DESIGN FOR SPIN

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Keywords: *aerodynamic design, rotary balance testing, flight mechanics, spinning*

Abstract

The Pilatus PC-21 advanced turboprop trainer was designed from the start to obtain desirable spin characteristics. This was achieved by conducting rotary and oscillatory balance wind tunnel tests very early in the program, by utilizing the wind tunnel data for real time flight simulation, and by comparing simulation results of a "proof-of-concept" configuration with flight tests of a prototype based on an existing design. A safe, efficient and highly successful flight test program dedicated to spin characteristics investigation confirmed the predictions based on wind tunnel testing and proved the validity of this "design for spin" approach.

1. Introduction

The PC-21 advanced turboprop trainer is the latest aircraft design developed and certified by Pilatus Aircraft Ltd. of Switzerland, a long established name in the field of military training with its highly successful PC-7, PC-9, and PC-7 MkII designs.

The operational requirements of the PC-21, designed to satisfy the basic and advanced flying training requirements, include the capability of safely demonstrating spin maneuvers. In a conventional aircraft like the PC-21, spin characteristics are mainly determined by the tail arrangement and (to a lesser extent) by the wing planform. It is obviously desirable to define the general wing and tail arrangement before refining the aerodynamic design with expensive large scale wind tunnel testing. Following this logic, the PC-21 configuration was "designed for spin" on the basis of Pilatus' past experience on similar aircraft (PC-7 and PC-9) and with the help of extensive tests in a special wind tunnel facility with a 1:8.5 scale model installed on a rotating balance. The goal was to achieve a stable spin mode, with a moderate rotation rate and a classical nose-down attitude, which could be easily recovered with conventional piloting techniques.

Figure 1. The PC-21 advanced turboprop trainer (prototype P01)

In order to gain more confidence in the use of rotating balance data (a field new to Pilatus, although not to the author), before the PC-21 development campaign a series of preliminary wind tunnel tests on a standard PC-9 configuration was conducted. The effect of a reduced wing span, spoiler roll controls and a swept vertical tail were checked by modifying the PC-9 wind tunnel model to represent the PC-21 "proof of concept" (PoC) prototype aircraft, which was built to collect experience on the new configuration before committing to the project launch.

2. Wind tunnel tests

2.1. General considerations

For previous Pilatus aircraft designs, such as the PC_7 [1] and the PC-12, model tests were performed in a so-called “spin tunnel” at the *Institut de Mécanique des Fluides* in Lille (F). This kind of facility, quite popular in the past and still in limited use in some research establishments, consists in a vertical wind tunnel where the airflow is directed upwards. An operator launches a free-flying model of the airplane, with pre-set controls, in the airflow and (with skill and some luck) the model enters a stable spin; by adjusting the wind tunnel speed, it is possible to keep the model spinning for some turns and record the spin characteristics on film or video. If the model scale is sufficiently large (as it was the case for the 1:16 PC-12 model tested in Lille) a radio control can be fitted to operate the elevator, rudder and ailerons, in order to investigate the spin recovery techniques. This kind of testing can give some useful indications, but has several shortcomings:

- the model must be in “dynamic similarity” to the aircraft for a given centre of gravity position, mass and inertia moments. This means that the results obtained with the model are strictly valid only for that particular mass, centre of gravity and inertia distribution that were assumed at the time of the tests. During the development of the aircraft, these parameters can change quite significantly, thus invalidating the spin tunnel test results.

- the results are mainly qualitative and have a synthetic character: it is not possible to determine the relative influence of the aerodynamic forces and moments and of the inertial and gyroscopic moments on the stabilized spin or recovery characteristics. As a consequence, no indication is available on how to correct or to modify these characteristics.

- Only a stable spin or a recovery maneuver can be simulated; no indication on spin entry characteristics can be obtained from these tests.

Since 1933, pioneer work was done at NPL in Britain and at NACA with a wind tunnel model mounted on a rotating balance, where the aerodynamic forces and moments could be measured as a function of model angle of attack, sideslip and rotation rate. A few years later, analytical techniques for calculating the steady state equilibrium spin conditions from rotating balance data were developed. In the 1950’s Aermacchi built its own rotating balance facility, which was used to study the spin characteristics of the well known MB-326 and MB-339 jet trainers [2] and of several other aircraft designs (Tornado, AM-X, EFA).

