Study of Tail Rudder Deflection Angles for Stabilizing the Twin Turboprop Small Passenger Aircraft in Critical Flight due to One Engine Failed Condition

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Abstract. An aircraft must have durability, whether for normal flight condition and for a critical flight condition. One of the critical flight conditions of a twin-engines aircraft is the failure of one engine while the aircraft is cruising. The aircraft with only one live engine on will still have enough power to generate thrust. However, the aircraft will experience a moment couple due to the thrust on the remaining engine that makes the aircraft to yaw. This yaw effect must be compensated by the flight control in order to maintain a stable flight condition. The rudder as one of the flight control systems manages the aircraft yaw motion. Therefore, the rudder deflection angle must be set properly as a treatment to overcome the moment force of the live engine. Study to determine best approximated optimum rudder deflection angle setting were conducted to get the figures of how the counter side forces generated on the rudder can maintain a stable flight. The result of the study can be applied as important guidance for a pilot to control the aircraft in a critical flight condition due to one engine fails. Considerations on the strength and integrity of the rudder structure especially at the hinge pivot points between the dynamic and the static parts are taken account as well.

1. Introduction

Twin turboprop engines are more fuel-efficient than the one that is using jet engines in slow to medium flight [1]. The turboprop engines make it possible for the aircraft to operate and take off from shorter runways and perform take-off and landing on unpaved surfaces [2], which is suitable to reach the varied condition of terrain in Indonesia. The twin engines aircraft must have durability for normal flight condition as well as for critical flight condition, i.e. one engine is failed. On period 2001-2016, engine failure is number 3 ranked out 10 leading cause of fatal general aviation accidents. The published accident investigation reports revealed that during the last 25 years there are more than 300 propulsion system malfunctions of multi-engine airplanes accidents happened. Also, it took casualties of more than 3,100 people lost their lives [3]. In such a critical flight condition, the aerodynamic consequences from the one engine failure lead to a very significant flight performance penalty. While the failure of an engine represents a 50% loss of available power, it can result in as much as an 80% loss of performance [4]. In general, aircraft with twin engines already being prepared to handle this kind of situation. With only one engine left the aircraft will experience yaw effect because of asymmetric thrust produced by remaining engine. The rudder needs to be deflected properly to handle the drag force until it able to land safely, or else the aircraft will experience stall. The information of
optimum rudder deflection to handle this situation is important as the pilot guidance. As a result, for the rudder deflection in certain time, the rudder will also experience forces that might affect the structure of the tail. The second deadliest plane crash that kills in total 265 passengers, American Airlines flight 587 to Santo Domingo (2001) happened because of the failure of the plane’s tail structure due to overstress when excessive rudder deflection applied. This accident provides a strong example that the study to inspect the effect of deflection in tail rudder structure is important. For safety precautions and improvement, it is needed to evaluate whether the structure able to handle the stress due to the rudder deflection in a one engine failed condition.

2. Literature Review

2.1 Asymmetric Thrust Due to One Engine Failed

Since all engines in a multi-engine aircraft are not in a same centreline and if one engine fails, then the thrust of the remaining operative engine will cause a force moment. In order to maintain a straight flight path, a yawing trim must be adjusted by controlling the rudder. The appropriate rudder deflection angles must be set to generate side forces according to the speed for countering such yawing motion. The illustration of the force moment due to the right engine and its conservation are described in figure 1 and figure 2.

![Figure 1](image1.png) **Figure 1.** Force moment due to right engine fail [5].

![Figure 2](image2.png) **Figure 2.** Conservation of Moment in one engine fail condition [5].

Each engine is at a distance of $l_T$ to the fuselage centreline. The asymmetrical thrust in one engine fail situation is resulting a yawing motion due to a force moment $(M_T)$ about the aircraft centre of gravity (CG), as described in the equation [5]:

$$M_T = T_L \times l_T$$

(1)

The convention for the negative rudder deflection is defined as the deflection to the right from pilot point of view. negative rudder deflection creates a positive side-force in the $z$ direction, which generates a positive yawing moment (clockwise). In reverse, positive rudder deflection (to the left) resulted to negative side-force in $z$ direction which generates a negative yawing moment (counter-clockwise). For a symmetrical aircraft with a zero-sideslip angle and zero-aileron deflection, a yawing moment $(M_V)$ of the vertical tail is determined from multiplication the side lift force of the vertical tail air foil with the vertical tail arm length [5]:

$$M_V = L_V \times l_V$$

(2)

