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Development of a stall sensor for low weight aircrafts

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Abstract. The phenomenon of stall or loss of lift is one of the main factors causing Loss of Flight Control (LOC) in an aircraft. In Brazil, between 2008 and 2017, most accidents that occurred due to loss of flight control occurred with aircraft weighing less than 2,250 kg. Thus, the objective of this work is to research the development of a low-cost solution about the devices currently available on the market, capable of identifying a possible stall situation, alerting, and assisting the pilot through auditory commands in the form of procedures during the flight envelope resumption maneuver. The results in this work come from tests carried out in a moving land motor vehicle, which have the purpose of simulating the functioning of the sensor developed in an operating aircraftwith longitudinal average acceleration variation of up to a maximum of 0.2 m/s^2. The preliminary results were promising since in addition to meeting the proposed objectives, enabled the mapping of low-cost improvements that can be implemented to increase the performance of the device, which can also be adapted for use in unmanned aerial vehicles.

Keywords: Stall, Flight Envelope, Angle of Attack.

1 Introduction

According to FAA [1] (Federal Aviation Administration), the phenomenon of stall or loss of lift is one of the main factors that cause an aircraft to lose control of flight. In Brazil, the CENIPA [2] (Centro de Investigação e Prevenção de Acidentes Aeronáuticos) reported that between 2008 and 2017, loss of flight control represented 19.09% of registered air accidents, of which 84% of these eventualities occurred with aircraft weighing less than 2,250 kg.

Aircraft belonging to this category are more vulnerable because they do not have avionics as developed as in large planes. So, if the stall condition is not quickly reversed, it can lead to fatal accidents. Furthermore, according to Sankaralingam and Ramprasadh [3], the stall sensor is also equally relevant in the operation of UAV (Unmanned Aerial Vehicles), especially those that fly at low altitudes.

Therefore, to research a low-cost solution to the devices currently available on the market for identifying the stall situation in aircraft of these categories becomes necessary. Thus, this research work to study and develop a didactic sensor capable of identifying a possible stall situation, alerting and assisting the pilot through audible commands in the form of audible procedures during the flight envelope resumption maneuver issued through an MP3 module.

In the didactic device developed, the identification of the pre-stall situation is limited only to movements with constant velocity or with a low variation of the mean longitudinal acceleration, since accelerations or decelerations with amplitude greater than 0.2 m/s^2 can produce changes significant at the measured pitch angle.

In this way, the didactic sensor developed in this research to identify two possible situations, the pre-stall and stall conditions. The identification of this first condition occurs when the aircraft speed is slightly higher than the stall speed and has a high pitch angle. The stall condition is identified exclusively when the aircraft speed becomes lower than the stall speed. Aircraft speed is monitored using a pressure differential airspeed gauge, while an inertial sensor is used to calculate the aircraft's pitch angle or attitude angle. As shown by Boeing [4], the variation in the pitch angle of the aircraft is directly proportional to the variation in the angle of attack (AoA) of the aircraft. Thus, the monitoring of the pitch angle in this work is used to issue an alert if the pilot exceeds a predetermined safety value. The purpose of this monitoring is to indirectly prevent the critical stall angle from being exceeded due to high pitch angle values.

2 Development

The development of this work began with the study of the main factors responsible for causing the stall situation. In this first stage, the technologies currently available on the market for this purpose were also evaluated. This analysis served to support the research proposal of a possible low-cost solution for the stall condition in light aircraft. In the next sections, the development of each part of this research work is presented in detail.

2.1 The Stall Situation

According to FAA [5], the thrust, drag, lift and weight forces act on any aircraft in flight. Thus, the stall situation is characterized by the loss of lift of the aircraft. In this scenario, the pressure difference between the lower and upper part of the wing, responsible for generating the lift force, becomes insufficient to keep the aircraft in flight. This force is defined by eq. (1).

$$Lift = \frac{C_L \cdot \rho \cdot V^2 \cdot S}{2} \tag{1}$$

where (ρ) is the air density, (V) is the aircraft's airspeed, (S) the wing surface area, and (C_L) is the coefficient of lift. This coefficient is directly proportional to the aircraft's angle of attack. The relationship between this angle and the lift force is described by the graph in Fig. 1.