Nowadays, the computing power readily available to the engineer makes it possible to perform complex six-degrees of freedom simulation of spin entry, equilibrium and recovery from the aerodynamic force and moment coefficients measured with a rotating balance, by introducing the appropriate inertia and gyroscopic moments. On the basis of the author’s experience at Aermacchi, it was decided to follow this approach for the PC-21 design, with the support of Bihrle Applied Research, Inc. (BAR), a consulting and wind tunnel testing firm established by Mr. William Bihrle in 1973. As part of a NASA contract, BAR developed the test techniques and the data acquisition and analytical tools needed to make the rotary balance apparatus in the NASA Langley 20 foot vertical wind tunnel into a viable tool for obtaining good quality, repeatable wind axis test data.

The availability of these data allowed the demonstration that the rotational data set was both necessary and sufficient to predict a configuration's steady state spin modes. The development of a spin prediction methodology by Bihrle [3] enabled the on-line prediction of aircraft spin modes as the wind tunnel data was being acquired. This capability, along with the ability to identify the source of aerodynamic characteristics using component rotary balance testing, made it possible to analyze and modify a configuration's post stall behavior early in the development cycle. This concept was applied for the first time in the design of a trainer aircraft by Pilatus, during the PC-21 initial aerodynamic design.

Further studies demonstrated that the rotational data, when used in a large-angle six degree-of-freedom simulation that properly mechanized static, wind axis, and body axis dynamic data sources, could accurately simulate all possible aircraft motions, including out-of-control motions in the post-stall region. Consequently, it became possible to simulate and analyze an aircraft behavior in post stall flight, as well as to evaluate control inputs and/or control system architectures' effectiveness in suppressing or recovering from out of control motions. Pilatus had previously acquired from BAR an adequate software tool for this task: the "D-Six" real time, six-degree of freedom flight simulation code, which was used to power the Pilatus engineering flight simulator [4].

In the late 1980's, BAR designed and built a new research facility: the Large Amplitude, Multi-Purpose (LAMP) wind tunnel in Neuburg an der Donau (D). It consists of an open return vertical wind tunnel with a 10-foot diameter test section, whose dynamic model support rig permits the acquisition of wind axis dynamic data (rotary balance), body axis dynamic data (forced oscillations), and combinations of the two types of motion, as well as static data. The Pilatus tests were performed at LAMP using all three types of aerodynamic force and moment coefficient measurements.

2.2. Baseline tests

The first two phases of testing at BAR were successfully completed in November 1997 and March 1998. They were dedicated to the investigation of the standard PC-9M configuration and of the PoC aircraft, a PC-7MkII modified to simulate the PC-21 main flight mechanic characteristics by reducing the wing span and fitting roll control spoilers, a swept vertical tail and prototype versions of the future PC-21 engine and propeller

Figure 2. The "Proof-of-Concept" PC-21 prototype.

The model was constructed by BAR in a 1:8.5 scale and could be configured either as a standard PC-9M, as a PC-9M with shorter wing or as the PoC configuration by replacing the outer wing panels and the vertical tail.

On the basis of the LAMP rotary balance test data measured with the model configured to represent a PC-9M, the stabilized spin modes were calculated at different centre of gravity positions and with ailerons neutral, "pro-spin" or "against spin".

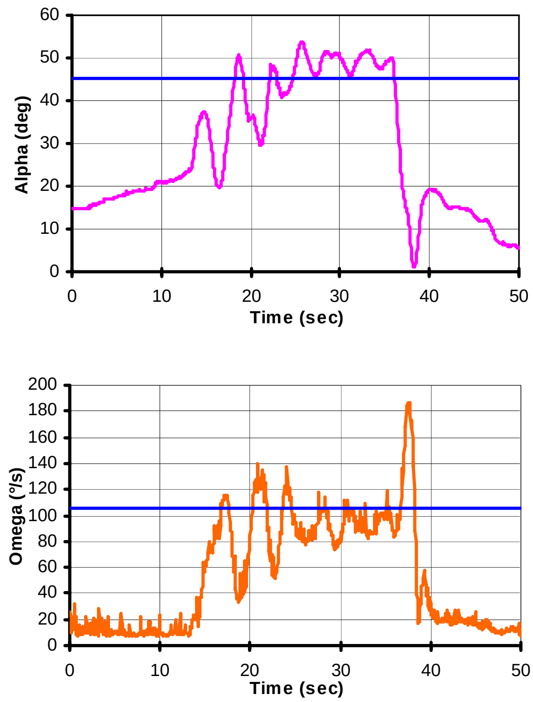

Figure 3. PC-9 flight test 09-001-F879, erect left spin, ailerons neutral: angle of attack (above) and rotational speed (below). The predicted values are indicated by the solid blue lines.