In the steady-state trimmed straight path of this critical flight, the total aircraft drag is overcome just by the single thrust $(T_L)$ of the operative engine. In order to maintain a relatively straight flight path, the summation of yawing moments is equal to zero [5]. Therefore:

$$\sum M_{CG} = M_T + M_V = 0$$

(3)
Aerodynamic yawing moment \( (M_V) \) of an aircraft can be calculated from the following equation [5]:

\[
M_V = q \cdot S \cdot b \cdot C_n
\]  

(4)

Which \( (q) \) is the dynamic pressure, \( (S) \) is the wing area, and \( (b) \) is the wing span, as well as \( C_n \) is the yawing moment coefficient that is a function of aircraft configuration of sideslip angle, rudder deflection and aileron deflection. In order to get the possible maximum rudder deflection for balancing the couple moment of the remaining engine thrust, the aircraft is assumed to be symmetrical about x z plane, with no sideslip and no deflection at the aileron. So, therefore the considered yawing moment coefficient is the yaw moment coefficient due to the rudder deflection, \( i.e. (C_{n\delta R} \delta R) \) [5].

\[
M_V = q \cdot S \cdot b \cdot C_{n\delta R} \delta R
\]  

(5)

In an asymmetrical thrust condition, the necessary rudder deflection angle to trim the straight flight path is [5]:

\[
\delta_R = \left( - \frac{T_{Lr}}{q \cdot S \cdot b \cdot C_{n\delta R}} \right)
\]  

(6)

The sign in equation represent the direction of the rudder, positive sign represent that the rudder is deflected into the left side of the pilot. In vise versa, minus sign represent that the rudder is deflected into the right side of the pilot [5] [6].

2.2. Minimum Control Speed (\( V_{mc} \))
The only aerodynamic control surface that could provide the required side force to counteract the asymmetrical thrust yawing moment is the vertical tail stabilizer with rudder. The rudder must be able compensate the yaw turning tendencies caused by the operating engine, the drag of the wind milling propeller, and the aileron drag caused from trying to hold the wings level. From Table 1, it can be seen that the speed directly affect the thrust generated by the engine which have inverse relationship, this affect the magnitude of the force needed to couple the thrust. In parallel, speed also affect the dynamic pressure which is one of the denominator parameters to determine the rudder deflection as used in equation (6). Which the Dynamic pressure \( (q) \) can be evaluated by the equation below:

\[
q = \frac{1}{2} \rho \cdot V^2
\]  

(7)

\( (V) \) in the equation above represent the speed. It can be understood when the air speed experienced by the aircraft is minimum, the thrust generated will become bigger and the deflection needed to be able to generate the force to handle it is also become greater. Thus, as airspeed decreases, the rudder becomes less effective until it reaches lowest possible minimum level when it loses its ability to control the yaw moment afterward. This speed level is called the minimum control speed \( (V_{mc}) \). Which is used for maintaining straight flight after one engine fails [6].

3. Methodology

![Figure 3. Flowchart of the Methodology](image-url)
The whole process in this paper is illustrated in the figure 3. The object in this research is an original multipurpose aircraft made by Indonesian Aerospace categorized as part 23 FAR aircraft. It can carry loads up to 6,940 kg on landing, with V stall at take-off mass 6700 Kg is 69 knots. Powered by Pratt Whitney PT6-42, connected with 4 Hartzell blades. The engine performance while in one engine failure condition is shown in table 1. The aircraft has 41.5 m² wing area, 19.5m wingspan, thrust line for each engine is 2.5 m from cg (Center of Gravity) and distance from cg to ac (Aerodynamic Center) tail is 8 m. The calculation is performed under specific condition which are altitude flight of 6000 ft with respected pressure 81199.6 Pa, and outside temperature of ISA +15 Celsius. Most of the calculation is done on a spreadsheet in Microsoft Excel®. The modelling and simulation were conducted using SOLIDWORKS 2018® software. The accuracy of the simulation is really dependent on the assumption of the object modelling and the boundary condition, which is in research the model is the simplified version and the boundary condition assumed is the ideal condition at respected altitude. The flow simulation is done with resolution 5 out of 7 which already describe not the best but good accuracy of the result.