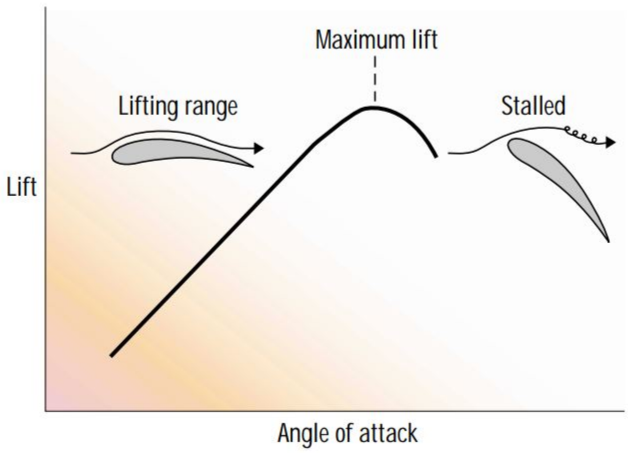

Figure 1. Ratio of lift force to increased angle of attack.

As present by the graph in Fig. 1, the high lift force occurs just before the aircraft enters a stall situation. The angle of attack and velocity for which this maximum lift force value occurs, as indicated in Fig. 1, is called the critical angle of attack and minimum stall speed, respectively. For this reason, no aircraft should operate below its stall speed. The value of this speed is defined in the aircraft manufacturer's manual. For example, according to Cessna [6] for the Cessna 172S, the value of stall speed is approximately 88 km/h.

This way, the stall alarm emitted by the research device developed throughout this work is based on the value of this speed found in each aircraft manufacturer's manual and must necessarily be provided by the user. The pre-stall warning is activated when the aircraft reaches a speed percentage higher than the stall speed and also has a pitch angle greater than the value D, also determined by the user. These values can be adjusted in the processing unit's program according to the level of safety and maneuverability desired in each aircraft. Pitch angle monitoring was chosen because its variation is directly proportional to the attack angle variation, thus representing a possibility of indirectly evaluating the AoA angle behavior, as indicated in Fig. 2.

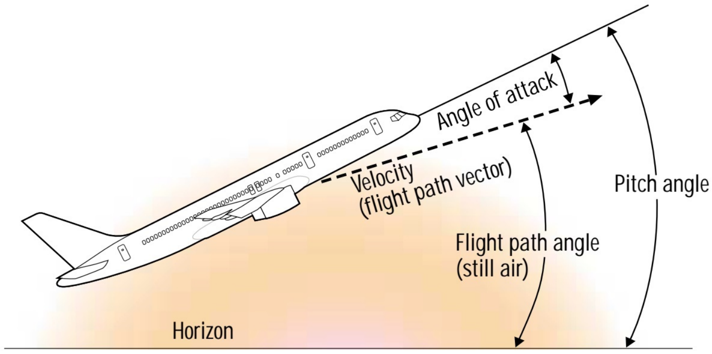

Figure 2. Main angles related to the operation of an aircraft.

In the next section, the operation of the didactic device to be developed is explained in detail, considering the pitch angle and aircraft speed data.

2.2 Data Acquisition and Processing

The research device to be developed in this work considers data from an airspeed sensor and an inertial sensor. The processing of these data provides the identification of the aircraft pre-stall and stall situation. These situations are informed to the pilot along with procedures to get around them through an electronic circuit that has an MP3 module for issuing the procedures through a synthesized voice. This design topology is synthesized through the diagram in Fig. 3.

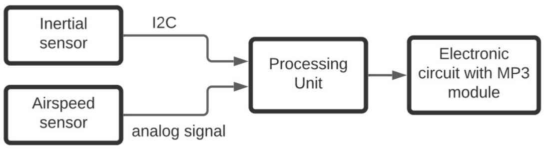

Figure 3. Schematic of the didactic device to be developed.