The predictions agreed perfectly with the flight test results, indicating that the standard PC-9 has a moderately oscillatory spin with an average angle of attack of 45° and a rate of 3 to 3.5 seconds per turn. If the ailerons are fully deflected “against spin” the angle of attack increases up to 52°, and the spin rate becomes faster. If they are deflected “with spin”, the angle of attack is reduced to 40°, and the spin rate slows down slightly. This, again, is confirmed by PC-9 flight test results.

The effect of stabilizer “strakes” which were added to the PC-9 to improve the spin characteristics was also investigated; the results indicated that they actually produce a stabilizing nose-down pitching moment effect in the critical spin angle of attack range. This results in a steeper and less oscillatory spin, in agreement with Pilatus’ experience during PC-9 development.

The results of the wind tunnel tests on the PoC configuration indicated that the effect of the clipped wing, together with the increased aircraft inertia in pitch and yaw, was to move the equilibrium spin angle of attack to about 50°, with a practically unchanged spin rate of 2.5 and 3 seconds per turn.

Figure 4. “Proof-of-Concept” (PoC) configuration ready to be tested in the LAMP facility

It was impossible to obtain a flat spin solution as neither the vertical tail nor the fuselage were developing a propelling yawing moment at high angle of attack; the data indicated a remarkable directional stability up to 40° alpha and a stable pitching moment behavior (this means that the rotation about the spin axis creates a nose-down pitching moment). Spin solutions were only possible with the elevator and rudder fully deflected; as soon as one of the controls is centralized, the spin could not be sustained. As expected, spoiler deflection had no effect at all on spinning, as spoilers are virtually ineffective beyond 20° alpha on this configuration. On the basis of these results, Pilatus confidently entered the spin test program of the PoC prototype, which once again confirmed the predictions form the LAMP tests.

