Engineering Notes

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Stall Margin Indication

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Introduction

THE landing and takeoff phases of flight require control of the aircraft at airspeeds and angles of attack close to stall. This is particularly true when a wind shear condition has been encountered. During the recovery from a wind shear, the aircraft must use all available energy, the most immediately available being kinetic energy in the form of airspeed. This paper covers the concept and hardware of a microprocessor-based stall margin display system. The LCD heads-up display provides accurate real-time data to the pilot allowing the precise use of the available airspeed. The precise use of this immediately available, but limited, energy source will increase the chance that ground contact can be avoided until the engines can provide the necessary additional energy for full recovery.

The stall/spin and wind shear scenarios continue to be major causes of fatal aviation accidents. The solutions lie along several paths, including airborne and ground-warning systems, instantaneous cockpit situation and control data displays, education, and training. This paper describes the concept of the stall margin indicator (SMI). The SMI falls into the category of an instantaneous cockpit situation and control data display, which not only provides real-time stall margin data to the pilot during routine operations, but also greatly enhances the education and training functions.

The stall margin is determined from wing-pressure data and is presented to the pilot on a heads-up LCD see-through display and/or a panel-mounted CRT display.

Theory of Operation

The stall margin (SM) is the percentage of lift coefficient remaining for use by the pilot at any given time in the airplane's flight operation.

$$SM = \left(1 - \frac{C_L}{C_{L\max}}\right)100\%$$

where

$C_L = 2L/\rho V^2 S$
L = present aircraft lift
ρ = sea level air density
V = calibrated airspeed
S = aircraft reference area
$C_{L\max} = 2L/\rho V_s^2 S$
V_s = calibrated stall speed for present lift (L)

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Substituting

$$SM = \left(1 - \left(\frac{V_s}{V}\right)^2\right)100\%$$

For example, if an airplane makes an approach at an SM of 40%, its airspeed will be about 1.3 times the stall speed in the present configuration. Previous research[1] has shown the airplane's SM to be a function of a pressure coefficient derived from three properly selected wing surface pressures. This coefficient is defined as

$$C_p = \frac{(P_1 - P_3)}{(P_2 - P_3)}$$

where

P_1 = surface pressure, typically located at the wing leading edge
P_2 = surface pressure, typically located at 50% chord on the wing upper surface
P_3 = surface pressure, typically located at 50% chord on the wing lower surface

Need

There are several scenarios that demonstrate the need for an instantaneous stall-margin display in the cockpit.

Improper Approach Speed

The inexperienced or complacent pilot often makes approaches with either insufficient or excessive airspeed. Excessive airspeed may lead to overshooting the runway or a high-speed touchdown and ground loop. Insufficient airspeed puts the aircraft close to the backside of the power curve and stall. The proper approach speed is primarily determined from the aircraft flight manual, knowing the aircraft weight and its configuration. The stall margin display provides the pilot with sufficient data to control power and pitch, and thus maintain the correct approach speed without the pilot's use of the flight manual.

VMC Demonstrations

In order to demonstrate minimum controllable airspeed (VMC) during multiengine training, the aircraft is slowed with one engine at idle. The instructor intends for the aircraft to reach an airspeed where the rudder can no longer offset the asymmetric thrust. At higher altitudes nonturbocharged engines will have a reduced thrust, which will cause the VMC to be lower than at sea level.

If stall is encountered first, the aircraft will be in a stall with an unbalanced yawing moment, and without quick pilot action, will enter a spin. Many instructors manually limit the available rudder in order to increase VMC above stall. For this technique to work, the pilot must determine the aircraft's stall speed from the flight manual and then make sure the airspeed remains above this speed. The airspeed indication presently provided to the pilot is not at all accurate near stall speed, and thus the pilot does not know how close the aircraft is to stall. If the aircraft is equipped with a stall-margin display, the aircraft's margin from stall would be known regardless of weight, configuration, or altitude.

Wind Shear

The most serious wind shear is the downburst phenomena. The aircraft first encounters the outflow winds that result in an initial increase in airspeed. As the aircraft passes into the core of the downburst, the airspeed decreases and the sink rate increases. If the pilot does not quickly recognize the situation, power may be reduced when the increase in airspeed is first indicated. When the core of the downburst is encountered and the wind shear is recognized, the pilot will initiate recovery. During the engine spool-up the aircraft falls below the glide slope. To avoid premature collision with the ground the pilot must "buy time" for the engines to come to full power. At this point the only excess energy available is kinetic. The pilot will trade the airplane's airspeed for a reduction of the sink rate. In doing so it is critical not to stall the aircraft. Given the fact that the stall speed is not exactly known by the pilot and that the airspeed is not accurate at these speeds, the optimum recovery will not be possible using airspeed alone.

