCL1} (n-1). V_{MCL2} (n-2) is the minimum control speed during approach or landing when two engines on the same wing are inoperative, or after failure of a second engine. If one engine is already inoperative prior to, or fails during the approach, V_{MCL2} applies from that moment on as the acting minimum control speed for landing, in anticipation of a second engine to fail. If the airspeed during the approach decreases below V_{MCL2}, increasing the asymmetrical thrust to maximum for a go-around will result in the loss of control (if both failed engines are on the same wing). Therefore, when two engines on the same wing are inoperative, the airplane is committed to land, unless the altitude can be exchanged for airspeed down the glideslope, before the remaining (asymmetric) engines are throttled up to maximum thrust.

During a go-around, following cleaning-up the airplane (gear up, flaps takeoff), $V_{MCA(1)}$ applies, or V_{MCA2} if one engine is inoperative. The Airplane Flight Manual will most probably state that a go-around with an inoperative engine is not recommended because the approach and/ or threshold speeds are lower than V_{MCA2}. V_{MCA2} is the applicable minimum control speed when the airplane is not in the landing configuration while one engine is inoperative, in anticipation of another engine to fail. If a second engine on the same wing fails during going-around with maximum thrust on the operative engines while the airspeed is as low as or lower than $V_{MCA(1)}$, airplane control will be lost right away. Although contrary to military regulations, civil regulations do not require V_{MCA2} to be determined and published anymore (§ 6.1), pilots should ask manufacturers to provide these data for their own safety and that of their passengers.

6.9. V_{MCL} testing

The flight-test to determine V_{MCL} is similar to V_{MCA} testing (§ 6.2), with the exception of airplane configuration. The airplane configuration for V_{MCL} testing is: low weight, aft center of gravity, landing configuration (flaps and gear down), trimmed for the approach, critical engine out, go-around power on the operative engine(s) and the propeller of the inoperative engine, if applicable, in the position it achieves without pilot action.

In addition, the test must demonstrate that lateral control at V_{MCL} (and V_{MCL2}, if applicable) is adequate to roll the airplane from straight flight through an angle of 20 degrees away from the inoperative engine in not more than 5 seconds (ref. [4], [9]).

6.10. Definition of V_{MCL} for pilots

V_{MCL} is the airspeed at which it is possible to maintain control of the airplane in the landing configuration when an engine fails or is inoperative and maintain straight flight provided a bank angle is being maintained of 3 – 5 degrees (exact number to be provided by the manufacturer) away from the inoperative engine.

6.11. Safety of minimum control speeds

Three types of minimum control speeds (V_{MC}) are defined (V_{MCG}, V_{MCA} and V_{MCL}) for different flight phases, but many more *actual* V_{MC}'s exist. Every factor that has influence on the asymmetrical forces and moments that act on an airplane while an engine is inoperative, leads to an *actual* V_{MC}. The defined V_{MC}'s are determined using the worst case of these factors. The defined and published V_{MC}'s are always safe though, provided the pilot maintains the required rudder deflection for zero yaw rate (straight flight) and a small bank angle between 3 and 5 degrees, as specified by the manufacturer, away from the inoperative engine when the asymmetrical thrust is maximum.

If rudder and ailerons seem not effective anymore and control cannot be maintained, the only action a pilot can take to save the airplane and its souls on board is to reduce the asymmetrical thrust a bit, temporarily, for rudder and aileron to be effective enough to regain control and attain the small favorable bank angle, after which the thrust can be restored if the airspeed is higher than V_{MCA}.

7. PERFORMANCE WHILE AN ENGINE IS INOPERATIVE

7.1. Engine-out performance

Paragraphs above showed that failure of an engine not only has consequences for airplane control. The remaining performance might be less than results from the loss of thrust of one engine alone: when the wings are kept level, a sideslip cannot be avoided (§ 3.3 and Figure 15). If the bank angle is larger than the favorable (3 – 5 degrees) bank angle away from the inoperative engine, or towards the inoperative engine, a sideslip cannot be avoided either. A sideslip means increased drag, which in turn means less or no climb performance. In order to achieve the highest possible climb performance while an engine is inoperative, the drag must be as low as possible. This will be the case only when using the small favorable bank angle, as should be specified by the manufacturer, which is usually between 3 and 5 degrees away from the inoperative engine (§ 5.1, Figure 15). Then the sideslip is minimal and hence, the climb performance maximal.