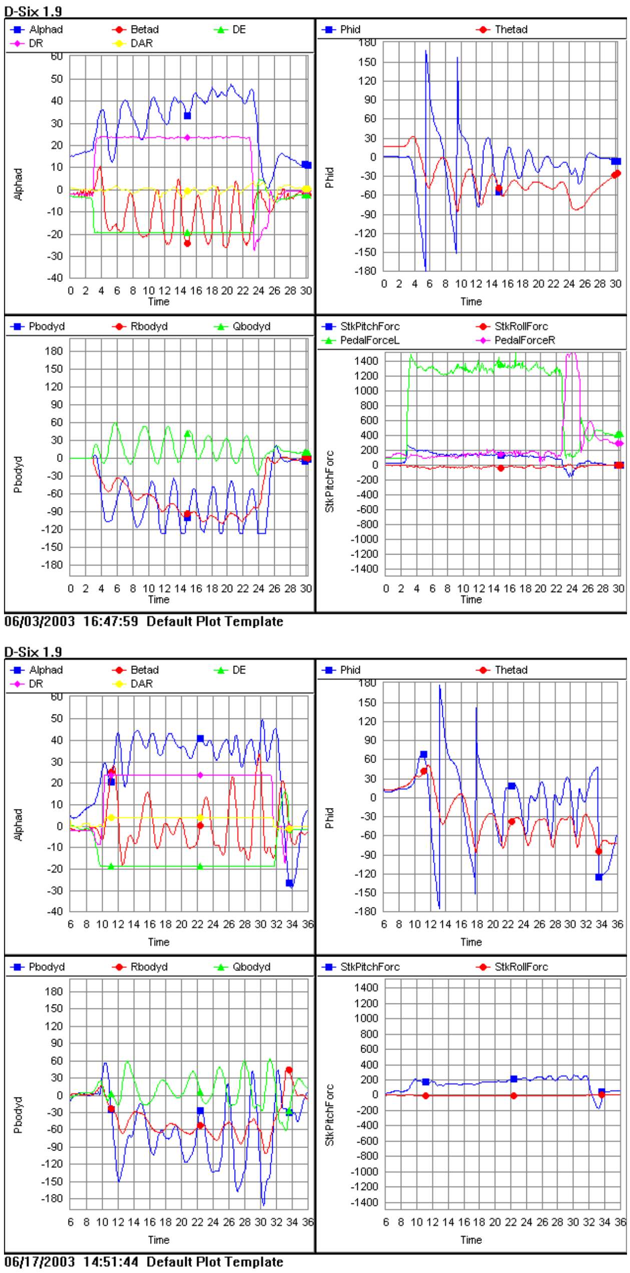

Figure 5. PoC Flight 21-011-F365, test point T10b. Erect left spin: comparison between flight test data (above)and simulation (below)

2.3. PC-21 configuration development

The first wind tunnel tests on the original PC-21 configuration at LAMP were conducted in February 1999.

The initial results showed the airplane to be completely spin-free: the damping in yaw was very good up to very high angle of attack, and the pitching moment slope remained stable up to 90° angle of attack. Moreover, the effect of rotation rate was to provide more nose-down pitching moment at all angles of attack, thus preventing the aircraft to stabilize in a spin. This would be obviously an excellent feature for a general aviation aircraft as well as for an operational military aircraft; however, since the PC-21 mission can include basic flight training, it was desirable to obtain a safe and stable spin mode with controls deflected (as in the PC-9). The following account describes how the configuration was “redesigned” for spinning in the wind tunnel.

The first attempt was to increase the rudder deflection from 24° to 30° and check the spin modes again. Still, no spin solution was found. By comparing the PC-21 control power data with the PC-9 and with the PoC data measured in the same facility last year, it was confirmed that the PC-21 had at least as much rudder power as the other two models, but a much more nose-down pitching moment even with the elevator fully deflected upwards It was therefore decided to remove the horizontal tail strakes, that has been shown to be very effective in the angle of attack range between 40° and 70° during the PoC model tests. The result was encouraging but not sufficient; the configuration was now closer to have a spin solution. At this point, two further changes were tested: the removal of the ventral fin and a backward shift of the vertical tail. The latter modification was tested first, initially with a 12 mm and then with a 25 mm backward shift (in model scale) of the vertical tail with respect to the horizontal tail. Once again, the effect was to come even closer to a spin solution but not sufficient to obtain it. Meanwhile, the design office at Pilatus was contacted, asking for an opinion about these modifications. The answer was that it was virtually impossible to simply shift the vertical tail backwards with the present structural concept, and that even the ventral fin could not be completely removed since it was needed to fair the horizontal tail strut attachment point to the rearmost fuselage frame. It was therefore decided to increase the rudder chord size from 30% to 35% so that the fin spar could be placed more forward and the whole vertical tail could be shifted backwards; in fact, the structural limitation is that the main fin spar of PC-21, which carries the rudder hinges, is attached to the rearmost fuselage frame and it carries also the attachment for the nose of the stabilizer. The fin was also swept back as much as possible to increase the aerodynamic interference between horizontal and vertical tail.

While the Pilatus design office was working at the modification, the ventral fin was removed and the vertical tail was shifted back to the baseline position. This time it was a success: a spin mode was found, with an angle of attack of 53° and a rotation rate of 2.3 seconds per turn, both in the heavy / aft c.g. configuration and in the light / forward c.g. configuration.

Later, a sketch of the new vertical tail was faxed from Pilatus. The ventral fin appeared to have been cut down by 60 mm only, and it was likely that, even with the new swept vertical, no spin mode could be obtained with this configuration. However, we proceeded with the modification of the model. When the new configuration with the slightly reduced ventral fin was tested, no spin solution could be reached, as expected. An attempt at increasing the elevator deflection from 20° to 30° did not bring any noticeable effect. The ventral fin was then replaced with a small fairing, just big enough to cover the strut attachment, and tested the model in this configuration.