In all of the above situations the pilot needs a real-time display of stall margin to most effectively control the aircraft.

Previous Work

In 1978 Western Michigan University (WMU) identified a need for a stall margin indication device for single-engine aircraft. By 1979 research had produced the relationship between stall margin and wing surface pressures that formed the basis for two patents.[3,4]

The first patent involved the selection of wing surface pressure tap locations and the second covered an analog stall-margin system. Several prototype analog systems were installed in WMU's training fleet. From the evaluation of this field test, the need for several enhancements were identified, the most important being pressure transducer stability. The solution to this problem led to a computer-based stall-margin system. This system provides opportunities to evaluate alternative cockpit displays and aid in pilot tasks such as checklist management. The purpose of this paper is to describe operational characteristics of the microprocessor-based system designed as a proof of concept prototype.

Operating Modes

Stall-Margin Display

The stall-margin display is shown in Fig. 1. The top of the left-hand bar indicates the present stall margin. When it reaches a point just below the word STALL on the display, the aircraft will stall regardless of its weight or flap configuration. Each mark down and left-hand side represents a 10% stall margin. The ⟨ ⟩ mark between the two bars represents the

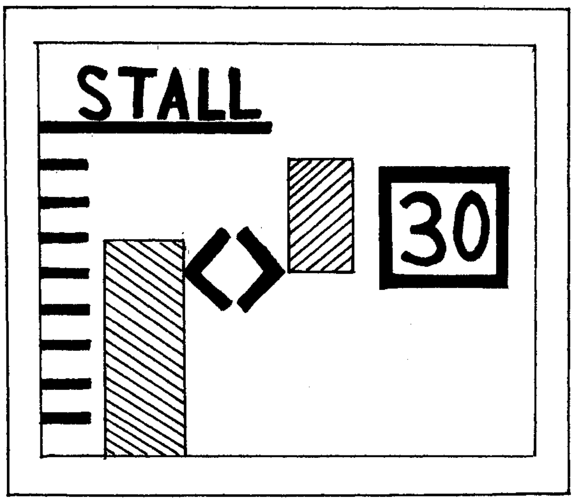

Fig. 1 Stall margin HUD display.

bug or target-approach stall margin. This would usually be set at 40%, which corresponds to an approach speed of 1.3 times the stall speed in the present configuration. The pilot can use the four-button keypad to set this bug to the desired value. The middle bar moves up and down from the bug and reaches full scale when the stall margin is + 10% or − 10% from the bug stall margin. This provides for a quick and easy method to read deviation. The pilot can change the response of the display by using the keypad. The boxed number to the right of the display is the stall margin in digital format, which is most useful during cruise flight.

Pilot transition from airspeed to SMI takes only a few approaches. The target stall margin is defaulted to 40% and is only changed by the pilot when special circumstances exist. Once set, the center deviation bar will show the direction and magnitude of needed correction. The pilot flies the deviation bar's outer surface; that is, if the bar is up, control inputs will be initiated to move the bar down and vice versa. If the bar is up, the stall margin is too small (low airspeed). To correct, the pilot pushes the stick forward and/or increases power. Conversely, if the bar is down, the stall margin is too large (high airspeed). To correct, the pilot pulls back on the stick and/or decreases power. The transition can also be made by considering the surface of the deviation bar as if it were the tip of the airspeed needle. During an approach the tip of the airspeed needle is pointing to the right-hand side of the airspeed indicator. The pilot can simply use the same control inputs to move the stall margin deviation bar as required to move the airspeed needle in the same up or down direction. By using a stall margin display as the primary approach reference, the precision by which the aircraft is operated is greatly improved, without increasing the pilot's task of making control decisions. This is accomplished by providing the pilot with data that is more pertinent to the task at hand.

Checklist Management

In order to demonstrate the ability of a stall margin display to be integrated with other cockpit avionics, a checklist management function was added. Using the keypad the pilot can select from several menus pertaining to the stall margin and the checklist. Also included is a streamlined operating mode that allows the pilot to move through a typical flight, switching back and forth between the checklist and the stall margin with minimal button operation.

System Components

A block diagram of the stall margin system is shown in Fig. 2 and a detailed description can be found in Ref. 2. The system consists of a data acquisition unit (DAU) located in the wing, a cockpit display, yoke-mounted buttons, and the computer located in the avionics bay.