NOTE

2° TO 3° BANK TOWARD OPERATING ENGINE

Figure 25. Note in the legend of the One Engine Inoperative climb performance graph in a Flight Manual for V_{YSE}.

Climb performance graphs – one engine operating – in some Airplane Flight Manuals (such as of the PA-44-180) include a **NOTE** in the legend as shown in Figure 25, meaning that the performance data presented in the graphs are valid only while maintaining the small favorable bank angle toward the operating engine at the recommended climb speed V_{YSE}. Attaining and maintaining a small 2 to 3-degree bank angle is definitely not only required for maintaining directional control, but also for minimum drag when the thrust is high and the airspeed low. This bank angle is a little smaller than the bank angle for V_{MCA} (5°), because V_{YSE} is higher than V_{MCA}.

In § 3.6 above, an on-line Engine-out Trainer was introduced, ref. [11], that should be used to visualize the effects that have influence on both V_{MCA} and climb performance.

Small multi-engine airplanes with a stall speed lower than 61 knots at maximum takeoff weight are not required to demonstrate a minimum rate of climb while the critical engine is inoperative at an altitude of 5,000 ft. Refer to the climb performance data in the Airplane Flight Manual to determine the maximum allowable weight for the desired minimum climb performance after engine failure.

7.2. Polar curve

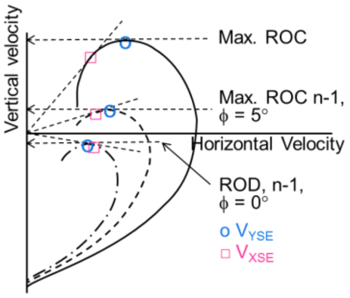

Figure 26. Polar curves; Rate of Climb (ROC) versus velocity and bank angle of a twin-engine airplane.

One of the learning objectives, ref. [1], is to identify particular points on a polar curve. Several types of polar curves exist. The polar curves in Figure 26 summarize the aircraft steady state performance, the rates of climb (ROC) or descend (ROD) for a twin-engine airplane versus horizontal velocity for constant weight, altitude and temperature. The top curve is for both engines operative; the speeds for maximum rate of climb (V_{YSE} - o) and maximum angle of climb (V_{XSE} - □ – tangent to the curve) are shown. The dashed curve approximates the polar curve for n-1, one engine inoperative, while maintaining the favorable bank angle of 5 degrees away from the inoperative engine. The bottom curve is an approximation for the n-1 case if the wings are kept level, rather than maintaining the favorable bank angle; the curve is completely below the x-axis meaning that climb performance is lost.

Any type of polar plot displaying one-engine inoperative performance data without a **NOTE** on bank angle is of no meaning in identifying particular points. Refer again to Figure 15 for the sideslip versus bank angle graph. That graph shows the loss of performance, i.e. the increase of sideslip (drag), for several bank angles.

8. FLIGHT OPERATIONS WITH AN INOPERATIVE ENGINE

8.1. V_{MCA} in Airplane Flight Manuals and Cockpits

The minimum control speed V_{MCA} of multi-engine airplanes is accurately determined during flight-testing (§ 6.2) and is published as a lower airspeed limit in the Limitations Section of the Airplane Flight Manuals. During flight-testing to determine V_{MCA}, maximum thrust (on the corresponding opposite engine) is used and the data are extrapolated to sea level and standard temperature. Some manuals present V_{MCA} data in a table or graph in which weight, altitude and temperature are the entry variables to facilitate hot and high operations more accurately.

Figure 27. Airspeed indicator of a Part 23 airplane with red V_{MCA} and blue V_{YSE} lines.

