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ANALYSIS OF METHODS USED TO ELIMINATE THE PROPELLER SLIPSTREAM EFFECT IN SINGLE-ENGINE AIRCRAFT

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Abstract

Propeller-driven single-engine aircraft are affected by unsymmetrical flow of air around the fuselage, and especially around the vertical stabilizer [1-3]. This unsymmetrical, propeller-induced slipstream produces sideslip [4,5] that needs to be compensated by the pilot using the rudder [6]. In order to relieve the pilot from this additional task, automatic rudder deflection systems are used that compensate for sideslip by trimming the rudder accordingly. Such compensation algorithms are based on flight parameter measurements.

This paper presents more complex systems used to eliminate the phenomenon in question. In addition, it analyzes the existing solutions, based on patents divided into two groups. The first group deals with active slipstream effect compensation solutions, based on aircraft movement parameters that are derived from aircraft performance characteristics defined in advance. The other group comprises solutions that are based directly on feedback containing actual or estimated sideslip angle values. The most advanced systems rely on a combination of the two methods described above.

Keywords: single-engine aircraft, propeller slipstream, sideslip angle

1. INTRODUCTION

In addition to the gyroscopic effect, the banking momentum and non-axial feed of air onto the propeller, propeller-driven single-engine aircraft are also affected by unsymmetrical flow of air around the fuselage, and especially around the vertical stabilizer. This phenomenon is particularly prominent if single-engine aircraft are fitted with high output powerplants, often producing in excess of 2,000 HP.

The intensity of the phenomenon experienced differs depending on the configuration of the aircraft and on the parameters of a specific flight. It is particularly strong at low velocities, where the full power of the engine is applied. This takes place, for instance, while taking off, landing, following a missed approach procedure or performing aerobatic maneuvers. The phenomenon in question is a nuisance for the pilot, as it requires that compensatory measure be taken, such as deflecting the rudder and, in some cases, the ailerons as well.

Two types of solutions are used in order to counteract the problem. The first group of solution relies on passive compensation of the phenomenon. The required results are achieved by using an unsymmetrical airframe, or by increasing rudder surface. Such measures may only be introduced while designing and building a new airframe. Solutions belonging to the other group are of the active variety and involve the use of a control surface actuation mechanism. The existing rudder trim mechanisms may be taken advantage of here. Active compensation systems may be of the closed type, meaning that the compensation value is based on a predefined dependency between the controlled value (e.g. rudder trim or additional control surface deflection) and different measured parameters that are of significance for the phenomenon in question. The parameters that are measured and used by such systems include the following: airspeed, engine power setting, throttle lever position, flap extension and gear position. Closed variety active compensation systems of may also rely on sideslip angle inputs. The system measures the sideslip angle and if a non-zero value is detected, the rudder trim surface or an additional control surface is deflected in order to achieve the zero sideslip value. The sideslip angle sensor is, most often, a mechanical device and its installation is not always possible. Therefore, it is often the case that the sideslip angle value is estimated based on other parameters measured.

2. REVIEW OF EXISTING SOLUTIONS

The existing solutions have been analyzed based on patents divided into two groups. The first group deals with active propeller slipstream effect compensation solutions, based on previous measured aircraft characteristics. The other group comprises solutions that are based directly on feedback containing actual or estimated sideslip angle values.

2.1. Active systems based on aircraft characteristics

Patent EP0410162B1 (*Einrichtung zur Seitenruder-Trimmung*) [8a]. A system for eliminating sideslip based on a database of parameters (28 in Fig. 1, to the right) determined during a test flight.

