Controlling Multi-Engine Airplanes after Engine Failure

Undisclosed And Forgotten Limitations Cause Fatal Accidents

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Preface

Engine failures on multi-engine airplanes continue to lead to fatal accidents all around the globe quite frequently, despite the fact that the airplanes were designed, flight tested and certified to continue to fly safely while an engine fails or is inoperative. After reviewing many accident investigation reports, it was noticed that most pilots, flight instructors and accident investigators explain and apply the *minimum control speed in the air* $V_{MC(A)}$ of an airplane in a different way than airplane design engineers, experimental test pilots and flight test engineers do. The conditions for which V_{MCA} is valid seem forgotten. This difference in interpretation has, to the opinion of Avio*Consult*, led to many fatal accidents caused by the loss of control and/or of performance after engine failure and also to incorrect and incomplete conclusions and recommendations in accident investigation reports.

This article intends to bridge the obvious (knowledge) gap between airplane design & flight-test on one side, and multi-engine rated (airline) pilots & accident investigators on the other by briefly explaining the design of the vertical tail, the effects of bank angle and weight on V_{MCA}, the flight test techniques that are used to determine V_{MCA} and the errors in the V_{MCA} definition in most airplane flight and training manuals. Many more factors and errors are presented in other papers by the author.

After reading this article, the real value of the V_{MCA} that is published in the airplane flight and training manuals and the conditions for which this V_{MCA} is valid will be understood much better, which is of vital importance for preventing engine failure related accidents and for getting home safely after engine failure. Accident and/ or Safety Investigations will also improve.

Motions and equilibrium after engine failure

During an all engines operating coordinated turn, a component of the wing lift acts as a horizontal centripetal force in the center of gravity. However, when an engine fails or is inoperative and rudder and aileron are required to counteract the asymmetrical thrust, a bank angle does not necessarily result in a turn. In order to explain the lateral-directional stability, the airplane motions and the required countermeasures by the pilot after engine failure to maintain controlled trimmed flight (an equilibrium), we need to analyze the rotations about the top axis (yaw), the longitudinal axis (roll), the lateral displacement due to control inputs and sideslip, and the thrust and drag – four of the six degrees of freedom. For describing these, a different coordinate system than the one used to explain the centripetal force is required and used at universities and test pilot schools: the body axes system which is aligned with the geometry of the airplane. There are more coordinate systems in use in aeronautics. The body axes run through the center of gravity and laterally out the wings (y axis), longitudinally out the nose (x axis) and out the bottom (z axis), all perpendicular to each other. In this system, wing lift does not have a component in the lateral y body axis because it acts perpendicular to this axis, but the weight has. Longitudinal stability is not subject of this article.

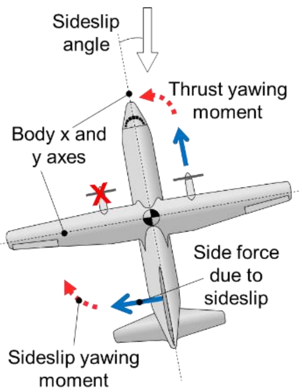

Figure 1. Forces and moments – right after failure #1, no rudder and aileron.

In general, an airplane is in equilibrium (in trim: no accelerations, no rotations) if both the sum of the forces and the sum of the moments (also called torque or rotating forces) that act on the airplane are zero. Not all forces and moments are presented in this article.

In Figure 1, the most relevant forces and moments are shown that act on a multi-engine airplane about the z body axes after failure of engine #1, while no rudder and aileron inputs are applied (yet). The airplane starts to yaw and roll, the latter as side effect of yawing, but also due to the difference in propulsive lift of both wings on propeller airplanes. A sideslip develops that continues to increase until the yawing moment generated by the sideslip acting on fuselage and fin (weathercock) is equal to the thrust yawing moment. The side force due to sideslip however, also causes the airplane to accelerate sidewards. This lateral acceleration results in an opposite side force due to the changing sideslip angle, which also reduces the sum of the yawing moments generated by fuselage and fin. As a result, the airplane continues to yaw, as does the sideward acceleration; the drag increases. Loss of control can only be prevented by pilot action.

An equilibrium without rudder input can only be achieved when attaining a bank angle into the good engine, at a high enough speed. The resulting angle of sideslip will still be large, which causes high drag and hence, a much reduced or a negative rate of climb. To reduce the drag, a rudder input is required which adds to the side force due to sideslip (Figure 1) and therewith increases the yawing moment to counteract the asymmetrical thrust yawing moment (Figure 2). An equilibrium is possible, but the sideslip is not zero.

