Imperfections and Deficiencies in FAA/ FAR and EASA/ CS 23 & 25 that might lead to Accidents after Engine Failure

Limited review

Harry Horlings

Avio*Consult*
Independent Aircraft Expert and Consultant
– *Committed to Improve Aviation Safety* –

This paper is an initiative of, and is written by Harry Horlings, Avio*Consult* because so many accidents after engine failure continue to happen all around the globe. The theory and background information for this paper can be found in papers Control and Performance during Asymmetrical Powered Flight (reference 1) and Airplane Control and Accident Investigation after Engine Failure (reference 2), both available from the downloads page of website www.avioconsult.com. An oral presentation to accompany this paper is available as well.

The author is graduate Flight Test Engineer (FTE) of the USAF Test Pilot School, Edwards Air Force Base, CA, USA, 1985; was assigned a flight-test position from 1986 and was Chief Flight Test of the Royal Netherlands Air Force from 1994 to 2000. He retired as Lt Col in 2003 and founded Avio*Consult*, an independent aircraft expertise and consultancy bureau. He also is an experienced private pilot. E-Mail: info@avioconsult.com.

First edition: 2005-10-02. This version: 2015-02-06 Paper Number: AC08

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INTRODUCTION

Accidents due to engine failure are still happening (too) frequently, not only during normal operations but also during pilot training, despite the fact that manufacturers design and thoroughly flight-test their airplanes and establish operational limitations to ensure the safe continuation of flight after an engine failure in any phase of flight. Manufacturers provide, and certifying authorities approve, flight manuals in which the limitations are published that are to be observed while operating the airplane. One of the limitations of multi-engine airplanes, that is used during designing the vertical tail with rudder and that is always determined during experimental flight-testing, is the minimum control speed in the air (V_{MCA}) that has to be observed in case an engine fails or is inoperative. V_{MCA} is often incompletely listed as V_{MC}. In this paper V_{MCA} is used, rather than V_{MC}. Most pilots of Part 23 airplanes consider their (multi-engine) airplane to be controllable as long as the airspeed is at or above V_{MCA} in the event that an engine suddenly fails or is inoperative during the remainder of the flight. Pilots of Part 25 airplanes use takeoff safety speed (V_2) and not V_{MCA} anymore; most of these pilots consider V_{MCA} a useless speed. However, both pilots and accident investigators explain and use V_{MCA} in a way that differs considerable from the way that experimental test pilots, flight test engineers (both graduates of Test Pilot Schools) and aircraft design engineers explain and use V_{MCA}. The pilots though, are not to be blamed; the cause is different.

The significance of V_{MCA} for the controllability of a multi-engine airplane after engine failure seems well documented in Federal Aviation Regulations (FAR), European Aviation Safety Agency Certification Specifications (EASA/ CS) 23 and 25 or equivalent and in flight manuals and textbooks, but – in fact – it is not. If the applicable V_{MCA} and/ or V_2 are readily available to pilots before every takeoff or go-around, why do engine failures or in-flight simulation or demonstration of engine failures during training still turn into catastrophes so often? Many publications were written to answer this question, but most reports and papers only discuss the early recognition of engine problems.
Therefore, more than 300 engine failure related accident investigation reports, airplane flight manuals, textbooks and FAR's and CS's were reviewed. The author concluded that most of the airplane manuals and accident investigation reports were imperfect, in many cases even incorrect and deficient on the subject of airplane control after engine failure, and must have been written by people who have a 'different understanding' of asymmetrical powered flight than experimental test pilots, experimental flight test engineers and airplane design engineers. Most of these people do obviously not know what parameters are used for designing the vertical tail of an airplane and what the test methods and conditions are to determine V_{MCA} during experimental flight-testing.

To improve the knowledge on engine-out flight, a paper for pilot training was written: *Control and Performance during Asymmetrical Powered Flight* (ref. 1) as well as a paper for accident investigators, certification pilots and flight instructors: *Airplane Control and Accident Investigation after Engine Failure* (ref. 2). The first version was published in the Aviation Safety Magazine of the Royal Netherlands Air Force in 1999 and was written after four catastrophic accidents happened following the failure of one or more engine(s) with both propeller and turbofan airplanes within a short period of time.
In ref. 2, following the thorough explanation of asymmetrical powered flight, several imperfections and deficiencies in flight manuals, in training manuals and in textbooks are discussed and recommendations for improvement are included.

This paper presents a limited number of imperfections in FAR and CS 23 and 25 paragraphs that definitely need improvement for increasing the safety of flight after engine failure (Ref. 4 and 5).

DO REGULATIONS LEAD TO ACCIDENTS?

Besides airplane manufacturers, many aviation organizations, flight planners, authors of flight manuals and textbooks, but also pilots and many more aviation personnel copy parts of regulatory paragraphs (rules) FAR and CS 23 and 25 into their own books, manuals or procedures. By doing so, they might believe to avoid approval problems with the certifying or approving authorities, but this copy work leads to incorrect airspeed definitions and use by pilots, because not all of the regulatory text that is intended for designing the airplane, for flight-test and for its certification is valid for operations with the airplane.

An example that already caused many accidents is the inappropriate and unchanged use of FAR/ CS 23.149 in operational manuals. The design engineer is allowed to use a small bank angle of maximum 5 degrees for sizing the vertical tail. The used bank angle is also applied while measuring V_{MCA} during flight-testing. The 'maximum 5 degree' allowance is, however, copied unchanged into pilot manuals. But pilots, in order to maintain control of their airplane following the failure of one of the engines, should maintain straight flight only, while maintaining the exact bank angle that was used to size the vertical tail (as long as the airspeed is low and the power of the other engine high). Many accidents happened because pilots started turning, because manufacturers are not required to publish the requirement for straight flight and the exact bank angle for which the published V_{MCA} is valid.

Of course, FAR/ CS are for publishing design criteria and certification requirements for manufacturers and certifying staff, but their contents should be unambiguous.

The inappropriate use of Regulations was also subject of paper *Staying Alive with a Dead Engine* (ref. 3), which was presented to the European Aviation Safety Seminar of the Flight Safety Foundation in March 2006. The certifying authorities inappropriately approved the incorrect use of regulatory sections in pilot manuals.

In order to prevent engine failure related accidents in the future, it is strongly recommended to start a regulation improvement process. To get this process going, this paper presents a few inappropriate and incomplete regulatory paragraphs.

IMPERFECTIONS AND DEFICIENCIES

In this paper, only a limited number of FAR and CS paragraphs and sections were reviewed and the reviewed paragraphs only for controllability issues after engine failure. The remarks and comments are presented below, in order of sub-paragraph number of Part 23 and 25. The (approximate) contents of regulations are printed in *italics*; comments are printed following a ● symbol and recommended changes, if any, following a ➢. Where applicable, reference is made to the paragraph in the papers ref. 1 and/ or ref. 2, where details can be found, like this: (ref. 1, § x). It is recommended to download this or these papers from the downloads page of website www.avioconsult.com. Readers who, after reading, still have doubts about the theory on V_{MCA} in these papers, should also refer to the formal FAA and EASA Flight Test Guides, references 4, 6 and 7, and review airplane tail design criteria in college books of aeronautical universities.

FAR AND CS DEFINITIONS, ABBREVIATIONS AND SYMBOLS

The definitions, abbreviations and symbols presented in Regulations apply to all FAR's, CS's and other formal Aviation Regulations. These definitions are often copied straight into Airplane Flight Manuals and course books, and therefore need to be unambiguous and applicable to both airplane engineering and operations. Some of them are not (yet).

''Critical engine' means the engine whose failure would most adversely affect the performance or handling qualities of an aircraft.'