Data Acquisition Unit

The DAU contains the temperature and pressure transducers. When the computer requires data, it sends a request message to the DAU by way of the RS232 serial data link. The DAU converts the sensor analog signals into a digital format and then sends the output to the computer over the data link. The computer can command the DAU to send an output that either corresponds to the wing pressures or to a zero differential pressure. The zero pressure is achieved in the DAU by the activation of pneumatic valves that shunt the pressure ports on each differential pressure transducer. By reading the zero output of the sensor while in flight, the computer can correct the major drift error of the sensor. The temperature sensor pro-

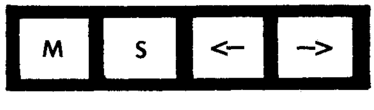

Fig. 2 Stall-margin system.

Table 1 SMI and checklist key functions

Mode	Keypad key functions			
	M	S	←	→
Master system menu	No affect	Selects option at cursor	Moves cursor up	Moves cursor down
SMI menu	Returns to master system menu	Selects SMI option at cursor	Moves cursor up	Moves cursor down
SMI display and test	Returns to SMI menu	Returns to next checklist item[a]	Change to SMI response setup mode	Changes to SMI bug setup mode
SMI response setup	Returns to SMI menu	Returns to SMI display or test mode	Decreases SMI response rate	Increases SMI response rate
SMI bug setup	Returns to SMI menu	Returns to SMI display or test mode	Decreases SMI bug setting	Increases SMI bug setting
Checklist menu	Returns to master system menu	Selects checklist category at cursor	Moves cursor up	Moves cursor down
Checklist category (e.g., taxi)	Returns to checklist menu	Toggles checklist item complete mark and moves to next item[a]	Moves cursor up	Moves cursor down

[a]When all items within a checklist category are complete the display switches directly to the SMI mode, when normal operations would require a stall-margin reference.

vides the computer with sufficient data for the correction of sensor and amplifier span or gain errors.

Cockpit Display

A pilot has the greatest need for stall margin data during landing and takeoff when attention is focused outside the aircraft. In order to provide real-time data to the pilot without redirecting attention inside the cockpit, a see-through LCD-type display mounted just above the pilot's normal field of view was chosen.

The LCD-type display is operated in a transmissive mode, providing high contrast in direct sunlight while allowing the pilot to see through the display. This method of making a heads-up display provides the usual HUD advantage of presenting data within the pilot's normal field of view. However, one disadvantage of the LCD display is that it is not focused at infinity as is a projection-type HUD. This means that the pilot must refocus when switching from the display to the outside environment and vice versa. For this type of data the focal distance is not a major problem, particularly when the relative display costs are considered.

Yoke-Mounted Buttons

The keypad is located on the yoke to reduce the amount of hand travel by the pilot. The key layout is shown in Fig. 3. In order to reduce the key count in the cockpit, the four keys have different functions depending on the operating mode. The key functions are given in Table 1.

Computer

The computer used for the proof of concept system was an IBM-PCjr. This computer was obviously not designed for use in-flight and can only be used in an experimental capacity. This computer provided a composite video output, RS232 serial communications link, button inputs, and a floppy-disk drive. The composite video gives the necessary flexibility to drive many different display types with only relatively small software modifications. The RS232 is required for communications with the data acquisition unit and the disk drive provided for easy software installation.

The input and output of the computer is a standard composite video and RS232. This allows virtually any computer to be used, even one normally dedicated to other tasks. The re-

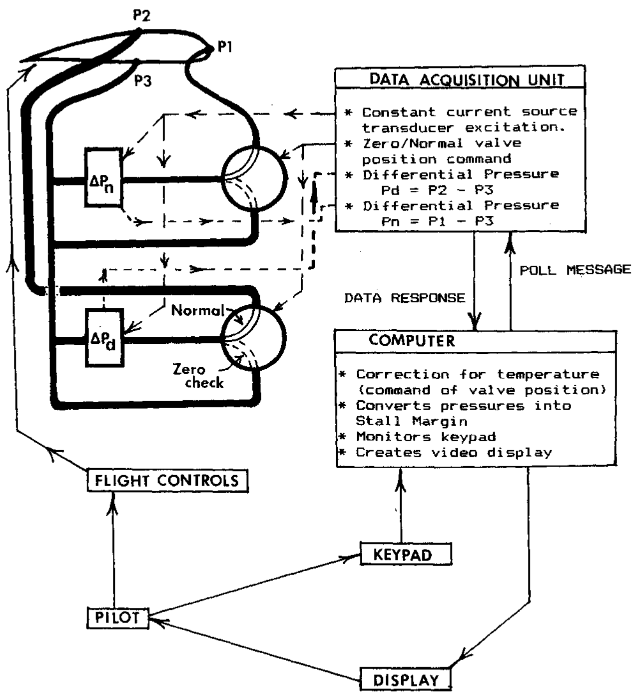

Fig. 3 Yoke keypad.

striction on the computer sharing such tasks would be the total computational speed requirements.