The processing of data provided by the sensors and the identification of pre-stall and stall situations is performed by an Arduino Uno platform. In Fig. 4 is presented a flowchart of how these two situations are identified through the data of airspeed and pitch angle of the aircraft. This aircraft status analysis takes place every 1 second. The airspeed values A and B in the diagram shown in Fig. 4 delimit a safety range slightly higher than the stall speed and are determined considering a percentage of the minimum lift speed found in the manufacturer's manual for each aircraft . The angular value of the variable D can be determined by the user considering a percentage of the critical angle of his aircraft, which according to FAA [5] is around $12°$ to $16°$ depending on each aircraft.

According to Fig. 4, the pre-stall warning is only activated in situations where the aircraft has a speed slightly higher than the stall speed and a high pitch angle. The recognition of a high of this angle to identify the pre-stall, search to prevent the pilot from exceeding the critical angle of attack by inadvertently increasing the pitch angle. The warning of the stall situation is activated exclusively when the aircraft speed is lower than the stall speed configured according to the user manual of each aircraft.

Once the general operation of the research device to be developed has been explained, the obtaining of velocity and pitch angle values is presented below, as well as the activation mode of the MP3 module, as exemplified in the diagram shown in Fig. 3.

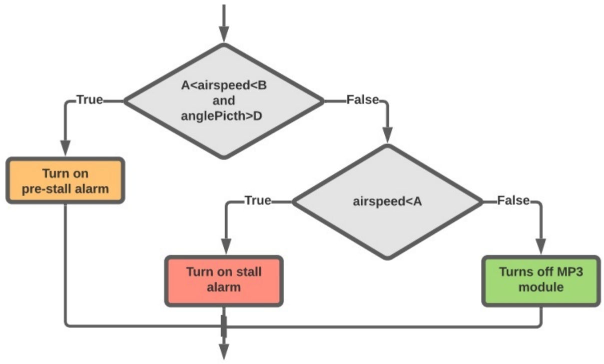

Figure 4. Flowchart for identifying pre-stall and stall conditions.

Getting the Airspeed

The airspeed sensor used in this didactic project is formed by a Pitot Tube JMT-PT60 and by the piezoresistive pressure differential sensor MPXV7002DP. This sensor measures the differential pressure provided by the Pitot Tube, representing the value measured through an analog signal from 0.5 V to 5 V. This analog signal is then converted to digital via the Arduino Uno 10-bit AD converter. Thus, according to D. and Jr. [7], the pressure differential value can be used to determine the aircraft speed through the Bernoulli principle. The final equation is presented in eq. (2), where (R) is the analog reading performed by Arduino, (ρ) is the air density and (v) is the airspeed in relation to the aircraft.

$$v = \sqrt{\frac{1000 \cdot (\frac{R}{2^{10}-1} - 0.5)}{\rho}} \tag{2}$$

Getting the Pitch Angle

The inertial sensor used in this research work is the MPU6050 module that contains an accelerometer and a triaxial gyroscope of the MEMS type, resulting in a device with 6 degrees of freedom (6DOF). Due to its 16-bit analog to digital converter, this module allows to accurately obtain the accelerations and angular rotations along the axes x, y and z. Through the values of the accelerations along the axes x and z and trigonometric calculations, the value of the pitch angle (α) is obtained based on the accelerometers according to eq. (3).

$$tan(\alpha) = \frac{a_z}{a_x} \Rightarrow \alpha = tan^{-1}(\frac{a_z}{a_x}) \tag{3}$$

The aircraft pitch angle value calculated using the eq. (3) equation is susceptible to variations in the thrust and drag forces. For this reason, the application of this didactic device at this stage of the project is restricted to movement with constant speed or with low variation in longitudinal acceleration.

In order to improve the accuracy of the pitch angle calculation and make the system more robust to external noise, the resulting pitch angle used by the didactic device developed in this work is calculated considering both the data from the triaxial accelerometer, according to the equation eq. (3), when also from the gyroscope of the MPU6050 module. Thus, as Beer and Johnston [8], knowing the angular velocity and the time interval between samples, it becomes possible to determine the pitch angle.