- *'Critical engine'* is meant to be for the controllability of the airplane after engine failure, as was explained in ref. 1 § 5.2 and in ref. 2 § 4.5, not for performance or handling qualities. Performance and handling qualities are airspeed related. The critical engine is supposed to be off for designing/sizing the vertical tail of a multi-engine airplane and is shut down to determine V_{MCA} and V_{MCL} during flight tests, because V_{MC}'s after failure of the critical engine are a little higher and therewith the most unsafe of V_{MC}'s after failure of anyone of the engines of the airplane. Failure of any engine, critical or not, of course affects the performance of an airplane, but any inoperative engine is nearly equally critical to the remaining performance and handling qualities; the drag after failure of the critical engine might be a little higher because the rudder deflection is a little larger.
  The very first task of a pilot after a sudden engine failure is to recover and regain control; thereafter to maintain control. The just a few knots higher V_{MC} resulting from the failure of the critical engine has effect on this recovery phase (handling qualities).
  Performance, i.e. rate of climb, only becomes important again once the pilot manages to re-establish controlled flight while an engine is inoperative. Best climb performance is normally achieved at an airspeed that is higher than V_{MC}, which is the reason that single-engine climb speeds V_{YSE}, V_{XSE} and take-off safety speed V_2 exist. This comment will become much clearer after reading the other comments below. The *critical engine* is just one of the factors that has effect on the magnitude of V_{MC}. The critical engine is assumed to be inoperative for calculating the required size of the vertical tail and is shut down during flight-test to determine the minimum control speed V_{MC} that is to be published or charted in airplane flight manuals and to determine the one engine inoperative climb performance. Hence, the effect of critical engine failure is included in the published (worst case) V_{MC}. Failure of any other engine results in a lower, safer V_{MC} than the published V_{MC}. Pilots should not have to worry about the criticality of a failed engine.
  - ➢ Recommended definition: Critical engine means the engine that is inoperative for sizing the vertical tail and during flight-tests to determine the minimum control speeds V_{MC} of the airplane (because its failure returns the highest V_{MC} after failure of anyone of the engines).

''V_{MC}' means minimum control speed with the critical engine inoperative'

- Three main types of minimum control speed V_{MC} exist: ground (V_{MCG}), airborne (V_{MCA}) and approach & landing (V_{MCL}). These V_{MC}'s are each defined individually in FAR/ CS §§ 23.149 and 25.149. Besides these main types, also sub-types exist on Part 25 airplanes: V_{MCA1}, V_{MCA2}, V_{MCL1} and V_{MCL2}. Furthermore, also dynamic and static V_{MCA}'s exist (FAA and EASA Flight Test Guides (FTG), ref. 6, page 73 and CS 23, ref. 4, respectively). So why use a definition of V_{MC} that only leads to inappropriate understanding because it is incomplete and cannot cover the common part of all three individual V_{MC} definitions?
- When the Regulations use V_{MC}, V_{MCA} is meant. The other V_{MC}'s (V_{MCG} and V_{MCL}) are used properly. VMC is also the abbreviation for Visual Meteorological Conditions. FTG's also use V_{MCA} more commonly and therefore, V_{MCA} will be used from here on.
- *Critical engine*. A reader might – after reading this definition – believe that V_{MC} does not apply after failure of any other engine than the *'critical engine'*. On the contrary, V_{MC} applies after failure of any of the engines, inboard or outboard, left wing or right wing, and definitely not only after failure of the *critical engine*. Nevertheless, the vertical tail is sized, and V_{MC}'s are determined with the critical engine inoperative, because then V_{MC}'s are a little higher than V_{MC}'s will be after failure of any other engine.
  If *'critical engine'* is mentioned in this definition, then also the other factors that influence V_{MCA}, like the longitudinal and lateral position of the center of gravity, weight, bank angle, etc., should be added. Bank angle has a much greater effect on minimum control speed V_{MCA} than failure of the critical engine as compared to any other engine (ref. 1, § 5.1 and § 5.2).
  It would be impractical to provide a separate V_{MCA} for failure of any engine. Therefore, the highest

V_{MCA} – the worst-case – is presented in flight manuals, which is always safe whichever engine fails (provided the remainder of the comments in this paragraph is taken into account as well).
A failing engine during takeoff or go-around should play no role in time-consuming pilot decision-making during this critical phase of flight. There is only one engine emergency procedure for any engine failure.

This widely used V_{MC} definition is therefore definitely incomplete and incorrect.

- It is recommended to delete the definition of V_{MC}, and leave only (improved) definitions of V_{MCG}, V_{MCA} and V_{MCL} in the Definitions Section. See below.
- In the remainder of FAR and CS 23 and 25 and other Regulations, V_{MC} should be replaced with V_{MCA}.

''V_{MCA}' means the minimum control speed, take-off climb'.

- The vertical tail (fin) of a multi-engine airplane is designed to be just large enough to generate the side force required to maintain *steady straight* flight (equilibrium of side forces and yawing moments) down to V_{MCA}, while the critical engine is inoperative. For calculating the required fin size, the design engineers use a small bank angle away from the inoperative engine, because this generates a side force that reduces the required side force generated by fin and rudder for balancing the side forces that act on the airplane and hence, reduces the size of the vertical fin (ref. 1 § 4 and ref. 2, § 2.3), while also reducing the sideslip/ drag to a minimum, and therewith maximizing the climb performance after engine failure. V_{MCA} is the speed below which steady straight flight cannot be maintained, simply because the vertical tail cannot generate the required side force anymore to counteract the asymmetrical thrust yawing moment. The resulting imbalance of side forces will increase the sideslip angle, hence drag. FAR and CS require V_{MCA} to be determined as a software fix (paper procedure) for a hardware shortcoming (too small a vertical tail). During the experimental flight-test phase following prototype production, experimental flight test crews determine/confirm V_{MCA}, besides other operational limitations, for one or more engine-out configurations, as well as a special type of V_{MCA} for landing (V_{MCL}).

- A V_{MCA} is determined for one or more configuration(s). A V_{MCA} is an operational limitation for a certain configuration and is the minimum speed for maintaining <u>steady straight flight</u> only, while banking a manufacturer-determined number of degrees (usually between 3 and 5) away from the inoperative engine to reduce the sideslip angle, hence drag and maximize the climb performance. V_{MCA} is not really a *minimum <u>control</u> speed*. The airplane cannot be "controlled" at V_{MCA} after engine failure, but only maintain straight flight while the thrust on the remaining engine(s) is maximum.
V_{MCA} applies as long as the thrust is maximum (ref. 2, § 5). For certain multi-engine airplanes, many different V_{MCA}'s might exist, for instance a V_{MCA} for in and a V_{MCA} for out of ground effect, for flaps up, for takeoff flaps, for landing flaps (V_{MCL}), for two engines inoperative (V_{MCA2}), etc.
The current definition suggests V_{MCA} to be applicable to takeoff climb only and not for a certain configuration. However, many accidents happened while returning to the airport for landing, a flight phase to which a V_{MCA} applies as well. The words *'take-off climb'* in this general definition are confusing, lead to accidents and should be replaced with 'in the air', or with 'airborne'. Therefore, it should be specified for which configuration the published V_{MCA} is valid.
- Bank angle has great effect on V_{MCA} (ref. 2, § 4.3). V_{MCA} is determined using a bank angle of maximum 5° away from the inoperative engine. This bank angle will be the same as was used for dimensioning the vertical tail. The V_{MCA} data need therefore to be accompanied by the bank angle that was used to determine it and for which the data are valid. The published V_{MCA} does not apply during turns! Then the actual V_{MCA} will be a lot higher, because the rudder generated side force will have to be higher.
The configuration and the bank angle for which the published V_{MCA} is valid should therefore be added to the V_{MCA} and V_{MCL} definitions.
- The comments on the definition of V_{MC} presented above apply here too (ref. 2, § 4 and § 5 for clarification).
  - Recommended definition: 'V_{MCA} is the lowest speed at which steady straight flight can be maintained while any one engine is inoperative and the other engine(s) is/ are set to provide maximum available takeoff thrust, given the specified configuration and bank angle.'
    An alternative is: 'V_{MCA} means air minimum control speed (or minimum control speed airborne) for the specified configuration and bank angle while any one of the engines is inoperative'.
  - Require manufacturers to include the bank angle for which the published V_{MCA} is valid.

''V_{MCG}' means the minimum control speed, on or near ground'.