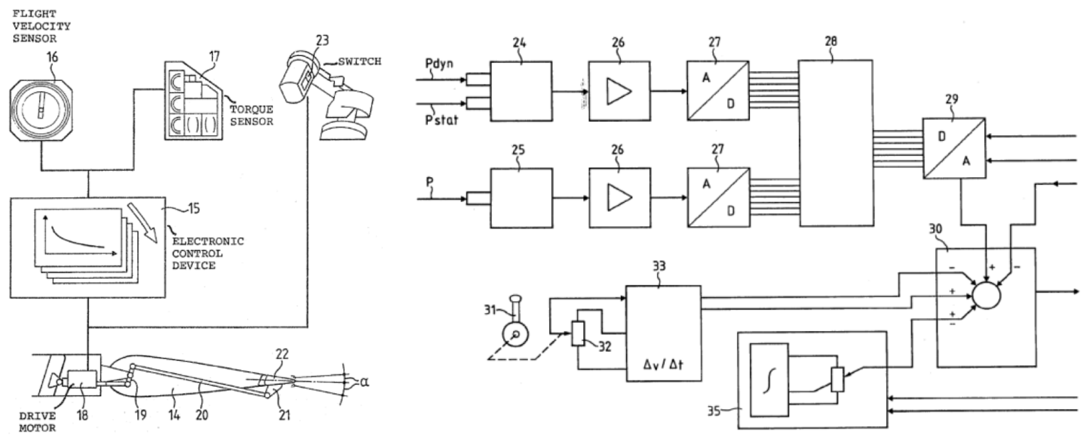

Fig. 1. Propeller slipstream compensation system, based on patent EP0410162B1[8a]

The measured values (Fig. 1, left), such as: airspeed (16), thrust torque of the propeller, i.e. power with taken into account the rotational speed of the engine (17), are relied upon by an electronic system (15) in order to calculate the rudder trim deflection value (22). The calculations are based on the model (15) described with the use of equations derived during a test flight, in which the rudder trim deflection angles (alpha) (22) are assigned to various airframe configurations and flight conditions.

Fig. 2 presents the relation between rudder trim deflection, various airspeeds and three power settings (I, II, III). The system is also equipped with a functionality speeding up sideslip compensation, as shown on the right in Fig. 1. The prediction signal is calculated based on the measurement (32) of throttle lever position (31), by differentiating (33) and low-pass filtering. That is how the system predicts imminent engine acceleration or deceleration, and the resulting change in power. This change is taken into consideration while working out (30) the rudder trim deflection setpoint. The pilot may correct the rudder trim setting manually, using the lever (35).

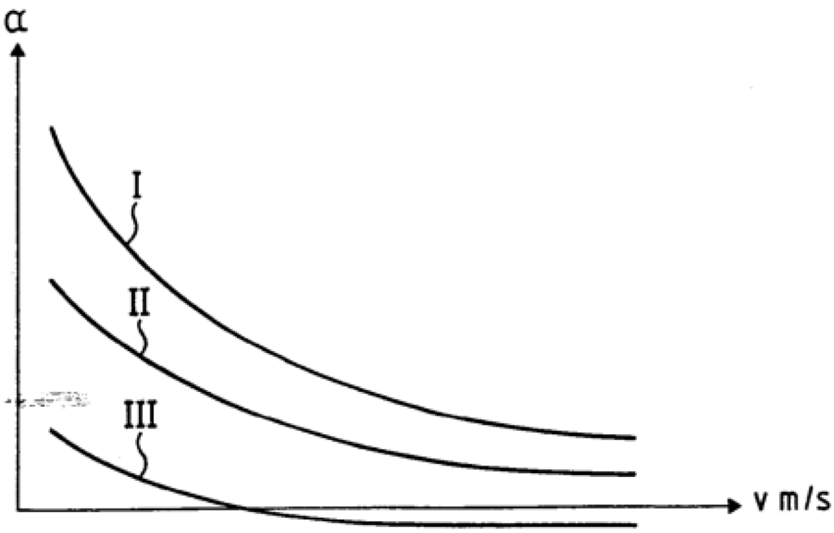

Fig. 2. Typical trim angle control characteristics as a function of airspeed and current engine power setting [8a]

The control system for propeller-driven aircraft shown in **patent US5465211** [8b] aims to enable pilots training to fly turbojet powered aircraft. The propeller slipstream effect is counteracted by trimming the rudder, so, that eliminates sideslip. The system relies on velocity (24) and thrust momentum (22) measurements, and performs calculations (30) based on the concept presented in EP0410162B1 in order to determine the trim angle required. In addition, the value used to eliminate the gyroscopic effect created by the propeller is added (based on banking speed (28) and airspeed (24) measurements), and the altitude correction is taken into consideration as well. The signal worked out by the manual trim correction system (60) is considered too. The final rudder trim deflection is achieved by means of a motor-driven servo (10).