In light Part 23 airplanes, a red radial line on the airspeed indicator also indicates V_{MCA} (Figure 27). On airplanes of 2722 kg (6000 lb) or more maximum weight, regulations require a placard in full view of the pilot (Figure 28), refs [4], [9]. As was elaborated above, the published V_{MCA} is not only a standardized V_{MCA}, but also a worst case V_{MCA}; it is a safe V_{MCA} whatever the configuration of the airplane is, provided the bank angle is the same that was used to design the vertical tail, the rudder is deflected to stop yawing and the asymmetrical thrust is maximum. The bank angle for which the published, indicated, and placarded V_{MCA} is valid is not (yet) included in most Airplane Flight Manuals, though.

ONE ENGINE INOPERATIVE MINIMUM CONTROL SPEED 80 KIAS

Figure 28. V_{MCA} placard in full view of the pilot, heavier Part 23 airplanes).

For Part 23 airplanes, the standardized V_{MCA} is used to calculate the takeoff speed, which is 1.05 V_{MCA}. The safety margin at lift off is only 5%! If the pilot keeps the wings level, the *actual* V_{MCA} might increase 8 knots above the standardized V_{MCA} which is more than 5% above the safety margin (§ 5.1). Controllability might be lost right away after liftoff (if the center of gravity is aft). It is therefore of utmost importance to attain and maintain the small favorable bank angle away from the inoperative engine as soon as possible after liftoff for establishing a minimum *actual* V_{MCA}

and lowest possible drag for maximum climb performance. But it is safer to increase the takeoff speed.

For Part 25 airplanes, V_{MCA} might be defined and published, but is not displayed on the instrument panel. V_{MCA} of these airplanes is used to calculate rotation speed V_R (5% higher than V_{MCA}) and minimum takeoff safety speed V_{2MIN} (the higher of 1.1 V_{MCA} and 1.13 V_S). The takeoff safety speed V_2, that is to be reached at 35 ft AGL, is higher than V_{2MIN}. Nevertheless, the bank angle condition will also apply to these airplanes for increasing the safety margin above V_{MCA} and to maximize the climb performance!

8.2. The operational use of V_{MCA}

The V_{MCA} of a multi-engine airplane that is published in the Limitation Section of Airplane Flight Manuals is a worst-case standardized minimum control speed (§ 5). V_{MCA} is often interpreted as a constant, fixed value; however, the *actual* V_{MCA}, i.e. the V_{MCA} that the pilot experiences in-flight, might increase above the published V_{MCA} if the bank angle and the rudder and aileron control deflections are dissimilar to the ones used during flight-testing to determine the published V_{MCA}. Bank angle, rudder and in some cases also aileron controls have considerable influence on the magnitude of the *actual* V_{MCA} as was shown in § 5.1 and § 5.4. The pilot controls these factors, as well as the asymmetrical thrust level (§ 5.3). In other words, the pilot "controls" the *actual* V_{MCA}.

The standardized, Flight Manual published V_{MCA} is for maintaining straight flight only. A small 3° – 5° bank angle, as determined by the manufacturer, needs to be maintained during straight flight with maximum thrust, for minimum drag and hence, maximum performance (and for a safe margin above V_{MCA}) as long as the airspeed is low. For a pilot, this small bank angle is not an option, but a requirement (if you need to gain or not loose altitude). The higher the airspeed, the less rudder deflection and the less bank angle are required for zero sideslip, for minimum drag.

If you need to make a turn at airspeeds as low as or close to V_{MCA} and one of the engines fails or is inoperative and the other is at, or is advanced to maximum thrust, control will be lost if any or more of the other factors that have influence on V_{MCA} for instance the center of gravity, happens to be at the worst case (aft) value (§ 5). To avoid loss of control and for maximum climb performance, first climb straight ahead, while banking a few degrees away from the inoperative engine, until reaching a safe altitude (§ 5.1 and § 7.1). Then increase the airspeed or reduce the asymmetrical thrust. If you need near or up to maximum control deflection to maintain control of the airplane, the indicated airspeed is very close to the *actual* V_{MCA} for the actual bank angle. During the turn, you cannot avoid the airplane from losing some altitude because of the increased sideslip, hence drag, because the flight is not coordinated due to the asymmetrical thrust. When reaching the required heading, attain and maintain the favorable bank angle of 3 – 5 degrees away from the inoperative engine first before increasing the (asymmetrical) thrust to maximum, if required. Don't forget to decrease and increase rudder with the thrust changes. Asymmetrical engine thrust has the largest effect on airplane control and performance. *Actual* V_{MCA} is most critical (highest) when the thrust setting is high but will be no factor for airplane control if the thrust is low.