- According to FAR/ CS § 25.115, the takeoff flight path begins at 35 ft which might be the reason that *'near ground'* is added here. However, V_{MCA} applies as soon as the airplane is airborne; V_{MCG} applies only while the airplane is on the ground during the takeoff run and definitely not after liftoff *near the ground* anymore. V_{MCG} is correctly defined in § 25.149 f.
  - Recommended is to replace *'on or near'* with 'on the', or with 'during the takeoff run'.

FAR AND CS 23 AND 25.

Definition V_1

'V_1 also means the minimum speed in the take-off, following a failure of the critical engine at V_{EF}, at which the pilot can continue the take-off and achieve the required height above the take-off surface within the takeoff distance.'

- An engine is called a *critical engine* because its failure results in the highest thrust yawing moment, because of the shift of the propulsion (P-)vector in the propeller disc when the angle of attack increases at decreasing airspeeds, hence the highest V_{MCA}. However, on the ground, where V_1 applies, there is no difference in P-vectors between the propellers; all engines are equally critical because the angle of attack of propellers left and right is the same. Turbofan engines are also equally critical.
  - ➢ Recommended is to replace *'the critical'* with *'an'*.
- The on-ground *critical engine* might be a different engine than used for determining V_{MCA}: the engine that drives the hydraulic pump for (maximum) braking action, or the upwind engine during crosswind takeoffs.
- *'can continue'*. It is not only *can continue*, but V_1 is the *minimum* speed above which the pilot must continue, since it will be impossible to perform a full stop with maximum effort braking to come to a stop or the remainder of the runway.
- V_1 for small airplanes is 1.05 V_{MCA} or V_{MCG}. This V_{MCA} is the V_{MCA} with a small bank angle. V_{MCA} at liftoff, when the wings are still level however, is higher (8 – 30 kt depending on airplane type). The remainder of the definition therefore needs to be carefully reconsidered, because it does not yet include the effect of bank angle on V_{MCA} in order to '*achieve the required height above the take-off surface within the takeoff distance'*. This definition also looks too much like being the V_R definition.
  - ➢ Recommended is to replace this definition with: V_1 is the minimum speed in the takeoff at which the takeoff may be safely continued following the failure of an engine. The required height above the takeoff surface can be achieved when applying the small bank angle for minimum drag (for V_{MCA}) immediately after liftoff.

§ 23.51 Take-off speeds

(a)(1) For twin-engined landplanes, V_R must not be less than the greater of 1·05 V_{MC} or 1.10 V_{S1}

- See also the review of § 25.107 Take-off speeds below.
- In this paragraph, for several occasions, a 5 or a 10% increment is required above V_{MCA} to obtain V_R. As shown in ref. 2, § 4.3, the difference between published V_{MCA}, which is determined with a small bank angle, and wings-level V_{MCA} for a small twin-engine airplane is 8 – 10 kt. At rotation, the wings are still level, so the actual V_{MCA} at that instant is 8 kt or more higher than the published V_{MCA}. Hence, the 5 and 10% increments required in this paragraph do not provide the expected level of safety.
  - ➢ It is recommended to introduce the wings-level V_{MCA} in FAR/ CS 23 and 25 and use this V_{MCA} for calculating takeoff speeds.

§ 23.63 Climb: General

'Compliance with the requirements of §§ 23.65, 23.66, 23.67, 23.69 and 23.77 must be shown …

(3) Unless otherwise specified, with one engine inoperative, at a bank angle not exceeding 5 degrees.'

- *'Unless otherwise specified'*. Is this for one-engine inoperative or for not exceeding 5° bank angle?
- *'not exceeding 5 degrees'* could be misinterpreted as 'keep the wings level', however, if the wings are indeed kept level, actual V_{MCA} will be many knots (8 – 30 kt) higher than the V_{MCA} that is determined under FAR/ CS 23/25.149 and is published in the flight manual (ref. 2, § 4.3). Loss of control might be unavoidable if this requirement is misinterpreted.
  - ➢ Recommended is to replace the last part of the sentence with 'and at a bank angle away from the inoperative engine as specified by the applicant.'

§ 23.66 Take-off climb: one engine inoperative

'The gradient of climb must be determined with …

(3) The landing gear extended except that, if the landing gear can be retracted in not more than 7 seconds, it may be assumed to be retracted.'

- *'Take-off climb'* as used in the title is not defined.
- Retracting the landing gear might draw much hydraulic power from a rudder boosting system, which decreases rudder deflection and therewith temporarily increases actual V_{MCA} and the risk of losing control in a critical phase of flight (ref. 2, § 4.12 and § 4.13).
- The requirement for *'7 seconds'* of the gear to retract is of unknown and unclear origin. Main concern should be to be able to maintain control after engine failure just before or during liftoff and during the remainder of takeoff, when the speed is still low and the (asymmetrical) power setting high.
  - ➢ Since a requirement for a minimum climb gradient exists (FAR/ CS § 23.67), it is recommended to leave it to the applicant to determine whether the landing gear should be retracted or left extended before reaching a safe climb speed and altitude, but require to include this in the emergency procedures of the airplane.

'(5) Wings level.'

- Requiring *'wings level'* during one engine inoperative climb increases the drag (sideslip not zero) and increases the actual V_{MCA} as well. '*Wings level'* might lead to accidents if an engine is inoperative and the airspeed is low (ref. 2. § 4.3).
  - ➢ Recommended is to require a bank angle of 5° away from the inoperative engine or a bank angle

as specified by the applicant (normally between 3° and 5°).

§ 25.107 Takeoff speeds

'(b) V_{2MIN} … may not be less than …

(3) 1.10 times V_{MC} established under CS 25.149

- It is unclear whether the V_{MC} meant here is V_{MCG} or V_{MCA}.
  - ➢ V_{MC} should be replaced with V_{MCA}.
- V_{MCA} depends very much on bank angle, as was explained above and in ref. 2, § 4.3. V_{MCA} with the wings level is for big airplanes between 10 and 30 kt higher than the published V_{MCA} that is determined with a small bank angle of 3 to 5 degrees away from the inoperative engine. If an engine failure occurs after passing V_1, or during rotation, the wings are still level and hence, the actual V_{MCA} is 10 to 30 kt higher than the V_{MCA} published in the manuals. If the crippled aircraft cannot be accelerated quickly enough to this higher speed, or if the wings are not banked immediately 3 to 5 degrees away from the inoperative engine, as should have been specified by the manufacturer, the actual V_{MCA} will increase easily above *1.10 times V_{MC}*. V_{2MIN} will be too low, see also ref. 2, § 6.4. Control will be lost right away if the other factors that have influence on V_{MCA} happen to be at their worst-case value too (ref. 2, § 4). V_{2MIN}, as calculated with 1.10 times V_{MCA}, does not provide the required safety level. Refer to ref. 2, § 6.4).
- Refer to a video on the YouTube channel of Avio*Consult* in which a V_2 accident with an EMB-120 is discussed (ref. 8).
  - ➢ *1.10 times V_{MC} should* be replaced by '1.10 times wings-level V_{MCA}' or factor 1.10 be increased to at least 1.20.
  - ➢ If an engine fails after passing V_1, it is required to bank 5º away from the inoperative engine as soon as the airplane gets airborne. It would be better to increase V_R from 1.05 to 1.10 wings-level V_{MCA}.

'(c) V_2 … may not be less than …

(3) A speed that provides the maneuvering capability specified in §25.143(g) (for coordinated turns with bank angles of 30° without stall warning).'

- V_2 at which the required maneuvering capability (*'coordinated turns'*) can be achieved does not necessarily mean the use of maximum takeoff thrust. Only the (reduced) thrust required to produce the minimum climb gradient specified in FAR/ CS 25.121 will have to be set. The actual V_{MCA} will then be much lower, increasing the safety margin between V_{MCA} and V_2. If the pilot for any reason decides to increase thrust to maximum takeoff, the actual V_{MCA} will increase and might become very close to or even exceed V_2 while maneuvering, rendering the airplane uncontrollable. From a tail design and flight-test point of view it is not wise to allow maneuvering with bank angles up to 30 degrees. It is not required to determine V_{MCA} at different bank angles (yet). Please review the effect of bank angle on V_{MCA} in ref. 2, § 4.3 and on V_2 in ref. 2, § 6.4.
  It is also a question whether a turn can be coordinated if the trust is asymmetrical.
  This requirement is not clear enough for asymmetrical powered flight and therefore cannot be meant to be applicable to asymmetrical powered flight.
  - ➢ Recommended is to add: 'except for asymmetrical powered flight' or require a V_{MCA} to be determined at the required maneuvering bank angles as well.