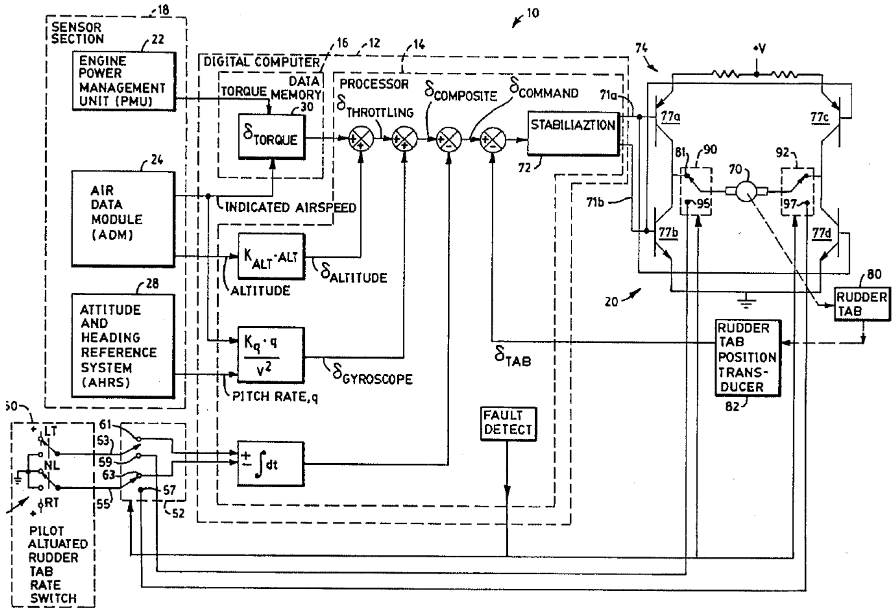

Fig. 3. Control system for propeller-powered aircraft based on patent US5465211 [8b]

2.2. Active systems relying on actual or estimated sideslip feedback

A typical system of this control category is presented in **patent US4992713** (Aircraft autopilot with yaw control by rudder force) [8c].

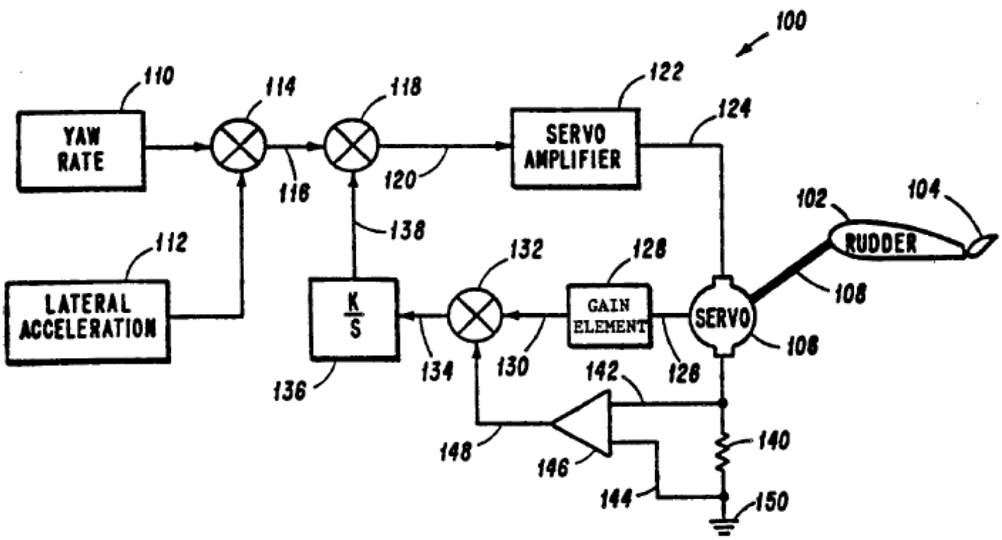

Fig. 4. Trim control system according to patent US4992713 [8c]

The system relies on an autopilot-controlled yaw damper. The classic autopilot system is based on a gyroscope measuring angular speed along the vertical axis of the airplane, and allows to precisely dampen short-term yaw. If long-term yaw is experienced, the autopilot needs to be disconnected and the deflection of the rudder needs to be corrected (for instance by changing the trim). The proposed solution accounts for lateral acceleration changes experienced over extended periods of time. The servo mechanism (118, 122, 108, 140, 146, 130, 136) is used to eliminate the aerodynamic forces affecting the rudder, enabling the pilot to directly change its position. This solution relies on the following feedback values: lateral acceleration and angular speed along the vertical axis.