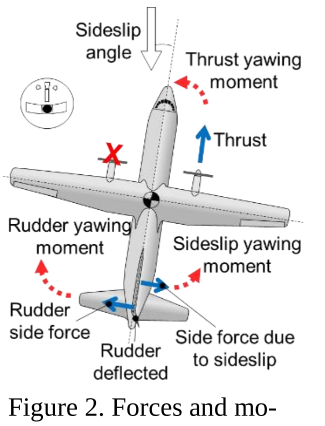

Figure 2. Forces and moments after rudder input, straight flight, wings level.

The still large sideslip in this wings-level equilibrium, can easily be reduced by a small bank angle. When banking, a component of the weight acts as a side force in the y body axis (W·sin ϕ in Figure 3). This side force reduces the lateral displacement of the airplane due to the rudder side force, and therewith decreases the sideslip angle to a minimum, decreasing the total drag and, hence, increasing climb performance. The side force due to banking 'replaced' the side force due to sideslip that was required to balance the rudder side force with the wings level. Side force W·sin ϕ acts in the center of gravity and therefore does not cause any adverse yawing moments.

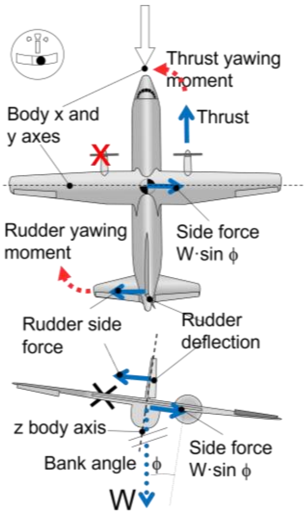

Figure 3. Forces and moments in the body axes, with a small bank angle into the good engine, during steady straight flight.

Because the side force generated by the rudder no longer has to overcome the side force due to sideslip anymore, but only the thrust yawing moment, the rudder deflection can be less, the airspeed can be lower until the deflection is again maximal, or the vertical tail can be dimensioned smaller to save manufacturing cost and weight. An interesting option for the manufacturer to produce a cheaper and less heavy vertical tail and airplane.

Reducing the size of the vertical tail however, increases the airspeed required to generate a large enough yawing moment to counteract the thrust yawing moment. Regulations do not allow the vertical tail to be made so small that minimum control speed V_{MCA} exceeds 1.2 times stall speed (V_S). Hence, the vertical tail is designed just big enough to be able to maintain *straight flight* while the thrust of the opposite engine is at the maximum level that the pilot can set from the cockpit, the rudder or the ailerons are at full throw and a small bank angle is being maintained between 3 and 5 degrees away from the inoperative engine as opted by the designer of the vertical tail, at airspeeds down to V_{MCA}. Airworthiness regulations allow the engineer designing the vertical tail to use a bank angle of maximum 5°. As mentioned, this small bank angle also reduces the sideslip, hence drag to a minimum.

The tail design engineer already determined the lowest airspeed at which equilibrium can be achieved and maintained, which is the reason that this speed is called the minimum control speed in the air V_{MCA}, sometimes also incompletely V_{MC}, because multi engine airplanes have more than one V_{MC}. The 'design' V_{MCA} is verified during experimental flight-tests, that are discussed below.

There are many more factors that have influence on the side forces and yawing moments that act on an airplane while an engine is inoperative and therewith affect V_{MCA}, including propeller feathering, weight and center of gravity. The design engineer will use the worst case of each of these factors to design a vertical tail that is just big enough to meet the requirements under all circumstances, but in-flight, the pilot controls the bank angle and therewith the controllability after engine failure. Therefore pilots must be aware of the conditions for which V_{MCA} is valid.

Effect of bank angle and weight on V_{MCA}

Figure 4 shows the required airspeed, rudder and aileron control deflections and the resulting sideslip during equilibrium (trimmed) flight at bank angles between 15° left and 15° right, while the asymmetrical thrust is maximal. Although the data are of a B707/DC-8 type airplane, the shape of the plots is the same for all multi-engine airplane types.

The manufacturer has, by solving the lateral-directional equations of motion with the stability derivatives of this airplane, analyzed that the sideslip angle is near zero, i.e. the drag is minimal, if the bank angle is 3 degrees away from the inoperative engine. For this reason, the bank angle for zero-sideslip should be included as a condition in the legend of engine inoperative performance diagrams for the presented data to be valid.