This way, by implementing a Kalman Filter considering these two measurement sources, an approximation for the most robust and accurate pitch angle is obtained. This implementation was made using the Kalman Filter Library in its version 1.0.2, available for free on the Arduino platform.

Activation of Alarms

The MP3 module used in the development of this didactic device is the MP3 module DFPlayer Mini. In this work, it is connected to the Arduino through a power circuit made up of relays and transistors. It is this connection format that allows the control of pre-stall and stall alarms according to the situation of the aircraft at any given time only through 3 digital outputs of the processing unit. The warnings and procedures to be performed in each of these situations were previously recorded in the memory card of the MP3 module and for this reason, during the device operation, only the control of which track must be played according to each situation. Therefore, in the section 3 the didactic prototype developed is presented, as well as the results achieved throughout this research work.

3 Results and Discussions

The development of this work was motivated by the research and didactic implementation of a possible low-cost solution for the identification of stall situations in aircraft of low weight. The Fig. 5 presents the final result of this didactic device for studying the identification of stall situations.

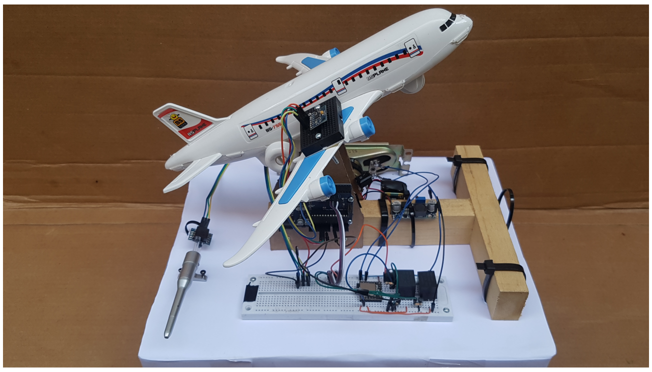

Figure 5. Didactic prototype developed for research to identify stall situations.

The study of the identification of the stall situation is carried out through the device developed presented in Fig. 5, through tests in an automobile traveling in the highway with a variation of average acceleration up in maximum 0.2 m/s^2. The objective of this test step is to verify if, through the implementation performed, it is possible to identify the pre-stall and stall situations in movements with low acceleration variation, simulating the operation of the device in a real aircraft. Thus, it is expected that the didactic device activates and presents a high logic level in its digital outputs according to each test condition, consequently providing the correct activation of alarms through the MP3 module, as exemplified in Fig. 4. In this wise, the Fig. 6 presents the fixation of the didactic device developed for the tests in a Fiat Mobi car.

Figure 6. Attachment of the research device to a car for performing dynamic tests.

Once the device was installed in the vehicle according to Fig. 6, the parameters A = 60 km/h, B = 70 km/h and D = 20° were determined. These values do not represent real aircraft data and were determined only considering the maximum allowable speeds and the terrain of the test site. The value of ρ = 1,1255 kg/m^3 was determined considering the weather conditions at the time of the test. The graph presented in Fig. 7 shows the results obtained during the pre-stall test. At the beginning of testing this condition, the pitch angle of the survey device was set to $25°$.

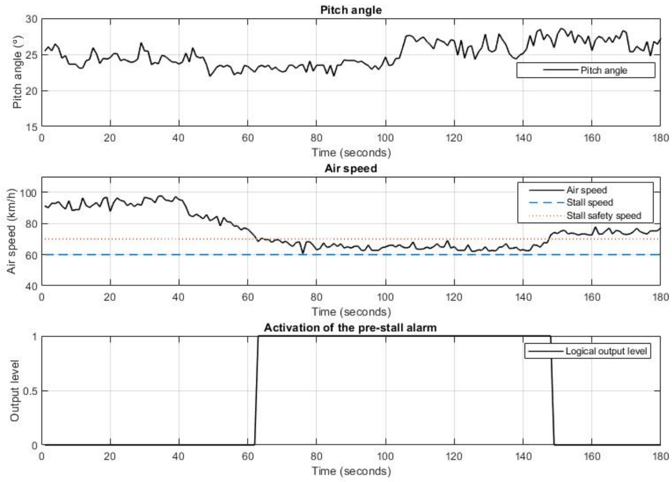

Figure 7. Test results with the device to identify the pre-stall condition.