Patent US4094479 (Sideslip angle command SCAS for aircraft) (Fig. 5) applies to the SCAS (Stability and Command Augmentation System) [8d]. This solution is stabilization and augmentation system. It is used, inter alia, to eliminate sideslip, and thus to compensate for the effect of propeller slipstream. Sideslip angle change estimates (44) (performed pursuant to [7]), sideslip angle measurements performed by relying on the classic method (33), as well as rudder deflection values set by the pilot pressing the pedals (26) are summed up (43), and the rudder deflection setpoint is worked out for the rudder servo (24). Due to the favorable performance of the system, especially at low speeds, it is commonly used in STOL aircraft.

Last two patents rely on sideslip angle b estimations. This issue has been discussed in detail in [7]. Furthermore, a relevant patent has been presented as well. **Patent US6928341** (Computational air data system for angle-of-attack and angle-of-sideslip) [8e] presents the computational method enabling to work out the angle of attack and angle of sideslip based on air data, inertial measurements and other signals derived from the aircraft's control systems. The system relies on the aircraft model and an expanded Kalman filter. The method does not use any traditional angle of attack and angle of sideslip sensors (cost and weight reduction, stealth requirements). It may also serve as another source of measurements in a redundant air data system.

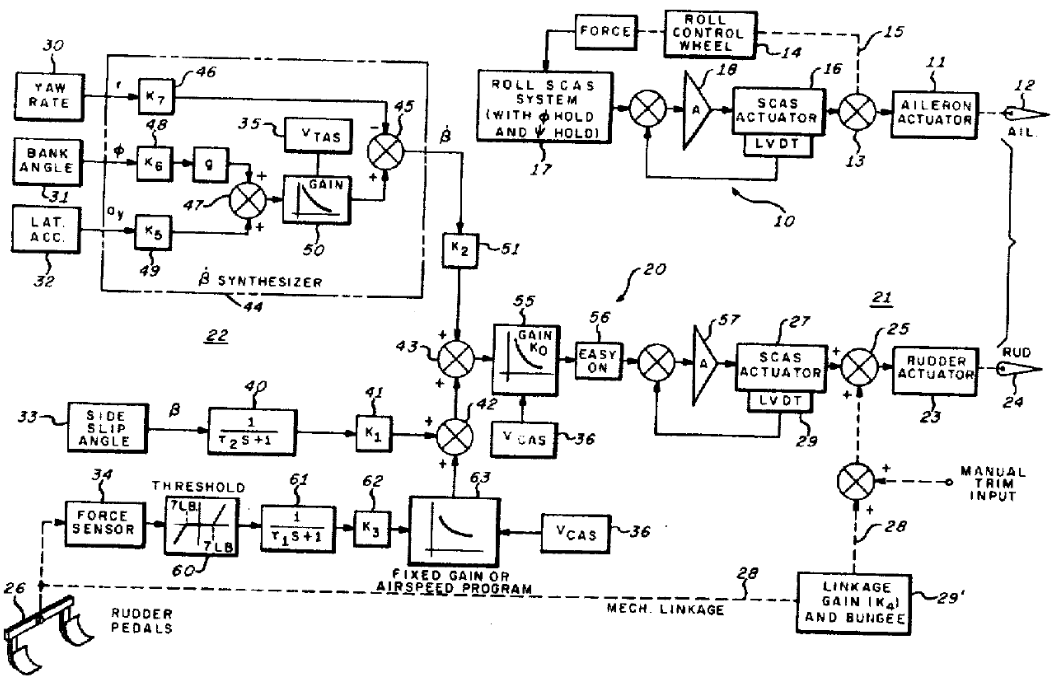

Fig. 5. System of stabilization and control augmentation based on patent US4094479 [8d]

The same model is used as relied upon while designing the flight control system. The input data (attitude angles, angular velocities, linear acceleration, dynamic air pressure, position of control system elements (control surfaces, throttle lever, gear) is filtered with the use of the Kalman filter and the sideslip and angle of attack values are estimated.