'(e) V_R …

(1) V_R may not be less than –

(ii) 105% of V_{MC};'

- It is again unclear whether V_{MC} meant here is V_{MCG} or V_{MCA}, also because the current definition of V_{MCG} includes the flight segment 'near the ground'. This cannot be correct. Why here 105% and not '1.05 times', like before?
  - ➢ V_{MC} should be replaced with V_{MCA} and '105% of' with '1.05 times'.
- Refer to comments on § 25.107 (b) above.
  - ➢ Recommended is to change (ii) to read: '1.05 times wings-level-V_{MCA}', or to increase factor 1.05 to at least 1.10.

§ 25.143 Controllability and Maneuverability

'(b) It must be possible to make a smooth transition from one flight condition to any other flight condition without exceptional piloting skill, alertness, or strength, and without danger of exceeding the airplane limit-load factor under any probable operating conditions, including –

'(2) For airplanes with three or more engines, the sudden failure of the second critical engine when the airplane is in the en-route, approach, or landing configuration and is trimmed with the critical engine inoperative.'

- On a 3-engine airplane, *'the second critical engine'* would be the other wing engine, unless the remaining (centerline) engine cannot provide the required (hydraulic) power for rudder boosting. However, failure of the other wing engine is not at all critical for controllability, on the contrary, its failure eliminates the asymmetrical yawing moment due to thrust (N_T) completely, after which there is no controllability problem anymore, but 'just' a performance problem (which is not the subject of this paragraph).
  The failure of a centerline engine changes the pitching moments but does not change the thrust yawing moments – and therefore does not change V_{MCA} or V_{MCL}; this engine is not critical (for control). Determining V_{MCA2} or V_{MCL2} of a three-engine airplane (with one engine in the centerline) does not make sense, $V_{MCA(1)}$ applies anyway.
  - ➢ The *'three or more'* part in the first line of *(2)* should be changed to 'four or more wing mounted engines'.

- On 4 or more engine turbofan airplanes, the outboard engines are equally critical. If one of the outboard (critical) engines has failed, which engine is '*the second critical engine*'? Not the opposite (equally critical) outboard engine, because then there are no asymmetrical thrust moments anymore; controllability is normal.
- On 4 or more engine propeller airplanes, *the second critical engine* might be another engine than the other outboard engine because of slipstream effects (ref. 2, § 4.9).
- For determining controllability after failure of a second engine, the highest possible asymmetrical yawing moment should be used: usually two (outboard) engines inoperative on the same wing. On any 4 or more engine airplane, V_{MCL2} is determined after shutting down the engine inboard of the first shut-down (critical) engine on the same wing (ref. 2, § 5.11). Military authorities also require V_{MCA2} to be determined. For civilian airplanes, this requirement should be reinstated, because V_{MCA2} is the minimum control speed when one engine is already inoperative (n-1), in anticipation of the failure of a second engine. Once this occurs, V_{MCA2} applies anyhow; V_{MCA2} is much higher than $V_{MCA(1)}$.
  - ➢ To avoid misunderstanding it is recommended not to use *'the second critical engine'*, but 'the engine inboard of the first failed engine on the same wing' instead.
- Takeoff is not included in this subparagraph *(2)*, but a second engine might fail during takeoff or go-around as well, for instance by bird ingestion.
  - ➢ 'Takeoff' should be added to *(2)*.

§ 25.147 Directional and lateral control

This paragraph presents many requirements that are to be demonstrated at an airspeed of 1.3 V_{SR} (CS 25) and 1.4 V_{SR} (FAR 25) including wings-level yawing maneuvers and 20° banked turns into and away from the inoperative engine. As was shown in ref. 2, § 4.3, bank angle has great influence on the minimum control speed V_{MCA}. If the wings are kept level, the actual V_{MCA} is 119 KCAS (in the example of ref. 2, Figure 4), which is higher than the published V_{MCA} (95 kt). If the power setting required for level flight is less than maximum available, i.e. less than used to determine V_{MCA}, the actual V_{MCA} experienced in-flight might be lower, which is safer. If however, the power setting needs to be maximum, actual V_{MCA} is again 119 kt. For the sample airplane in ref. 2 § 4.3 with an estimated weight of 200,000 lb, 1.3 V_{SR} is 123 kt. This is only 4 kt above the actual V_{MCA} with the wings level: control problems are very close. At 123 kt (1.3 V_{SR}) and 200,000 lb, the rudder deflection on the sample 4-engine turbojet airplane of ref. 2 § 4.3 with maximum available thrust and level wings is almost 28°, very close to the limit of 30°, and the sideslip is 12°, also close to the limit (fin stall occurs at a fin angle of attack of 14°). Please refer to ref. 2, Figure 14 for the control deflections versus bank angle required for maintaining equilibrium.

The same applies to this requirement for two-engines inoperative. 1.3 V_{SR} is again 123 kt, but the actual V_{MCA} with wings level is now 150 kt (ref. 2, figure 16). This actual V_{MCA} will be a factor to consider while approaching the 1.3 V_{SR} data point to show compliance with the requirement.

V_{MCA} is a minimum control speed for steady straight – equilibrium – flight, implying that maneuvering in yaw and roll axes might become dangerous if the airspeed is close to V_{MCA}. V_{MCA} is a minimum speed to be observed all the time, just like the stall speed of an airplane. The author of this paper has no confidence in the correctness of this FAR/ CS paragraph. It should be reviewed in-depth for flight safety purposes.

§ 23.149 Minimum Control Speed

'(a) V_{MC} is the calibrated airspeed at which, when the critical engine is suddenly made inoperative, it is possible to maintain control of the airplane, with that engine still inoperative, and thereafter maintain straight flight at the same speed with an angle of bank not more than 5°. The method used to simulate critical engine failure must represent the most critical mode of power plant failure with respect to controllability expected in service.'

This paragraph is ***the most important*** one on minimum control speed, not only because the engineer who designs the vertical tail and the test pilots use it, but it is also copied inappropriately, i.e. without change, into most airplane flight manuals, textbooks, etc. as ***the*** definition of V_{MCA} for pilots. It should therefore be perfect for everybody, but it is not. It is not in agreement with the Flight Test Guides either (ref. 4, ref. 6, ref. 7). The comments on this subparagraph in order of appearance are:

- The section begins with the abbreviation *'V_{MC}'*. This might lead to the interpretation that *'V_{MC}'* includes V_{MCG}, V_{MCA} and V_{MCL}. However, the remainder of the definition of *'V_{MC}'* under (a) is about V_{MCA}, the minimum control speed in the air because *'straight flight and angle of bank not more than 5°'* are specified; V_{MCG} is defined under 149 (e) and V_{MCL} under 149 (f). See also the comments on V_{MC} in the Definitions section on page 6 above.
  - ➢ V_{MC} should be replaced by V_{MCA}.
- If *'critical engine'* is mentioned, other variables that have an even greater influence on V_{MCA} than the critical engine, like bank angle, position of the center of gravity, gross weight as well as any other factor that influences V_{MCA}, should be mentioned here as well (ref. 2, § 4). The *'critical engine'* is just one of many variable factors of which the worst-case values are used for sizing the vertical tail and as test conditions to determine V_{MCA}. The other variable factors are already published in subparagraph 23.149 (b). In any way, V_{MCA} applies after failure of any engine, not only following the failure of the *'critical engine'* (ref. 2, § 4.5).
  - ➢ *'critical engine'* should be moved to paragraph 23.149 (b).