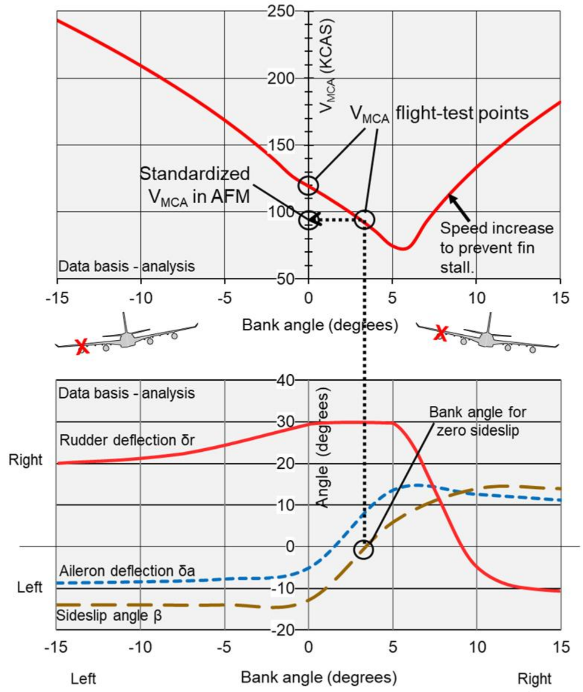

Figure 4. Effect of bank angle on V_{MCA}.

If the opted bank angle to design the vertical tail is 3°, the standardized V_{MCA} will be 95 kt. Then the rudder is maximum deflected into the good engine and the aileron is deflected as required for equilibrium, in this case 8° to that side as well. Figure 4 shows that when the bank angle is increased into the good engine, the *actual* V_{MCA}, which is the V_{MCA} that the pilot will experience in-flight, initially decreases, but above 6° of bank increases to avoid the fin to stall when the sideslip angle increases above 14°. Then also the rudder deflection needs to be reversed to reduce the lateral acceleration caused by the increasing side force W·sin ϕ. This force does not cause a yawing moment, because it acts in the center of gravity. The lateral acceleration however, causes the sideslip and hence yawing to increase due to the weathercock effect. Therefore opposite rudder is then required to maintain equilibrium of side forces, as shown in Figure 4. Hence, a turn into the good engine is not always the favorable direction as often said, and should only be performed if the sideslip can be monitored or at a much higher airspeed than V_{MCA}.

Banking away from the favorable 3° bank angle to the other side, into the inoperative engine, results in an increasing large sideslip to the left that can only be constrained by an increasing airspeed to avoid the fin to stall; *actual* V_{MCA} increases.

Bank angle not only has effect on sideslip and drag. Weight (W) and bank angle (ϕ) both have great influence on the *actual* V_{MCA} of the airplane through side force W·sin ϕ, as was explained above and is illustrated in another way in Figure 5 below. Lockheed C-130 Hercules pilots will recognize Figure 5 from their performance manual (SMP777, page 3-18).

The figure shows that when bank angle ϕ = 0, weight has no

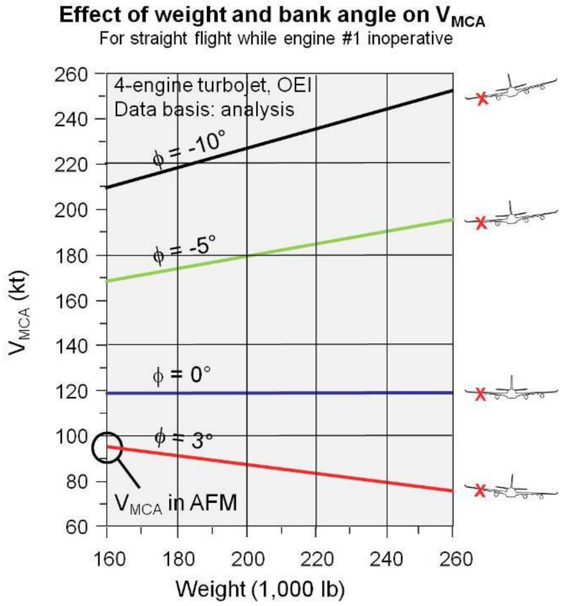

Figure 5. Effect of bank angle ϕ and weight W on V_{MCA} on a sample 4-engine airplane.

effect on V_{MCA} because side force W·sin ϕ is zero; the actual V_{MCA} with the wings level for all weights is 119 kt, as also shown in Figure 4. When the bank angle ϕ = 3° into the good engine, actual V_{MCA} decreases with increasing weight, because side force W·sin ϕ increases. Regulations however, require V_{MCA} to be determined at lowest weight, which is the worst case weight. When banked into the inoperative engine, actual V_{MCA} at low weight is already much higher than published V_{MCA} and increases considerably with weight, as the data shows.