As shown in Fig. 7, the activation of the pre-stall alarm warning occurs from the moment the pitch angle is greater than $20°$ and the aircraft airspeed is less than 70 km/h, according to the condition provided for the initially predetermined values of A and B and D. Furthermore, it is a possible note that although the implementation of the Kalman Filter has improved the robustness of this measure about external noise, it is still more sensitive than the airspeed measure. The Fig. 8 shows the result of the test performed to identify the stall condition. Already for the beginning of testing this condition, the pitch angle of the device was set to $12°$.

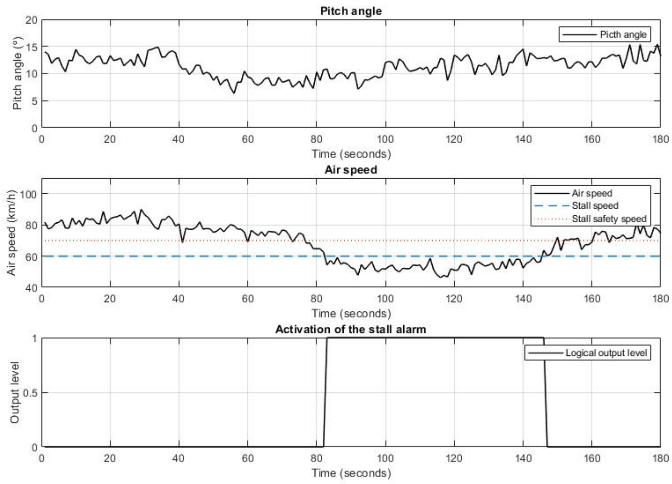

Figure 8. Test results with the device to identify the stall condition.

As shown in Fig. 8, the activation of the stall alarm warning occurs exclusively while the aircraft speed becomes lower than the stall speed. So, the preliminary results presented in Fig. 7 and Fig. 8 demonstrate that despite the signals being susceptible to noise and external disturbances, even was possible to identify the pre-stall and stall situations during the tests performed. Thus, the results achieved in this first phase of this study, make it possible to infer that they can still be improved from the implementation of digital filters, such as the Moving Average filter. The implementation of filters like this will enable a more stable measurement of the pitch angle and aircraft airspeed, making them more robust to noise. According to Antoniou [9], these filters represent a good signal processing alternative for microprocessor systems, limited only to the processing capacity of the processing unit.

Through the use of a GPS module it would be possible to obtain the variation of the average speed and consequently the average acceleration of the aircraft. This value can be used to correct errors due to acceleration variations in the inertial module, thus enabling the application of this device in aircraft with accelerated movements. However, this possibility of implementation using the GPS module needs to be studied in greater depth, in order to verify its functionality. Therefore, this implementation step will only be carried out in the next phase of the development of this project.

4 Conclusions

The development of this work was motivated by the research of a low-cost solution to prevent stall situations in light aircraft. For this purpose, a didactic device was developed, as shown in Fig. 5, with the purpose of evaluating the possibilities of solutions for the stall condition.

The tests performed with the developed didactic device showed promising results, as shown in Fig. 7 and Fig. 8. This way, it was possible to identify both the pre-stall and stall situations during the terrestrial tests performed. Although the Kalman filter implementation strategy has reduced slightly noise interference in the pitch angle, it was noticed that it is still necessary to implement digital filters to further improve the robustness of both pitch angle and airspeed.

The development of this work also allowed the perception of implementations that can be developed to further improve the accuracy of these variables, such as the use of GPS modules. It is believed that through the implementations to be carried out in the continuation of this work, this device may represent a low-cost alternative for identifying stall situations in aircraft in flight.

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