- *'Critical engine'* is used excessively, though inappropriately in the reviewed sections of FAR's and CS's. Refer to the explanation in the FTG, ref. 6, page 71 and/ or ref. 2, § 4.5.
  - ➢ The use of *'critical engine'* in many FAR/ CS paragraphs should be carefully reconsidered.
- *'Suddenly made inoperative'* refers to the dynamic or transient effects of an engine failure that are always included in the flight-testing to determine the dynamic V_{MCA} (FTG, ref. 6, page 73 and ref. 2, § 5.3 and 5.4).
  The engineer who designs the vertical tail of the airplane uses a static (assumed) V_{MCA} to determine the minimum required size. During flight-testing, this static V_{MCA} is also determined to confirm the V_{MCA} used during the tail design process (ref. 2, § 5.3, ref. 6, page 73). The highest of static and dynamic V_{MCA} is published in flight manuals as an operating limitation. It is irrelevant to engine emergency procedures and to airline pilots whether an engine suddenly fails or slowly spools down; the published V_{MCA} applies in any case. If *'suddenly made inoperative'* is copied into airplane manuals or textbooks, the readers might think that V_{MCA} only applies after a sudden failure. V_{MCA} definitely does not apply only after a sudden failure, but a V_{MCA} applies for as long as an engine is inoperative. Many accidents after engine failure do not occur right after a 'sudden failure', but while continuing the flight with an inoperative engine for instance while initiating turns at low (traffic pattern) speed and high power settings.
  - ➢ *'when the critical engine is suddenly made inoperative'* should be replaced with*: 'w*hen the variables that have influence on V_{MCA} as listed in § 23.149 (b) are all at their worst case value.'
- *'maintain straight flight with an angle of bank of not more than 5 degrees'*. As was explained in ref. 2, § 2, many combinations of bank angle and sideslip are possible for maintaining steady straight flight, i.e. for establishing an equilibrium of lateral and directional forces and moments, after engine failure. This regulation paragraph allows the design engineer of the vertical tail to use a bank angle of not more than 5° because the side force generated by this bank angle ($W \cdot \sin \phi$) can replace the side force due to sideslip, decreasing the required side force to be generated by the vertical tail to counteract both the asymmetrical thrust yawing moment and the side force due to sideslip, and therewith reduce the required size of the vertical tail, which saves weight and production cost. In addition, because the sideslip is zero, the small bank angle (provided it is away from the inoperative engine) decreases the drag, maximizing the remaining climb performance.
  During flight-testing to determine V_{MCA}, the same small bank angle – usually between 3° and 5° – is applied in accordance with Flight Test Guides (ref.'s 5 and 6). V_{MCA} measured this way is, after interpolation to sea level etc., published as standardized V_{MCA} in the limitations section of the Airplane Flight Manual. For this V_{MCA} to be valid, the small bank angle is therefore not only required to be applied by test pilots during flight-testing to determine V_{MCA}, but by airline pilots as well after engine failure. Then the sideslip angle, hence drag, is as small as possible and V_{MCA} is low enough to ensure adequate directional and/ or lateral control power for maintaining steady straight flight. However, the second part of this regulatory paragraph currently suggests that a pilot should limit the angle of bank to 5° either side or, in other words, keep the wings level. Five degrees is the maximum allowable bank angle, that is correct, but airline pilots should, when the thrust is maximal, definitely apply the same small bank angle away from the inoperative engine that was used to design the vertical tail and to determine V_{MCA} for the AFM-published V_{MCA} to be valid (ref. 2, § 2.7). Therefore, the requirement to use the same bank angle as was used to design the tail and/ or determine the V_{MCA} during flight-tests should be included in this paragraph.
  - ➢ It is recommended to change this part to: 'maintain straight flight with an angle of bank, as opted by the manufacturer for sizing the vertical tail, of 5 degrees or less away from the inoperative engine'.
  - ➢ Add to this paragraph: 'The bank angle used to determine V_{MCA} should be published with V_{MCA} data in the limitations section of the Airplane Flight Manual.'
  - ➢ The bank angle used to determine V_{MCA} should also be published with the V_{MCA} data in the Type Certificate.
- *'Most critical mode of power plant failure'*. What exactly is meant with this requirement? Does it mean the failure of the feathering system? Fast of slow spooling down rate?
- Using all of the comments above, the recommended new § 23.149 (a) is as follows:
  - ➢ 'V_{MCA} is the lowest airspeed at which the airplane can regain and subsequently maintain steady straight flight (equilibrium) while an engine fails or is inoperative and the remaining engine(s) are set to provide maximum available takeoff power or thrust, provided a small bank angle, as opted by the manufacturer for sizing the vertical tail, is maintained away from the inoperative engine. The bank angle used to determine V_{MCA} should be published with V_{MCA} data in the limitations section of the Airplane Flight Manual. The test configuration is defined in 23.149 (b) and in the Flight Test Guides.' (ref.'s 4, 6 and 7).
- This paragraph, out of a regulation that is intended to be used for designing and certifying airplanes, is also inappropriately used by flight instructors, manual and textbook writers, etc., because the correct guidance on (the use of) V_{MC}'s is not presented in operations regulations, like Part 91 or ARO.

- ➢ It is strongly recommended to include the real operational value of all V_{MC}'s in airplane operations FAR's and CS's/ARO's.

'(b) V_{MC} for takeoff must not exceed 1.2 V_{S1}, (where V_{S1} is determined at the maximum takeoff weight) and must be determined with the most unfavorable weight and center of gravity position and with the airplane airborne and the ground effect negligible, for the takeoff configuration(s) with maximum takeoff power initially on each engine, with the airplane trimmed for takeoff, with the flaps in the takeoff position(s), landing gear retracted and all propeller controls in the recommended takeoff position throughout.'

This regulatory paragraph describes the required configuration for determining the V_{MCA} that has to be used for calculating the required minimum size of the vertical tail. It is currently aimed at performance only, not at maintaining control as well, while an engine is inoperative. The purpose is that the vertical tail is not sized too small; the smaller the vertical tail, the higher the airspeed needs to be for generating a high enough yawing moment to counteract the asymmetrical thrust yawing moment. Comments to this subparagraph are:

- For comment on *'V_{MC}'*, see the first bullet under *(a)* above and the comments on the FAR/ CS definitions on page 6 above. For most airplanes, only one V_{MC} 'Airborne' (V_{MCA}) is determined that applies not only to takeoff but also to the remainder of the flight, even during the final turn for landing while an engine is inoperative (or in anticipation of an engine failure). V_{MCA} is to be determined while all factors that have influence on the magnitude of V_{MCA} are at their worst-case value, leading to the worst-case, highest V_{MCA} that a pilot will ever experience in-flight (if rudder and bank angle are used as intended; ref. 2, § 2.8 and 4.12). The use of *'for takeoff'* is confusing and makes no sense unless '*V_{MC} for takeoff*' is meant to be V_{MCA} with the wings level, which would be favorable to the takeoff safety. This V_{MCA} is however used nowhere (yet). See also the recommendations for § 25.107 above to introduce a wings-level V_{MCA}.
  - ➢ The change of *'V_{MC}'* into 'V_{MCA}' was already recommended under Definitions.
  - ➢ Delete *'for takeoff* unless it is decided to require a wings-level V_{MCA} to be determined and used for calculating takeoff speeds V_R and V_2. Then *'V_{MC} for takeoff* should be replaced with 'V_{MCA} with the wings level for takeoff'.
- The requirement $V_{MCA} \leq$ *1.2 V_{S1} (where V_{S1} is determined at the maximum takeoff weight)* is for defining the minimum size of the vertical tail. Dr. Jan Roskam, Kansas University, uses in his Airplane Design series of books the lowest, the landing weight V_S and not *'V_{S1} determined at the maximum takeoff weight'*!
  - ➢ The line between parenthesis should be replaced by: '(where V_{S1} is determined at the minimum landing weight)'.
- If the bank angle is not 3° – 5° away from the inoperative engine as was used to design the vertical tail, actual V_{MCA} will easily increase above 1.2 V_{S1} (ref. 2, § 4.15 and Figure 1 below). The vertical tail of a multi-engine airplane is not designed to generate a high enough side force for maintaining steady straight flight at a different bank angle. For designing the vertical tail and for determining V_{MCA} during flight-test, the worst-cases of all factors that have influence on V_{MCA} are used. Bank angle has, besides thrust, the highest influence on V_{MCA} and should be specified in this paragraph. Refer to the comment on bank angle below.