As shown in Figures 4 and 5, the *actual* V_{MCA} of this sample airplane increases to 119 kt if the wings are kept level, 24 kt higher than the published standardized V_{MCA}. In addition, keeping the wings level or turning to either side results in an unavoidable sideslip of up to 14° for balancing the side forces at the increased actual V_{MCA}. The drag is much higher and hence, the climb performance less or negative. When banking at airspeeds below the V-shaped line in Figure 4, control will be lost; the required rudder and aileron deflections for equilibrium of forces and moments exceed the available control power. The airplane was not designed to turn at V_{MCA} and maximum thrust, only to maintain straight flight.

It will be obvious that the requirement for maintaining straight flight and a small favorable bank angle for V_{MCA} to be valid must be made well known to pilots of multi-engine airplanes; the saved weight and manufacturing cost of a smaller vertical tail (hardware) needs to be replaced by a quite 'heavy' software condition/ warning in AFM's for maintaining the mandatory small bank angle while an engine is inoperative, the airspeed is low and the power setting is high. This condition is regrettably not presented anymore in most AFM's and course books, with the exception of Lockheed and some Piper manuals. Attaining and maintaining the small favorable bank angle ASAP after engine failure is not included in emergency procedures either.

Experimental flight-testing to determine V_{MCA}

During the flight-test for determining or verifying V_{MCA}, the airplane is in the same configuration that was used to design the vertical tail, of which the most important factors are the *lowest* weight possible (for smallest side force W·sin ϕ), an aft center of gravity (for smallest rudder moment arm), maximum takeoff power setting on the engine opposite of the inoperative (critical) engine (for max. thrust yawing moment) and a feathered propeller, if automatic. This configuration results in the 'worst case' V_{MCA}. Two types of V_{MCA} are determined, first the static V_{MCA} and then the dynamic V_{MCA}.

The *static V_{MCA}* is of vital importance for continuing the flight safely while an engine is inoperative. The airspeed is slowly reduced (with the wings level) until the heading can no longer 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). This first test point is the wings-level V_{MCA} (Figure 4). Then, while applying the same bank angle that was used to design the vertical tail (3 to 5 degrees away from the inoperative, as opted by the manufacturer), the speed is (and can be) further decreased until again the heading can no longer be maintained. This speed is the static V_{MCA}. This V_{MCA} is usually between 8 (small twin) and 25 knots (B707) lower than the wings-level V_{MCA}.

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

The static V_{MCA} is usually higher than the dynamic V_{MCA}. The highest of static and dynamic V_{MCA} will be published as the V_{MCA} of the airplane in the AFM, but the static V_{MCA} applies anyhow too, during the entire remaining engine-out flight and approach.

Testing (and demo of) V_{MCA} is not without danger; therefore the test data are acquired at a safe altitude and extrapolated to Sea Level, following thorough preparation.

Definition of V_{MCA}

The $V_{MC(A)}$ definition in an AFM 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"*

and is copied inappropriately out of an aviation regulation that is intended to be used by airplane design engineers for designing airplanes (including sizing the vertical tail) and for the airworthiness certification of the airplane, and by experimental test pilots. Once the airplane is in operational use, for which the AFM 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 is, and that the remaining climb performance is as high as possible, pilots need to maintain the same bank angle that was used to design the vertical tail and that was also used to determine the AFM listed V_{MCA} during flight testing, which is usually between 3 and 5 degrees away from the inoperative engine. Any other bank angle, or 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.

Critical engine is for certification, not for (airline) pilots: only one V_{MCA} is published, the highest after failure of any engine. The *actual* V_{MCA} after failure of a non-critical engine is a little lower, safer, because the moment arm of the thrust vector is smaller. There is only one engine emergency procedure that applies after either engine failure, not only for the *critical engine*. The word *suddenly* in the V_{MCA} definition in an AFM (for pilots) does not make sense at all, is misleading. V_{MCA} applies always, even en-route, during drift-down or during the approach when an engine already failed during takeoff and the (asymmetrical) thrust is high.