| Np rpm | Speed knots | Thrust Kgf | Fuel Flow lb/hr | Efficiency | Efficiency g/s |
|-------|-------------|------------|----------------|------------|---------------|
| 2000  | 60          | 30.87      | 860.98         | 8443.3     | 485.56        | 61.1796       | 0.45          |
| 2000  | 80          | 41.16      | 815.34         | 7995.8     | 488.24        | 61.5173       | 0.562         |
| 2000  | 100         | 51.44      | 763.61         | 7488.5     | 491.52        | 61.9305       | 0.652         |

3.1. Calculation of Generated force Due to Rudder Deflection Rounding
For the realistic practical condition when the pilot adjusts the rudder degree in flight test and to eliminate redundancy, the degrees of deflection are being rounded to the nearest possible non-decimal number. The rounding process is performed with considering the structural limit of deflection is 25 degree for each side. The number of forces generated supposed to increase with the increment of the deflection. Thus, the rounding up method is endeavoured for safety flight reason to make the force is great enough to be able to counteract the asymmetric thrust and easier to reduce if the force is exressed. The expected generated force by rounding the rudder deflection, can be evaluated using the equation (5), divided by the distance from cg to ac tail:

\[ F_V = \frac{q S b c_{\alpha R} \delta_R}{l_V} \]  

3.2. Calculation of Needed force
Needed side force from the vertical tail can be evaluated by applying conservation of moment at equation (3) without considering the rudder deflection as shown in figure 2.

4. Results and Discussions
The flow trajectories for speed in x direction on its respected rudder deflection angle are illustrated in figure 4. The velocity was changing according to the air foil shape, where the higher velocity in the left side and lower velocity in the right side of the vertical tail of the deflection was heading to. The maximum velocity is shown on the surface of the vertical tail hinge for each figure. The vortexes occurred on the root of trailing edge of the vertical tail and on the horn feature. It increased as the increment of the deflection. It also worked accordingly for the horn feature. The velocity of the massive vortex generated by the horn feature became slower in both side, this would help to alleviate the overall force that experienced by the rudder.
Figure 4. Flow Trajectories at 78 knots with 18 Degrees of Rudder Deflection

Figure 5. Surface Pressure Distribution at 78 Knots with 18 Degrees of Rudder Deflection

The load pressure on the surface of the tail is illustrated in figure 5. The pressure distribution can be observed from front and back view or the vertical tail. It is shown that the pressure increased when the air flew through the leading edge of the vertical stabilizer, and then the pressure decreased in the outside of the generated curvature of the deflecting rudder. After that, the pressure increased again when it passed the end of the rudder tip. From the back view it can be observed that the pressure was already in average magnitude between 81055.56 – 81611.11 Pa, then it reached its maximum at the hinge area with a value of 82166.67 Pa approximately. The pressure then slightly decreased as the flow travelled to the end of the rudder tip. By evaluating table 1, it was known that the fuel consumption decreased as the speed decreased, thus by operating aircraft at the lowest $V_{mc}$, the fuel consumption would be minimum. To determine the lowest possible optimum $V_{mc}$, the forces generated from simulation as well as due to rounding rudder deflection angle were compared with the forces needed from manual calculation. The comparison among those three results are shown in the table 2 and in the figure 6 and 7. From figures 6 and 7, it can be observed that the rudder worked properly with the decreasing airspeed from 82.8 knots. Then it lost its effectiveness after 22 degree of rudder deflection at 72 knots airspeed. Decreasing airspeed of 70 to 68 knots were considered as stall speed since the rudder could not generate forces as needed even though already at its maximum deflection angle of 25 degree. The rudder capability limit was considered as the best approximated optimum minimum control speed at airspeed of 78 knots and rudder deflection angle of 18 degree, for long time operation and safety reasons. At those airspeed and degree of rudder deflection, the generated forces by the manual calculation and the simulation were nearly the same and adequate for handling the yawing moment force since had only small difference from the needed force.