This produced the desired result: the spin mode was there again, with elevator at –20°, rudder at 30° and roll controls fully against the spin. The predicted angle of attack was 53° and a spin turn required 2.4 seconds. With ailerons neutral, a spin solution was still found, although a little weaker. Angle of attack 50° and 2.3 seconds per turn at high weight and aft c.g., 45°

and 2.6 seconds per turn at light weight and forward c.g.

To summarize, the final configuration used for the remainder of the testing had the following modifications:

- The strakes in front of the horizontal tail were removed
- The vertical tail was modified to a more swept configuration with a slightly larger rudder
- The ventral fin was removed and replaced with a ventral "bump"

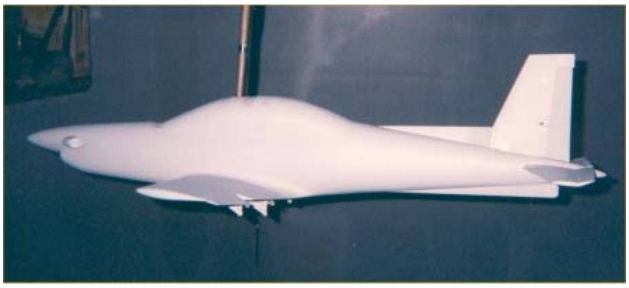

Figure 6. Figure 1. Original PC-21 model tested at LAMP in February 1999, final configuration

In April, a large scale (1:3.5) model of this configuration was tested in the 8m by 5m wind tunnel facility in Emmen. On the basis of the test results, the wing dihedral was reduced and the wingtip profile was slightly modified with a "nose droop" to improve stall characteristics. Moreover, the fuselage was redesigned to improve the visibility from the rear and front cockpits. This new baseline configuration was tested in LAMP in August 1999 to evaluate the effect of the modifications described above.

The predicted spin characteristics of the new configuration were very similar to those of the previously tested configuration. The airplane was close to an equilibrium spin condition with neutral controls, at an angle of attack comprised between about 45° and 50°. With pro-spin rudder a spin mode was predicted at around 50° angle of attack and approximately two seconds per turn. Ailerons, either with or against, did not change the spin characteristics significantly. Trailing edge up elevator had a slight influence on the turn rate due to the influence on pitching moment.

Figure 7. Figure 2. New PC-21 configuration, tested at LAMP in August 1999

The PC-21 did not have any flat spin modes due to very good yaw damping (due to the vertical tail and fuselage configuration) and large nose-down pitching moments at high angles of attack.

3. Simulation

During the last two wind tunnel test entries at LAMP, a comprehensive program was conducted with the scope of collecting rotating and oscillatory balance data for a PC-21 high angle of attack simulation data base and model to be implemented in the engineering flight simulator. It was therefore possible to investigate the effect of variations in mass, center of gravity and inertia, as well as to conduct parametric studies on the effect of an increase in yaw, pitch or roll damping, for example. During the PC-21 spin test campaign, the simulator was be used to compare the predicted and measured spin time histories and the aerodynamic database will be updated if and where necessary. This increased the level of safety and confidence, since it was possible to simulate the effect of a mass or centre of gravity change before performing the test, on the basis of the most recent flight test results.

4. Flight testing

4.1. Safety aspects

During the PC-12 spin resistance flight test program, a spin recovery chute activated by a pyrotechnic device was installed on the prototype. The precaution was justified by the potential danger to the pilot (only a rudimentary egress system was installed) and by the worries on exceeding limit load factors and airspeeds during recovery on such a large and heavy airplane.

The spin chute system, developed and manufactured by Syndex Recovery Systems (ref. 6) had a mass of approximately 60 kg including the necessary reinforcements of the aft fuselage. This additional mass concentrated on the tail increased the pitch and yaw inertia moments of the prototype by at least 5%.

If such a system would have been installed on the PC-21, as originally requested by the Swiss certification authorities, a similar weight increase could be expected, but the effect on the moments of inertia would have been far more dramatic, making it practically impossible to centre the aircraft at the forward c.g. position, as shown in the following table:

Config.	Mass (kg)	cg (%mac)	Spin chute	I_{XX} (kg*m^2)	I_{YY} (kg*m^2)	I_{ZZ} (kg*m^2)	I_{XZ} (kg*m^2)
1	2633	25.5	no	3533	12467	13677	1291
1a	2633	25.5	yes	3732	13186	15169	1074
2	3100	28	no	5092	12682	15206	680
2a	3100	28	yes	5363	12732	17831	677

(note: for this example, the increase in mass due to the spin chute was compensated by removing ballast or non-essential equipment).