If, during the turn to final approach for landing, the asymmetrical thrust is increased for maintaining the approach path, the rudder deflection needs to be increased as well. If the airspeed is low during the turn, maximum rudder pedal travel for counteracting the asymmetrical thrust might be reached before reaching the thrust for maintaining the flight path. The *actual* V_{MCA} is higher than the indicated airspeed, leading to the loss of control (§ 5.1), unless thrust is not increased any further. Attain the favorable bank angle first and then increase thrust. Control the yawing with rudder, not by banking. A long straight-in approach is a lot safer.

V_{MC}'s are in fact minimum speeds in anticipation of engine failure(s). If an engine fails while the airspeed is lower than V_{MCA} and the thrust is (increased to) maximum, then control might be lost right away. If an engine is inoperative and the airspeed drops below (the actual) V_{MCA} or $V_{MCL,}$ for instance during the final turn for landing, control will be lost as the thrust is increased and the bank angle is not the favorable bank angle (for lowest V_{MCA}, Figure 15).

If on a 4 or more engine airplane a second engine on the same wing fails, the applicable minimum control speed is V_{MCA2}, which is 30 – 40 knots higher than $V_{MCA(1)}$. Therefore, V_{MCA2} is the minimum airspeed to be maintained when one engine is already inoperative. If during takeoff or a go-around a second engine or two engines fail on the same wing (bird strike), while the airspeed is way below V_{MCA2}, control will be lost (by definition) if the thrust is (increased to) maximum.

Some Part 25 airplanes have spoiler assisted roll control at low speed when the wing flaps are extended. If the control wheel is deflected more than 7 degrees, the spoilers kick in asymmetrically to assist the ailerons. Spoilers cause drag, loss of lift and hence, loss of performance. These airplanes might not have a favorable bank angle but procedures to keep the aileron deflection smaller than 7 degrees. Hence, the drag will not be minimal. Check the Flight Manual for the appropriate procedures.

Most of the above also applies to V_{MCL}. V_{MCL} (or V_{MCA} if no V_{MCL} published) though, in the landing configuration with landing flaps (§ 6.10). If during final approach with a 2 or 3 engine airplane, while the airspeed is below V_{MCL} (or V_{MCA}) a go-around is initiated and the throttles are moved forward to maximum, then control will be lost right away; the *actual* V_{MCL} (or V_{MCA}) increases simultaneously with the (asymmetrical) thrust. If one engine is inoperative, V_{MCL2} (or V_{MCA2}) applies and after initiating a go-around, V_{MCA2} applies as soon as the flaps are at takeoff setting. To avoid controllability problems when the airspeed is low, the acceleration to the go-around speed must be performed while still flying down the glide path before initiating the climb, using symmetrical thrust, if applicable, while adding as much asymmetrical thrust as possible to maintain straight flight, until the rudder is (or the ailerons are) maximum deflected. While adding asymmetrical thrust, both a gradual increase of rudder deflection as well as simultaneous banking to the specified favorable bank angle (between 3 and 5 degrees) away from the inoperative engine is required to keep the *actual* V_{MCA} as low as possible and to prevent the loss of control. If the altitude is already too low to exchange altitude for the airspeed to increase to V_{MCA2} or V_{MCL2} before increasing the asymmetrical thrust to maximum, the airplane is committed to land. Civil aviation authorities regrettably do not require V_{MCA2} to be determined anymore; the military do.

8.3. Engine failure emergency procedures

On ground. When an engine fails during the takeoff run when the airspeed is below V_{MCG} (or V_1), close the throttles at once to avoid veering off the runway.

Airborne. When just airborne in a small twin and with adequate runway length remaining, close the throttles and land.