The above quoted AFM definition of V_{MCA} and similar definitions are definitely deficient and should be improved. A better definition would be:

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

It is strongly recommended to include the following **warning**:

> *Do not initiate a turn away from this bank angle while the 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.*

Takeoff speeds

The AFM-listed V_{MCA} is one of the factors used for calculating takeoff speeds. Since V_{MCA} is valid only while maintaining a bank angle of 3 to 5 degrees, as opted by the manufacturer, away from the inoperative engine, the calculated takeoff speeds are also valid only when maintaining a small bank angle, that will be a bit smaller though because the takeoff speeds are higher than V_{MCA}. This applies to V_2 and V_{YSE} as well.

How to get home safely after engine failure

As was explained above, the vertical tail of a multi-engine airplane is just big enough to maintain straight flight after engine failure at airspeeds down to the AFM-listed V_{MCA}, provided a small bank angle between 3° and 5° (as opted by the manufacturer) is maintained away from the inoperative engine when the power setting of the opposite engine is high. Directional control at V_{MCA} can only be maintained during straight flight, not during turns; this is not required in Regulations and is not subject to flight testing.

If an engine fails on takeoff, input rudder with the thrust decay as required to maintain heading (dead leg – dead engine) and continue straight ahead while attaining 3 to 5 degrees ASAP away from the inoperative engine (to the same side as rudder pressure). Do not turn until the speed is increased to at least V_{MCA} + 20 kt.

This does not mean that an airplane, while an engine is inoperative, can never safely execute a turn at airspeeds as low as V_{MCA} and at high thrust settings. If one or more of the factors that have influence on V_{MCA} are not at their worst case value, as used during the design of the vertical tail and during V_{MCA} flight testing, then the actual V_{MCA} is lower, and a shallow turn might be possible, but you may never count on this.

En-route, the airspeed will usually be high enough for the tail to provide a large enough side force. Rudder will not have to be maximal. A small bank angle might be favorable though to minimize drag and hence, maximize range.

In case the airplane does not respond appropriately to control inputs, then the airspeed is below the *actual* V_{MCA} and the airplane is out of control, but you are not yet lost; don't give up. Just reduce the engine yawing moment by reducing the thrust (and the rudder) a little to reduce the *actual* V_{MCA}, attain the small favorable bank angle ASAP. As soon as the speed is at or above V_{MCA} select maximum thrust again, increase rudder with it and maintain straight flight. If at very low altitude, the only option that might be left is closing the throttles and land wings-level, which is more survivable than colliding with the ground with a wing tip first, or even inverted.

If during approach an engine is inoperative and high asymmetrical thrust becomes necessary (for a go-around) while the airspeed is low, first bank a few degrees (between 3 and 5, as the manufacturer should have specified with the V_{MCA} definition in the AFM) into the good engine and accelerate to V_{MCA} before pushing the throttles forward. Increase rudder with increasing thrust for maintaining straight flight and maintain the small bank angle as long as the thrust is maximum (and climb to a safe altitude which might take quite some time). Remember:

Published V_{MCA} is not a safe minimum speed for turning!

Plan an engine inoperative landing well ahead, make sure you will not be needing maximum thrust during the final turn for landing; a long straight-in approach is a lot safer.

Conclusion

This article might have disclosed some always improperly explained conditions and also unknown limitations that are an inherent consequence of the application of approved design methods and airworthiness regulations concerning the controllability of a multi-engine airplane after engine failure, and that will assist pilots to improve their flight skills and get themselves and their passengers home safely following an engine failure.

References

This article was written using college books by Dr. Jan Roskam of Kansas University, course books of the US Air Force and US Naval Test Pilot Schools and FAA and EASA Flight Test Guides (Advisory Circulars 23-8C, 25-7D and CS23 FTG). The referenced books and course books that are approved for public release can be downloaded from the US Archives for which links are provided on the Links page of website https://www.avioconsult.com, as is also a link to a video lecture on the subject of this article on the Avio*Consult* channel of YouTube.

On the Downloads and Accident pages, this article and other papers on the subject, reviews of flight and training manuals and of accident reports can be found, including a detailed report for flight instructors and accident investigators that includes suggestions for improvement of flight training, accident investigations, flight, operating, training and course manuals, etc.

Need help or have questions? Please do not hesitate to ask. Together we can make aviation still safer than it already is.

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