It is well known that spin characteristics are influenced by inertias as much as by aerodynamic factors, and an increase in pitch and yaw moment of inertia typically results in a flatter spin attitude. The installation of a spin chute, intended to increase safety, would actually have brought the risk of making the PC-21 spin characteristics more critical. In a discussion with the certification authorities, the author objected have such a system installed on the aircraft precisely for its potential negative impact on flight safety.

Moreover, the 10% to 15% increase in pitch and yaw inertias, together with the change in yaw damping due to the spin chute container placed under the tail, would have undermined the applicability of the flight test results to the standard aircraft.

It was argued that the safety of the PC-21 spin test program was more efficiently guaranteed by the following considerations and measures:

- For a conventional configuration, the spin characteristics are dominated by the tail arrangement, as shown by the wind tunnel tests and by Pilatus' past experience on several similar designs (PC-7, PC-9, PC-7MkII, and PoC). In this respect, the PC-21 had by design a better yaw damping and good rudder control authority at high angle of attack thanks to its tall vertical fin.
- the reliability of the prediction of spin characteristics based on rotating balance wind tunnel data was demonstrated for two different configurations (PC-9M and PoC). Wind tunnel tests on PC-21 did not evidence any critical condition for spinning;
- the engineering flight simulator could be used to reduce risk by exploring the effect of configuration changes before the actual test is performed;
- a state of the art crew escape system was fitted to the aircraft.

After a careful examination of the wind tunnel test data and of the simulation results, the Swiss authorities finally authorized Pilatus to start the spin test program without installing a recovery system on the prototype.

4.2. Flight test conduction

The spin test program was conducted and coordinated by a qualified flight test engineer who monitored the tests via telemetry, coordinated activities in the ground station and communicated with the pilot via radio. The flight test conductor was supported by a team of engineering specialists who were continuously monitoring the testing via telemetry and via radio. On the basis of the simulation results, a "build-up" approach was followed for the test program, starting with the simpler spin maneuvers (e.g. wings level entry, one-turn, low power, no roll control inputs, standard recovery procedure) and less critical aircraft configurations, to gradually progress to the more complex maneuvers (e.g. six turns, roll control input, high power, abnormal or delayed recovery procedure) and more critical aircraft configurations. With the help of a portable computer and a specially developed data analysis program, it was possible to produce plots of all relevant aircraft parameters and easily compare the data with the simulation predictions, less than two minutes after the completion of a critical test point. Based on the result of this comparison, the authorization to perform the next test point was given to the test conductor, that relayed it to the pilot, or an interruption of the test sequence was decided in order to better analyze the data and discuss it with the pilot. This procedure allowed us to remain fully in control all the time and identify possible problems early enough to avoid potentially dangerous situation, and at the same time to progress quickly through the program.

4.3. Test summary

More than 700 spins were performed during the development and the certification phase to evaluate the following effects:

- aircraft weight and c.g. position;
- direction of the spin;
- engine power;
- airbrake deflection;
- roll control input;
- abnormal control usage during recovery;
- lateral fuel imbalance;
- type of entry (from wings level or from turning flight);
- alternative recovery techniques (centralizing or simply releasing the controls to start recovery).

4.4. PC-21 spin characteristics

In general, the behavior and handling in spin maneuvers was judged positively by the test pilots during the certification flight test program. The aircraft always remained controllable, allowing recovery without requiring exceptional piloting skill or excessive control force applications.

At the spin entry, the initial tendency of the PC-21 is to roll in the direction of rudder application (rolling entry) and the angle of attack progressively builds up; as the spin develops, the yaw rate increases and, in most cases, the aircraft tends to stabilize in a moderately steep spin mode, depending on the direction of spin and the c.g. position. The angles of attack in a developed spin vary from 40° to 65°, with a yaw rate of 70° to 110°/s. The typical spin period is 2.5 to 3 seconds per turn.

The classical recovery technique of simultaneously applying full rudder against the spin direction and pushing the stick forward was found to be the most effective. "Wrongly" executed recoveries, such as pushing the elevator control forward before the rudder or slowly releasing the elevator, did not produce uncontrollable spin modes.