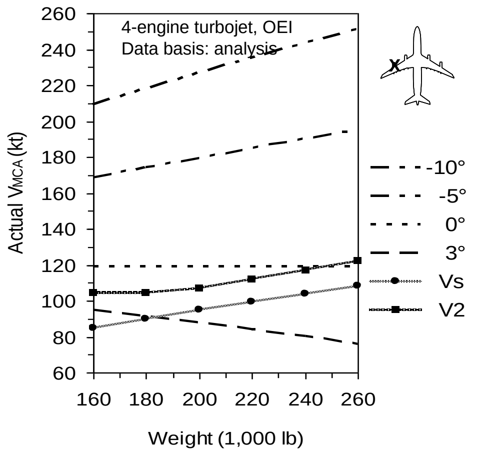

Figure 1. Effect of bank angle and weight on V_{MCA} of a sample airplane after failure of engine #1. Stall speed V_S and takeoff safety speed V_2 are included as well.

- *'most unfavorable weight'*. Most unfavorable for V_S is high weight, but most unfavorable for controllability (for V_{MCA} which is the subject of this paragraph) is usually low weight because then the measured V_{MCA} is higher while using the proper bank angle for zero drag (ref. 6, page 71 and ref. 2, § 4.3). Low weight is usually the worst-case weight for V_{MCA} of rudder-limited airplanes, while almost all pilot publications inappropriately use high weight.
  - ➢ To make this paragraph unmistakable, it is recommended to add 'which is usually lowest weight' to *'most unfavorable weight'*.
- *'ground effect negligible'*. V_{MCA} should be determined both in and out of ground effect, not just in a little bit of ground effect (ref. 2, § 4.14). The highest (most unsafe) V_{MCA} of in or out of ground effect should be published.
  - ➢ Recommended is to use 'the highest of V_{MCA} in or out of ground effect'.
- *'takeoff power initially'*. V_{MCA} is defined and flight-tested with maximum power set throughout, not only initially or takeoff power; full throttle, i.e. the maximum thrust that a pilot can set from the cockpit, is used rather than a (reduced) takeoff setting. V_{MCA} remains a factor of concern as long as one of the engines is inoperative and the other engine is, or the other engines are, providing maximum available thrust.
  - ➢ Delete *'takeoff'* and *'initially'*.

- *'landing gear retracted'*. See the comment on § 23.66 above.
- **Critical engine** is not included in this paragraph. The failure, or shut down of the critical engine leads to the highest V_{MCA} (ref. 2, § 4.5)). Therefore this engine is assumed inoperative for tail design, and shut down to determine V_{MCA} during flight-testing. Failure of any other engine results in a lower, safer V_{MCA}.
  - ➢ If the other test conditions are listed in this paragraph, 'critical engine' cannot be left out, as was already suggested before.
- **Rudder and aileron** are not included either. Zero rudder leads to a much higher V_{MCA} on rudder limited airplanes. On aileron limited airplanes, maximum aileron deflection or force is reached before maximum rudder when the airspeed decreases.
  - ➢ Add behind *'landing gear retracted':* 'maximum rudder or aileron'.
- **Bank angle.** As already mentioned in the second bullet above, bank angle is not stated here at all, but bank angle has an even greater effect on V_{MCA} than weight, center of gravity position and the critical engine, as was explained in ref. 2, § 4.3 and is shown in the Figure 2 below. Manufacturers almost certainly use a bank angle for designing the vertical tail because it saves weight and cost and reduces the drag and maximizes climb performance. The same bank angle should be used during flight-testing to determine V_{MCA} and during operational use after engine failure, or while an engine is inoperative.
  - ➢ Add to this paragraph: 'and while maintaining the bank angle that was used to design the vertical tail of the airplane (usually 3 – 5 degrees away from the inoperative engine)'.
  - ➢ Add 'critical engine' as recommended above.

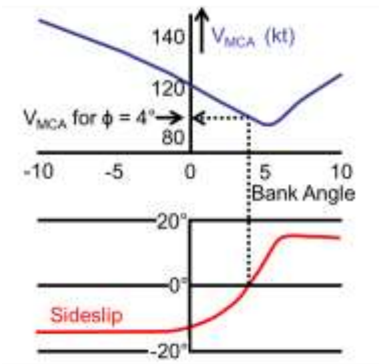

Figure 2. Effect of bank angle on sideslip angle and V_{MCA} when engine #1 is inoperative for another airplane.

'(d) A minimum speed to intentionally render the critical engine inoperative must be established and designated as the safe, intentional, one engine inoperative speed, V_{SSE}.'

- This paragraph suggests being applicable only *'to intentionally render the critical engine inoperative'*. However, it should apply if another engine than the critical engine is rendered inoperative as well. Any inoperative engine comes with its 'own' actual V_{MCA} that will be only a few knots lower (safer) than the published V_{MCA} in the flight manual that is determined with the critical engine inoperative. In addition, airplane weight and the position of the center of gravity during training will most probably never be identical to the worst-cases of these variables that were used during flight-testing to determine V_{MCA}. The actual V_{MCA} will therefore be lower (safer) than the published V_{MCA}. In-flight duplication of the published V_{MCA} during a training flight will be hard to do because there are many factors that have influence on V_{MCA}, so why only use the *'critical engine'*. Just maintaining wings level already increases V_{MCA} approximately 8 – 10 kt (Part 23 airplane). Alternating inoperative engines will teach pilots to control the airplane after the failure of the other engine too.
  - ➢ It is recommended to change this paragraph to: '(d) A speed, below which any engine may not intentionally be rendered inoperative for V_{MCA} training purposes, must be established and designated as V_{SSE}.' The definition of V_{SSE} should be included in the definitions section.

'(e) At V_{MC}, the rudder pedal force required to maintain control must not exceed 667 N (150 lb) and it must not be necessary to reduce power of the operative engine. During the maneuver the airplane must not assume any dangerous attitude and it must be possible to prevent a heading change of more than 20°.'

- This paragraph seems concerned with both the static and the dynamic V_{MCA}. *'During the maneuver'* ... might refer to the transient effects, the motions of the airplane after (sudden) engine failure, not to a pilot induced maneuver. The limited heading change is not the only condition, the bank angle should not exceed 45° and no dangerous attitudes may occur (ref.'s 4, 5; § 23.147b).
  - ➢ Replace *'During the maneuver'* with 'During the transient effects/ motions following a sudden engine failure and the pilot's response, the airplane'…, and add a reference to § 23.147b.

§ 25.149 Minimum Control Speed

This paragraph, like the corresponding paragraph in FAR/ CS 23, is the most important one on V_{MCA} because it is copied to most airplane flight manuals, textbooks, etc. It should be perfect, otherwise pilots reading these manuals and textbooks will get a wrong, unsafe understanding of V_{MCA}. The comments on the subparagraphs of this section are:

'(a) In establishing the minimum control speeds required by this paragraph, the method used to simulate critical engine failure must represent the most critical mode of powerplant failure with respect to controllability expected in service.'

- Same comment as in bullet on *'most critical mode of powerplant failure'* in § 23.149 *(a)* above.

'(b) V_{MC} is the calibrated airspeed, at which, when the critical engine is suddenly made inoperative, it is possible to maintain control of the aeroplane with that engine still

inoperative, and maintain straight flight with an angle of bank of not more than 5º.'

- Refer to comments on § 23.149 *(a)* above.

'(4) The maximum sea level takeoff weight (or any lesser weight to show V_{MC}).'