Table 2. Needed side force (Manual Calculation) and Generated force (Simulation)

| Speed knots | Rudder Deflection $\delta_R$ | Needed force (calculation) | Rounding $\delta_R$ F. Generated (Calculation) | Generated force (Simulation) |
|-------------|-----------------------------|-----------------------------|-----------------------------------------------|------------------------------|
|             | Calculated Degree | Rounding Degree | N       | N       | N       |
| 68          | 24.1             | 25               | 2544.28696 | 2640.98275 | 2514.43232 |
| 70          | 22.6             | 23               | 2531.22431 | 2574.72972 | 2531.04000 |
| 72          | 21.3             | 22               | 2518.16166 | 2605.52596 | 2589.40000 |
| 74          | 20.0             | 20               | 2505.09902 | 2502.07985 | 2497.92000 |
| 76          | 18.9             | 19               | 2492.03637 | 2507.19732 | 2526.53000 |
| 78          | 17.8             | 18               | 2478.97372 | 2501.89708 | 2512.93735 |
| 82.8        | 15.6             | 16               | 2447.62337 | 2506.04224 | 2471.53000 |
Figure 6. Airspeed vs Side Force Comparison

Figure 7. Rudder Deflection vs Side Force Comparison

Figure 8. Stress and Displacement distribution at 18 Degrees of Rudder Deflection with Loaded Force 2512.9 N

Figure 9. Stress and Displacement distribution at 22 Degrees of Rudder Deflection with Loaded Force 2589.4 N

Static stress simulation results for the rudder model with material of Aluminium Alloy 7050-T7651 was also conducted with consideration of the structure as one solid body to give approximation of the location of overall structure critical stress which were shown in figure 8 - 9 and in the table 3 as well. Observing from figures 8 and 9, the high stress for each deflection happened mainly on hinge area and
the tip end of the rudder, but with the displacements were progressively decreasing to the root. At 18 degree of deflection angle, the maximum stress is located inside the pivot hinge of the tail. But at 22 degree, the stress inside the pivot hinge is also high but the maximum stress was at the end tip of the rudder. However, the maximum stress at each deflection angle was not over the material’s yield strength.

Table 3. Static Stress Simulation Result

| Simulation Result          | Rudder Deflection | Units |
|----------------------------|-------------------|-------|
|                            | 18 Degree         | 22 Degree |
| Side Force                 | Max               | 2512.937353 | 2589.4000 |
| Von Mises Stress           | Max               | 1.604 e+06 | 1.609 e+06 |
|                            | Min               | 4.475 e+01 | 6.620 e-01 |
| Yield Strength [8]         | Max               | 4.900 e+08 | 4.900 e+08 |
| Strain                     | Max               | 1.725 e-05 | 1.706 e-05 |
|                            | Min               | 1.127 e-11 | 1.379 e-11 |
| Displacement               | Max               | 1.915 e-01 | 1.947 e-01 |
|                            | Min               | 1.000 e-30 | 1.000 e-30 |
| Safety Factor              | Max               | 1.095 e+09 | 7.402 e+08 |
|                            | Min               | 3.055 e+02 | 3.045 e+02 |

5. Conclusion
The rudder system of the twin engines aircraft model has an approximated optimum capability to maintain the stable flight in a critical condition due to one engine failed, which are at 18 degree of rudder deflection angle with airspeed best approximated optimum $V_{mc}$ of 78 knots. The best approximated lowest possible $V_{mc}$ that this Aircraft could achieved is 72 knots with the rudder deflection of 22 degree. The maximum generated force is 2512.9 N at the optimum $V_{mc}$ and 2589.4 N at the minimum possible $V_{mc}$. The tail structure of the twin engines aircraft model can stand the load due to the generated force by the rudder systems at the airspeed optimum $V_{mc}$ and minimum possible $V_{mc}$. For safety precaution, the critical parts which experienced the high stress, i.e. the pivot hinge area and the rudder end tip, need to be designed well and maintained regularly.

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References
[1] Kundu A K, Price M A, and Riordan D. 2019. Conceptual Aircraft Design: An Industrial Approach. United State of America, John Willet & Sons Ltd.
[2] FAA (Federal Aviation Administration). 2011. Airplane Flying Handbook. FAA-H-8083-3A. New York, Skyhorse Publishing.
[3] Dorr L. 2018. Fact Sheet – General Aviation Safety. FAA (Federal Aviation Administration).
[4] Admin. 2020. Multi Engine Airplane. Accessed on Monday, 20 April 2020 12.07 am from mycfibook.com.
[5] Sadraey M. 2012. Aircraft Design: A System Engineering Approach. Wiley Publication.
[6] Horlings H. 2012. Control and Performance During Asymmetrical Powered Flight for Multi-engine. Avio Consult.
[7] Commuter Aircraft with 2 Turboprop Engine and 19 Passengers. Engineering data. PT. DI.
[8] ASM Aerospace Specification Metal Inc. Aluminium 7075-T651. Accessed on Tuesday, 21 April 2020 at 9:23 pm from http://asm.matweb.com.