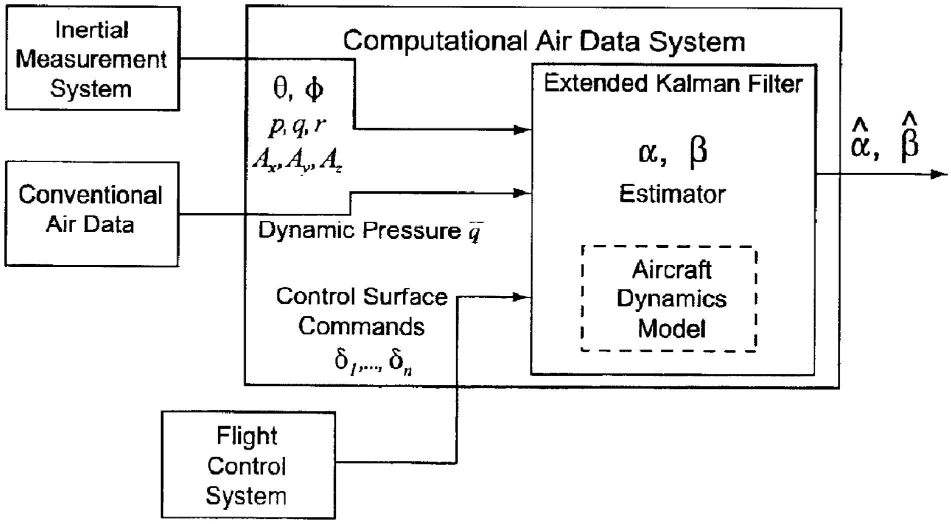

Fig. 6. Angle of attack and sideslip estimation based on patent US6928341 [8e]

3. CONCLUSIONS

Two main methods for compensating the propeller slipstream effect in single-engine aircraft (first the active approach relying on the characteristics of the aircraft, and second with feedback based on the angle of sideslip), are used to achieve various objectives.

Active compensation based on aircraft characteristics, such as tabulated trimmer angles depending on airspeed and current engine power setting, may be used under any flight conditions in order to achieve a zero sideslip value. Such a configuration does not offer the ability to fully compensate the propeller slipstream effect under any flight conditions, but considerably reduces the workload of the pilot. The pilot only corrects the movements by applying rudder inputs. A much greater workload is taken care of by the rudder trim. Such a solution enables the pilot to practice proper control inputs, with the overall required forces being considerably lower. The solution is particularly recommendable for mid-air maneuvering.

An active control system relying on sideslip angle feedback, in turn, is recommended during smooth, coordinated flights and while cruising. The feedback considerably improves the quality of compensation of discussed phenomena. This is very comfortable for the pilot, as such a system eliminates, almost completely, the need to provide any compensating inputs manually. However, during mid-air maneuvers, when sudden changes in the values measured (sideslip angle, lateral acceleration) are experienced, the system's inputs may render the aircraft unstable, which may be a rather dangerously surprise for the pilot.

Table 1. Typical parameters of active rudder trim compensation systems [own compilation].

Input parameters	**Active propeller slipstream compensation systems**			
	Based on aircraft characteristics		**Based on measured or estimate sideslip angle**	
		Remarks		Remarks
β sideslip angle			X	
p_{sl} p_{sp} static pressure on port and starboard side of the fuselage			X	for sideslip angle estimation
Φ roll angle			X	for sideslip angle estimation
r angular speed along the z axis			X	
a_y lateral acceleration			X	
δ_g throttle lever position	X	to determine, without delay, the current power setting		
V_{IAS}	X		X	for sideslip angle estimation
P current power setting	X			

Table 1 presents the typical parameters relied upon to control the position of the rudder trim, depending on whether the system is based on predetermined characteristics of the aircraft, or based on actual measurements or estimations of the angle of sideslip. As one can see, in the first case tabulated trimmer deflection angles are used most frequently, which are correlated with airspeed and current engine power settings. In some cases, in order to eliminate the delay caused by engine acceleration, an auxiliary throttle lever movement signal is used to estimate the current power output. In the case of the other system, it is the sideslip angle that serves as the primary parameter. It may be measured directly, but it is very often the case that its value is estimated based on other, indirect measurements. One of the methods of determining sideslip relies on measuring the differences in static pressure on both sides of the fuselage. Another method described in the patents [8d] is based on lateral acceleration, airspeed and, possibly, also the bank angle and angular speed along the z axis. The angle of sideslip may be determined by analyzing equations describing the movement of the aircraft. When the model of the aircraft is known, such a solution ensures good accuracy of the measurements (up to one decimal point of a degree [8e]).