The checklist management function was added to the system to demonstrate the integration potential of the stall margin indicator.

Conclusion

The stall margin indicator described in this paper was developed as a flexible test bed. The hardware has been designed to provide the software with as much control over the system as possible, thus allowing new innovations to be implemented with minimal reconfiguration of the hardware. The system will be used for continued research into effective application of stall margin indication as a useful pilot information source. The display technology and configuration will be studied along with effective integration of stall margin with other cockpit functions.

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[1]Hoadley, A., "Conversion of Wing Surface Pressure Into Normalized Lift Coefficient," SAE 790567, April 1979; also, SAE Transactions, 1979.

[2]Hoadley, A., "Stall Margin Indicator Development," AIAA Paper 86-2694, Oct. 1986.

[3]Hoadley, A., "Normalized Coefficient of Lift Indicator," U.S. Patent No. 4,325,104.

[4]Hoadley, A., "Wing Mounted Stall Condition Detector," U.S. Patent No. 4,350,314.

Evaluation of Two Singular Integrals fromThin Airfoil Theory

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Introduction

IN the analysis of thin airfoils using second-order small-perturbation potential flow theory, a need arises to evaluate integrals of the type

$$\int_{-1}^{1} \frac{\xi^n \ln\sqrt{(1+\xi)/(1-\xi)}}{\sqrt{1-\xi^2}\,(x-\xi)}\,\mathrm{d}\xi \tag{1}$$

and

$$\int_{-1}^{1} \frac{\xi^n \ln\sqrt{(1+\xi)/(1-\xi)}}{(x-\xi)}\,\mathrm{d}\xi \tag{2}$$

for $-1 < x < 1$.

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These integrals were evaluated in closed form by Van Dyke and are available in Appendix B of Ref. 1.

However, in airfoil theory one frequently works in terms of the Glauert variables θ, ϕ, defined as

$$\theta = \cos^{-1}x, \qquad \phi = \cos^{-1}\xi \tag{3}$$

In these variables, integrals (1) and (2) may be expressed, respectively, in terms of sums of integrals of the type

$$H_n(\theta) \equiv \int_0^{\pi} \frac{\cos n\phi \ln \cot\phi/2}{\cos\phi - \cos\theta}\,\mathrm{d}\phi \tag{4}$$

and

$$I_n(\theta) \equiv \int_0^{\pi} \frac{\sin n\phi \ln \cot\phi/2}{\cos\phi - \cos\theta}\,\mathrm{d}\phi \tag{5}$$

where $0 < \theta < \pi$.

In this brief Note, these two integrals are evaluated in closed form.

Evaluation of the Integrals

Integral H_n

For this integral, the following recurrence relation ($n \geq 0$ and integer) can be derived:

$$H_{n+1}(\theta) + H_{n-1}(\theta) = 2\cos\theta H_n(\theta) + 2\int_0^{\pi} \cos n\phi \ln \cot\frac{\phi}{2}\,\mathrm{d}\phi \tag{6}$$

Now,

$$\int_0^{\pi} \cos n\phi \ln \cot\frac{\phi}{2}\,\mathrm{d}\phi = \int_0^{\pi} \frac{\sin n\phi}{n \sin\phi}\,\mathrm{d}\phi = \begin{cases} 0 & \text{if } n \text{ is even} \\ \pi/n & \text{if } n \text{ is odd} \end{cases} \tag{7}$$

Hence, Eq. (6) may be rewritten as

$$H_{n+1}(\theta) + H_{n-1}(\theta) = 2\cos\theta H_n(\theta) + \left[1-(-1)^n\right]\pi/n \tag{8}$$

whose solution is

$$H_n(\theta) = A\sin n\theta + B\cos n\theta + \pi \sum_{k=1}^{n-1} \frac{\left[1-(-1)^k\right]}{k} \frac{\sin(n-k)\theta}{\sin\theta} \tag{9}$$

The two conditions needed to evaluate the constants A and B are obtained by evaluating H_0 and H_1, which are

$$H_0(\theta) = \pi^2/(2\sin\theta) \tag{10}$$

$$H_1(\theta) = \pi^2 \cot\theta/2 \tag{11}$$

from which

$$A = 0, \qquad B = \pi^2/(2\sin\theta)$$

Therefore,

$$H_n(\theta) = \frac{\pi^2}{2}\frac{\cos n\theta}{\sin\theta} + \pi \sum_{k=1}^{n-1} \frac{\left[1-(-1)^k\right]}{k\sin\theta} \sin(n-k)\theta \tag{12}$$