When an engine fails after passing V_{MCG} or V_1, the takeoff should normally be continued. To avoid loss of control and for maximum performance, the safety margin to minimum control speed V_{MCA} as well as the climb performance should be maximal. This can be achieved by immediately attaining the favorable bank angle of the airplane (usually 3 – 5 degrees away from the inoperative engine) and maintain straight flight until a safe altitude is reached (which might take up to 30 minutes). The ball of the slip indicator is a half ball width to the good engine' side, as shown in Figure 10. Under asymmetrical thrust, this is not a slip indicator anymore. The effect of bank angle on the engine-out performance and on V_{MCA} was discussed in § 5.1 in detail.

The recommended first steps of the engine failure emergency procedure, limited to the subject of this paper, should therefore be as follows:

- Identify which engine failed (e.g. dead leg …dead engine/ the airplane yaws into the dead engine);
- Apply both rudder and aileron to stop the yaw and roll as soon as possible. Foot pressure is to the good engine side;
- Bank the specified number of degrees (between 3° and 5°) to the same side as foot pressure (is away from the inoperative engine – live engine low) and maintain this bank angle until a safe altitude and airspeed are reached (V_{MCA} + 20);
  CAUTION: Do not turn until reaching either a safe altitude or a safe airspeed.
  NOTE: If rudder and/ or ailerons do not develop large enough control power for recovery, reduce the throttle of the corresponding opposite

engine temporarily as much as required to re-establish control. Reapply maximum thrust after establishing the favorable bank angle;

- Feather the propeller of the failed engine, if applicable;
- Increase airspeed using pitch control, if feasible, to the best single engine rate of climb speed, the best angle of climb speed, or to takeoff safety speed V_2 and trim the controls.

NOTE. Some Part 25 airplane manufacturers publish their own specific engine failure procedures in which the deployment of roll assisting spoilers needs to be avoided to keep the drag low, by not exceeding 7 degrees of roll control deflection. Some drag and a smaller margin above V_{MCA} is obviously accepted.

It is recommended to include the following ***warnings***:

- During flight with an inoperative engine, maintain a speed well above V_{MCA}.
- Do not initiate a turn away from the favorable bank angle while the asymmetrical thrust is maximal and the airspeed is or is close to V_{MCA}. Not only the loss of control is imminent, climb performance might become less than positive as well. V_{MCA} is not a safe minimum airspeed for making turns, only for straight flight.
- Do not increase the power setting while in a turn at low speed; attain and maintain the safe favorable bank angle first.
- Consider a long straight-in approach if one of the engines is inoperative and power adjustments might be required.
- If the airplane does not respond to the control inputs, reduce the throttle of the corresponding opposite engine as much as required to re-establish control or, at low altitude, close the throttles and land straight ahead.

If an engine failed in-flight, consider moving the center of gravity forward and into the good engine before the approach for landing to increase the safety margin to V_{MCA}, or V_{MCL}.

Remember:

1. The $\mathbf{V_{MCA}}$ that is presented in Airplane Flight Manuals, and as red-lined speed on the airspeed indicators and/ or placarded on instrument panels, is the standardized minimum speed for **maintaining straight flight** while an (outboard) engine is inoperative, the thrust of the remaining engine(s) is at maximum available (takeoff) setting, **provided**:

- **a small favorable bank angle** is maintained away from the inoperative engine, **and**
- **the rudder is deflected** for zero yaw rate (to maintain heading).

The airplane manufacturer should specify the required favorable bank angle for lowest drag and for the published V_{MCA} to be valid, which is usually between 3 and 5 degrees away from the inoperative engine.

*V_{MCA} is definitely not a safe minimum speed for maneuvering; the vertical tail of the airplane was **not** designed large enough for turning at high asymmetrical thrust levels and low speeds. V_{MCA} increases considerably during turns at maximum. thrust.*

2. The $\mathbf{V_{YSE}}$ that is presented in Airplane Flight Manuals, and as blue-lined speed on airspeed indicators, is the speed for zero sideslip at that speed, i.e. minimum drag, and hence maximum range and maximum rate of climb, **provided**:

a **small** favorable bank angle (usually 3°), that is published with the engine-out performance data, is maintained away from the inoperative engine.

Fly safely

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