The solutions presented above make the work of a pilot more comfortable, as they reduce the pressure that needs to be applied to the rudder, and eliminate the need to adjust trimmer settings frequently. A properly tuned compensation system enables also the pilot to practice and establish proper control behaviors. Compensating systems may also be used on aircraft flown by pilots training to switch to jet-powered machines, where the propeller slipstream effect is not present.

The solutions used to compensate for the propeller slipstream effect, designed for single-engine turboprops, may be also used in jet aircraft, also of the two-engine variety. The F-15 may serve as a good example here [9]. Operation of such a system is presented in Fig. 7.

The system aims to reduce and eliminate uncontrolled and persistent mid-turn sideslip. Appropriate inputs are taken care of by the plane's Control Augmentation System. The position of pedals is measured by a sensor (Pedal Position LVDT) and is compared with the angle of sideslip calculated based on the yaw (Yaw Rate Gyro) and lateral acceleration (Lateral Accelerometer) measurements. Once worked out, the signal is fed to the rudder servo (Servo Amp). If not compensated fully, sideslip may of course be corrected manually, using a signal generated by the relevant sensor (Trim Position LVDT Pedals). The PI (proportional-integral) control system used requires that manual corrections be introduced at a slow pace.

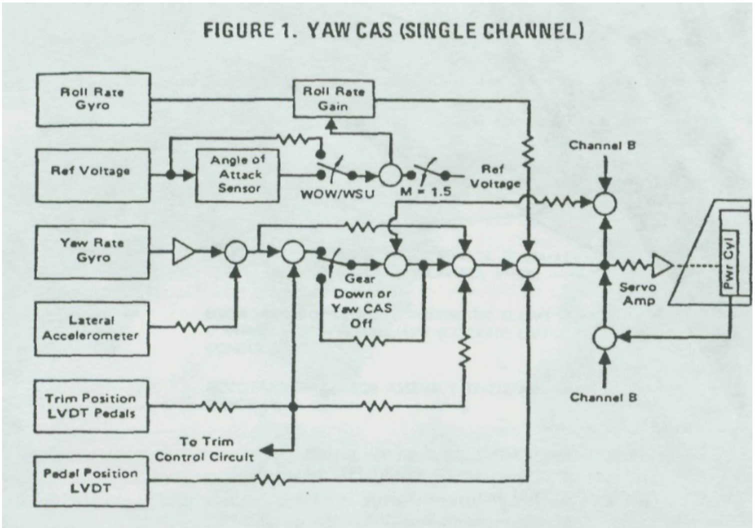

Fig. 7 Control augmentation system used on the F-15 [9]

Operation of the control system is modified by various signals, such as ones generated by the WOW (Weight On Wheels) or Gear Down circuits.

The solutions presented above play a significant role in reducing the pilot's workload, and, therefore, in enhancing flight safety.

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PRZEGLĄD METOD ELIMINACJI WPŁYWU STRUGI ZAŚMIGŁOWEJ W SAMOLOTACH JEDNOSILNIKOWYCH

Streszczenie

Napęd śmigłowy samolotu jednosilnikowego powoduje niesymetrię opływu samolotu a szczególnie statecznika pionowego. W następstwie niesymetrycznego opływu samolotu przez strumień zaśmigłowy występuje kąt ślizgu, który kompensowany jest przez pilota za pomocą steru kierunku. Aby odciążyć pilota od tej dodatkowej czynności wprowadza się automatyczną kompensację wychylenia steru kierunku przez odpowiednie sterowanie trymerem steru kierunku. Sterowanie to uzależnione jest od mierzonych parametrów lotu.

W pracy przedstawiono bardziej rozbudowane układy usuwania następstw tego zjawiska. Dokonano przeglądu rozwiązań w oparciu o istniejące patenty w dwóch grupach. Pierwsza grupa zawiera rozwiązania aktywnego kompensowania zjawiska strugi zaśmigłowej ze sprzężeniem od parametrów ruchu samolotu w oparciu o zdjęte wcześniej charakterystyki samolotu, druga grupa to rozwiązania ze sprzężeniem zwrotnym bezpośrednio od kąta ślizgu lub estymowanego kąta ślizgu. Bardziej rozbudowane układy zawierają połączenie obu sposobów.

Słowa kluczowe: samolot jednosilnikowy, strumień zaśmigłowy, kąt ślizgu.