- This requirement does not agree with the flight test techniques to determine V_{MCA}. In accordance with the Flight Test Guides (FAA: ref. 7, § (2)(b)1 on page 104 and EASA: ref. 4), V_{MCA} is normally determined with a bank angle of maximum 5° (as opted by the applicant) away from the inoperative engine and at the most unfavorable weight, the worst-case weight for V_{MCA}, which is usually the lowest weight possible – refer to Figure 1. Then V_{MCA} is highest, most unsafe for the used bank angle. If the weight is higher, the actual V_{MCA} will be lower, safer, as long as the small bank angle is being maintained. The most important reason for using minimum weight for pilots is to avoid looking up the applicable V_{MCA} for the actual takeoff or landing weight, which would require too much data and be prone to failures. Therefore, low weight is used being the worst-case weight for V_{MCA}. Any other bank angle than the favorable (3 – 5 degree) bank angle for a given weight increases the actual V_{MCA} above the published V_{MCA} (ref. 2, § 4.3 and § 5.2 and Figure 1 above).
  - ➢ Replace this subparagraph *(4)* with only: 'The lowest weight possible.'

'(5) …except with the landing gear retracted.'

- V_{MCA} is important for takeoff and go-around. Retracting a gear might temporarily increase V_{MCA} due to a small rudder boost pressure reduction (ref. 2 § 4.13). Therefore, it should be left to the applicant to decide whether to retract the gear or leave it extended for determining V_{MCA} and include this in the engine emergency procedures.
  - ➢ Delete this exception.

'(6) Ground effect negligible'.

- The ground effect might influence V_{MCA} itself or the airspeed measurement by the pitot-static system (ref. 2, § 4.14). Both V_{MCA} in and out of ground effect should be published or only the highest, but not V_{MCA} in 'a little' ground effect.
  - ➢ Replace with 'in or out of ground effect, whichever returns the highest V_{MCA}.'

'(f) V_{MCL}'. Comments as for V_{MCA} apply; refer to comments on § 23.149 (a) on page 10. The difference between V_{MCA} and V_{MCL} is the power/ thrust setting (maximum power and *go-around power* respectively), configuration (approach versus takeoff) and the requirement *'to roll the airplane from steady straight flight through an angle of 20° to initiate a turn away from the inoperative engine in not more than 5 seconds*.'

- V_{MCL} in landing configuration might not differ very much from V_{MCA} in takeoff configuration. Therefore, it is as if V_{MCL} has to be determined for the small period in time between selecting go-around power and the flaps reaching the takeoff setting. Because after that, V_{MCA} applies again. **Why does V_{MCL} exist?**
- A bank angle beyond 5 degrees away from the inoperative engine will increase side force W·sin ϕ, hence the sideslip and will start to accelerate the airplane to the good engine side while the sideslip and drag also increase. The risk of fin stall will increase as well. Refer to Figures 4 and 10 in Ref. 2 and Figure 2 above, which was made with a limiting aileron deflection of 20 degrees. A bank angle into the other, the inoperative engine' side will also accelerate the airplane to that side and increases the sideslip.

'(g). For airplanes with three or more engines, V_{MCL2}, the minimum control speed during approach and landing with one critical engine inoperative, is the calibrated airspeed at which, when a second critical engine is suddenly made inoperative, it is possible to maintain control of the airplane with both engines still inoperative, and maintain straight flight with an angle of bank of not more than 5°.'

- *For airplanes with three engines*, it is of no use to determine V_{MCL2}. refer to the first bullet under § 23.143 above.
  - ➢ Refer to comments and recommended changes on the 3-engine airplane in § 25.143, under (2) above.
- Again, *'critical engine'* is (mis-)used here. This requirement should also be applicable after failure of any two engines, and not only of the critical engine and another one. If engine #1 on a propeller airplane is the critical engine, V_{MCL2} should definitely also apply after failure of both engines #3 and #4 and not only after failure of the first critical engine #1 and of #2.
- Comment on the bank angle portion is as before in § 23.149 on page 10.
  - ➢ Recommended is to re-evaluate the real value of V_{MCL} and V_{MCL2}, and delete if not found practical.

Why does V_{MCL2} exist in civilian certification requirements and not V_{MCA2}? Refer to ref. 2, § 4.3. As soon as the throttles are advanced to go-around power (while one engine is inoperative) and the flaps are up from approach to takeoff setting, a V_{MCA2} would apply and not V_{MCL2} anymore, unless go-around power is different from maximum available takeoff power. The most dangerous part in this maneuver is setting high asymmetric thrust. Therefore, before advancing the throttles to go-around power, the airspeed should be increased to the higher of V_{MCA2} and V_{MCL2} by exchanging altitude for speed. In many cases, an airplane will however be committed to land once two engines have failed and the airspeed is below V_{MCA2}. It will be nearly impossible to accelerate from approach speed to V_{MCA2} once the altitude is too low and hence cannot be exchanged for speed. Please refer to V_{MCA2} discussion in the review of § 25.143 above. Examples of catastrophic accidents after failure of two engines are the C-130H accident at Eindhoven Airbase (1996) and a Boeing 747 in Amsterdam (1992). V_{MCA2} is a lot higher than V_{MCA} (V_{MCA1}). Military 4- and more engined airplanes still require V_{MCA2} to be determined and published in Flight Manuals.

- ➢ Recommended is to reinstate V_{MCA2} in FAR and CS 25.

§ 23.157 Rate of roll

'This section presents a roll rate requirement from a steady 30-degree banked turn through an angle of 60 degrees in takeoff. It applies also to a multiengine airplane with the critical engine inoperative, the propeller in the minimum drag position and the remaining engine at maximum takeoff power. The airplane trimmed at a speed equal to the greater of 1.2 V_{S1} or 1.1 V_{MC}, or as nearly as possible in trim for straight flight.'

- This is not a very safe requirement (to test). Only airplanes with the engines very close to the fuselage or with propellers both rotating inboard might be able do this safely, because the V_{MCA} on these airplanes is very low and might be lower than V_S. I'd rather not be flying this test at an airspeed of only 1.1 V_{MCA} on any other airplane while the power setting is maximum. After banking 30 degrees, the actual V_{MCA} will by far have exceeded 1.1 times the AFM published V_{MCA}, and the airplane will become uncontrollable if the other factors that have influence on V_{MCA} happen to be at their worst-case values. Airplane control will be lost for sure if the weight is low and/ or center of gravity is aft (ref. 2, § 4.3) and the thrust high.
  - ➢ Reconsider this requirement for multi-engine airplanes with an inoperative engine.

§ 23.1513 Minimum control speed

The minimum control speed(s) V_{MC}, determined under FAR/ CS 23.149 (b), must be established as an operating limitation(s).

- All flight manuals list the flight-test determined, the worst-case – standardized – V_{MCA}, but the V_{MCA} that is experienced in-flight (the actual V_{MCA}) depends very much with bank angle as well as on other variables (ref. 2, § 4). Not maintaining the bank angle that was used to design the vertical tail and to determine V_{MCA} during flight-test already resulted in many fatal accidents.
  - ➢ It is strongly recommended to add to this paragraph the requirement to include the bank angle that was used by the applicant (the manufacturer) during straight flight to determine the minimum control speed V_{MCA}, and for which the published V_{MCA} is valid, as an operating limitation with V_{MCA} as well.

§ 23.1545(b)(6) Airspeed Indicator (Marking)

This paragraph requires the airspeed indicator of reciprocating twin-engine powered airplanes of 2,722 kg (6,000 lb) or less maximum weight to be marked with a red radial line showing the maximum value of the one engine inoperative minimum control speed determined under § 23.149 (b).

- The words *'the maximum value of''* might refer to V_{MCA}'s determined for different takeoff configurations, but is most probably an error. §23.149(b) requires only one V_{MCA} to be determined. V_{MCA} continues to increase with increasing bank angles to both sides (ref. 1, § 5.1).
  - ➢ *'maximum value of the'* should be deleted.
- *'... one engine inoperative minimum control speed ...'* Here it looks like V_{MCA1} is introduced, but is Part 23 not for two-engine airplanes only?
  - ➢ Recommend to delete *'one engine inoperative'*.
- The bank angle that was used to determine V_{MCA} and for which V_{MCA} is valid, is not required to be marked or placarded. Without presenting this bank angle, a maximum value of V_{MCA} cannot be given, because any other bank angle than used to design the vertical tail and to determine V_{MCA} increases V_{MCA} (ref. 2, § 4.3 and § 5).
  - ➢ This paragraph should be supplemented with the requirement to mark or placard the bank angle that is required for the redlined V_{MCA} to be valid. See also the next paragraph.