The non-standard recovery procedures of centralizing the controls and releasing all controls were also briefly investigated for intentional six turns spins. Recovery was obtained in all tested configurations, although with some delay (up to one additional turn).

The spin characteristics were found to be particularly dependant on spin direction, c.g. position and roll control input, as summarized below:

- direction of spin: left spins tend to be more stable and "flatter" (i.e., characterized by a higher angle of attack and a less pronounced nose-down attitude) than right spins;
- c.g. position: spins at high weight, max. aft c.g. tend to stabilize faster, reaching a "flatter" attitude, and require more additional rotations to recover;
- roll control input: by applying a roll control input "with" the spin, in general a "steeper" spin (i.e., characterized by a lower angle of attack and a more nose-down attitude) accompanied by roll and pitch oscillations results.

It was found that these effects are cumulative: spins with roll control "against", aft c.g. position and high weight are very stable, with almost no residual oscillation (one of these spins was once dubbed a "sightseeing tour" by one of our test pilots) and relatively flat. Angles of attack of up to 65° could be reached, accompanied by high yaw rates; the recovery was initially quite slow and sometimes required more than two turns.

On the other hand, right spins with roll controls "with", forward c.g. position and low weight are less stable, with clear yaw and pitch oscillations (although never such as to disorient the pilot or cause severe discomfort), and quite steep. The angles of attack vary between 35° and 45° degrees, and recovery is almost instantaneous (less than one-half turn). For one turn spins in this configuration, in some case no proper spin could be obtained, and the aircraft merely performed a gyration at an angle of attack just above the stall, which stopped immediately when recovery controls were applied.

In general, these observations agreed well with the predictions based on wind tunnel data and simulation, but the effect of roll controls "against" the spin was more severe than anticipated, and the equilibrium angle of attack and yaw rates measured during the tests were higher than predicted. There was never a problem to recover the aircraft from the spin, but the number of additional turns slightly exceeded the certification requirements.

Thanks to the preliminary design work carried out in the LAMP wind tunnel, simple aerodynamic "fixes" were already available: the horizontal tail strakes (Figure 8), which were known to reduce the stabilized angle of attack in the spin, hence slowing down the rotation, and the ventral fin (Figure 9), which had the effect of increasing the yaw damping. The application of these "fixes" was immediately successful, reducing the number of additional rotations needed for recovery by one turn in the most critical configuration.

Figure 8. Horizontal tail strakes

Figure 9. Ventral fin

An intentional spin maneuver in a typical training configuration (mid c.g. position, mid to high weight, no roll control input) is typically quite stable and moderately steep (approximately 40° to 45° nose-down pitch attitude), with light yaw and pitch oscillations, and period of 2.5 seconds per turn. The recovery with the standard procedure (apply rudder against the spin direction and simultaneously push the stick forward), normally takes about one additional turn.

At high altitude, the reduction in relative aerodynamic damping does slightly delay the recovery, but the number of additional turns specified by the regulations for the various cases in not exceeded. However, the altitude loss is generally larger.

The effect of fuel imbalance on spin characteristics was found to be negligible, except for a slight delay in recovery for some configurations. Airbrake deflection, flap and gear position did not have a significant effect on spin characteristics, except for the speed increase during recovery.

5. Conclusions

The design goal of achieving safe and predictable spin characteristic, adequate for demonstrating spinning to flight students, has been fully achieved on the PC-21. The spin characteristic requirements have been considered from the very beginning of the project, and tailored with rotary and oscillatory balance wind tunnel tests conducted on a small, easily modifiable model before the aircraft configuration was frozen.

The wind tunnel data was utilized for real time flight simulation, and the simulation results of a "proof-of-concept" configuration were compared with flight tests of a corresponding prototype to gain confidence on the validity of the approach.

At the end of the development phase, the safe, efficient and highly successful flight test program dedicated to investigate the PC-21 spin characteristics generally confirmed the predictions based on wind tunnel testing. An undesirable characteristic found during the flight tests could be quickly corrected by applying aerodynamic fixes that had already been tested and proven in the wind tunnel.

It can be concluded that the “design for spin” approach has been indeed the right choice for the PC-21.

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