§ 23.1563 Airspeed placards

'There must be an airspeed placard in clear view of the pilot and as close as practicable to the airspeed indicator. This placard must list:

(c) For reciprocating multiengine-powered airplanes of more than 6,000 pounds maximum weight, and turbine engine-powered airplanes, the maximum value of the minimum control speed, V_{MC} (one engine inoperative) determined under §23.149(b).'

- The same comment applies here as for the previous paragraph.
  - ➢ It is recommended to include the bank angle, for which the placarded V_{MCA} is valid, on the placard.

JAR-OPS 1.495 Takeoff turn procedures

'(c) (1) Tracks changes shall not be allowed up to the point at which the net takeoff flight path has achieved a height equal to one half the wingspan but not less than 50 ft above the elevation of the end of the take-off run available. Thereafter, up to a height of 400 ft it is assumed that the airplane is banked by no more than 15°. Above 400 ft height bank angle greater 15° but not more than 25° may be scheduled.'

- From 35 ft up to a height of 400 ft, the airspeed maintained will normally be V_2, which is calculated using V_{MCA} and V_S (ref. 2, § 6.4). Bank angle influences V_{MCA} considerably; a bank angle of 15° after engine failure will affect the side forces acting on the airplane and might cause the vertical fin to stall or increase actual V_{MCA} 60 knots or more on certain airplane types (ref. 2, § 4.3). Therefore, this requirement is not a safe requirement (for airplanes at a low takeoff or go-around gross weight following engine failure and with the other engine(s) at maximum thrust).
- If obstacle clearance procedures require bank angles of 15°, the airspeed should be increased first well above V_2 for a safe clearance of obstacles after engine failure, or the asymmetrical thrust (opposite en-

gine) reduced a little (temporarily) to reduce the yawing moments.

- If a crosswind is from the side of the inoperative engine, track changes might be dangerous as long as V_2 is maintained, normally up to a height of 400 ft (ref. 2, § 6.4).

CAT.POL.A.215 En-route — one-engine-inoperative (OEI)

'(b) The gradient of the net flight path shall be positive at least 1 000 ft above all terrain and obstructions along the route within 9,3 km (5 NM) on either side of the intended track'.

- If the manufacturer did present OEI performance data, the data will include a recommended airspeed and a bank angle, to prevent the airplane from drifting down too much. The drift down altitude will in most cases be presented in that performance data, but the required bank angle for minimum drag under asymmetrical thrust conditions might not be included.
  - ➢ It is recommended to add to this paragraph: …while the airspeed is the recommended airspeed for maximum rate of climb, and the bank angle is the bank angle for minimum drag while maintaining straight flight.

CAT.POL.A.220 En-route — aeroplanes with three or more engines, two engines inoperative

'(d) The net flight path shall have a positive gradient at 1 500 ft above the aerodrome where the landing is assumed to be made after the failure of two engines.'

- Same remark and recommendation as in the previous paragraph.

EASA CAT.POL.A.340 Takeoff and landing climb requirements

'Takeoff climb and Landing climb/ (2) OEI'.

- These paragraphs present the requirements for steady gradient of climb when an engine is inoperative, and determine the airplane configuration. Not mentioned is the effect of bank angle on the drag, i.e. the climb performance, and on the minimum control speed. CS 23 and 25 require straight flight while banking a certain constant bank angle (max. 5 degrees) away from the inoperative engine for min. drag and for determining V_{MCA}.
  - ➢ Recommend to add to both (i) and (ii): (F) Maintain straight flight while banking the bank angle that results in the lowest drag possible, usually 3 to 5 degrees away from the inoperative engine. The exact bank angle is to be published by the manufacturer.

Obstacle clearance

Some regulations and performance manuals include the following on departures after engine failure: *'Obstacle clearance or departure clearance may require a turn shortly after takeoff. Climb performance is slightly reduced while turning, but is accounted for in the airport analysis. Maintain V_2 to V_2 + 20 and takeoff flap setting while maneuvering. Limit bank angle to 15 degrees until V_2 + 15 knots (minimum maneuvering speed on speed tape equipped airplanes).'*

- Performance might indeed be slightly reduced, but airplane control might have become impossible after engine failure at V_2 (+20), even with a bank angle of only 15 degrees (ref. 2, § 4.3 and 6.4).

Final and major conclusions and recommendations on FAR/ CS

In most paragraphs above, conclusions and recommendations were already presented on many, but not all FAR/ CS paragraphs and sections. The most important conclusions will be summarized here.

The most critical imperfection in FAR's and CS's is that the powerful influence of bank angle on V_{MCA}, as was discussed before in this paper – although correctly addressed in the FAR/ CS 23 Flight Test Guides (ref.'s 4, 6 and 7) – is not appropriately included in the formal Regulations and Specifications of FAR/ CS 23 and 25 (ref.'s 4 and 5). FAR and CS 23 and 25 concentrate mainly on the remaining performance after engine failure and not on the controllability of an airplane while the thrust distribution is asymmetrical. Consequently, the profound influence of thrust asymmetry almost never made it to be revealed appropriately in flight manuals, because manual writers and verifiers use FAR/CS 23 and 25 as a source and do obviously not read the Flight Test Guides and hence do not know how the vertical tail is designed, how V_{MCA} is determined and what the conditions are under which V_{MCA} and V_2 are valid. Although some of the reviewed textbooks are correct for describing V_{MCA}, most do not discuss the powerful influence of bank angle on V_{MCA} and are therefore deficient. It will be impossible to review all textbooks; it would be better to improve FAR's and CS's on the subject and recommend authors to review their books, etc. themselves.
Unfortunately, many accidents due to propulsion system malfunctions happen because of controllability problems rather than due to the lack of performance. The current FAR/CS 23 and 25 do not concentrate enough on controllability. The major recommendation that is required to lower the number of accidents is to change FAR/ CS 23 and 25 using the recommendations presented in this paper.

'Critical engine' is used throughout the regulatory paragraphs, but it seems that it is unclear to the writers what a critical engine exactly is and that its influence is a lot less than bank angle. The failure of a non-critical engine is almost as critical to airplane control as the failure of the critical engine and is nearly equally critical to the (remaining) performance.

The FAR and CS Flight Test Guides are nearly correct; experimental flight-test crews must have written them. It is unclear why these guides are not used to write and improve the regulatory paragraphs of FAR/ CS 23, 25 and others.

A minimum control speed not only exists for takeoff or approach and landing, as requirements in FAR and CS might let believe, but is an operational limitation applicable to all flight phases, all the time. It is also a minimum speed to be observed in anticipation of an engine failure. Once an engine is indeed inoperative, V_{MCA} becomes the minimum speed at which only straight (equilibrium) flight is possible, provided the small bank angle that was used to design the vertical tail is maintained away from the inoperative engine. V_{MCA} does not guarantee controllability during turns, not even with only a small bank angle of maximum 5 degrees. V_{MCA} can be seen as a software/ procedural fix for a hardware shortcoming (the limited size of the vertical tail).

One final recommendation for increasing safety of flight with an inoperative engine is to increase the awareness of pilots of the influence of many variable factors on V_{MCA} of which bank angle is the most important. This could be done by incorporating in Aviation Regulations and Certification Specifications the requirement to determine V_{MCA} not only at bank angles at the option of the applicant, but also to determine V_{MCA} using several different bank angles into and away from the inoperative engine and to publish these data in flight manuals as a caution. Only then, the applicants, authorities as well as operators and textbook writers will become aware of the effect of bank angle on V_{MCA} of the subject airplane and of the catastrophic consequences of maneuvering the airplane after engine failure at too low a speed.

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