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MSc. in mechanical engineering

Development of simulation and measurement environment for investigating paragliders

booklet of PhD dissertation

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1 Introduction, hypothesis

This dissertation aims to investigate the paragliders' turning mechanism based on dedicated measurements and simulations. Paragliders have a quite unique flying characteristic, which comes from their unique structure, as presented by the Figure 1.

Despite of the fact that the evolution of the paragliders was started from the parachutes, nowadays it is necessary to make a difference between them. The main function of a parachute is to decrease the speed of a free falling object (e.g. human, load) to a survivable value, while the main function of the paraglider is to glide efficiently. Hence, they are designed for different purpose, on a different way and made from different materials.

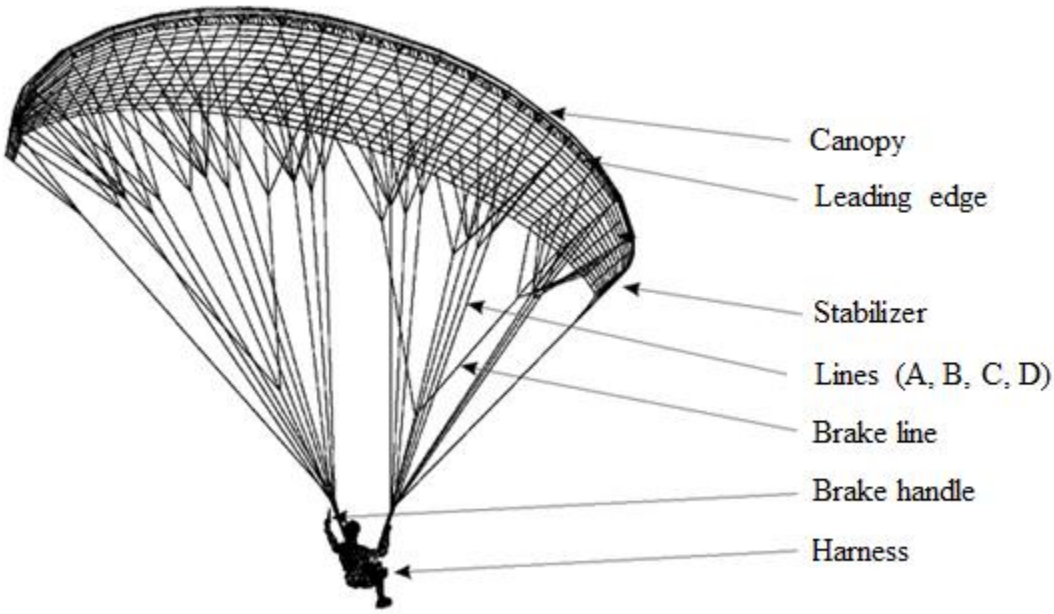

Figure 1: The general structure of a paraglider

Thanks for the more than 25 years of development, paragliders today have rather good gliding performance, they are lightweight and rather small when packed. They are made from high-tech materials (e.g. composites, carbon or aramid fibres).

Development models used till now are based on experimental (in-flight) procedures, mainly, which tend to reach their limits, therefore the improvement of paragliders is slowing down. For further improvement in flight performances it is necessary to develop new development models based on advanced scientific methods.

The goal of this dissertation is to develop a simulation and measurement environment, which is suitable to investigate some flying characteristics (mainly the turning characteristics) of paragliders based on scientific approach. In addition, it also aims to understand more deeply the unique turning features of paragliders by using the measurement and simulation environment developed.

Unfortunately, nowadays just a limited amount of the investigations address the paragliders. These mainly focus on the dynamical modelling by developing and solving 6 or higher degree-of-freedom (DOF) models [A10], [A11], [A12], while others design and use measurement systems to investigate the movement in flight.

The existing measurement systems are mainly designed to be used in the classification (DHV, LTH, AFNOR, etc.) of paragliders. All paragliders on the market must be classified by an official organisation in order to obtain the appropriate safety class. The classifications are based on test flights, being performed by several test pilots to create balanced test reports. The evaluation of some of the tests is strongly subjective, while some tests are performed by using measurement systems. In some cases, the measured data is evaluated with qualitative methods. To obtain quantitative and comparable results, new methods should be developed to process the output data of this kind of measurements. Any system for paragliders that provide warnings to the pilot at critical flying situations (e.g. stall, low / high speed) is not generally used presently.

For example, the measurement system used in DHV classification collects and record data as follows [A5]:

- pitch, yaw, bank angles
- X, Y, Z axis acceleration
- vertical speed
- speed over ground, using 5 Hz GPS module
- barometric and GPS altitude

Another existing measurement system measures the forces in the line rows separately [A6], and contains the elements as follows:

- Tension force cells, for converting the strain of the line to analogue signal
- Bridge amplifier, signal conditioner for every channel
- Digital data acquisition system, with A/D conversion and storage

This system is quite large in size, rather difficult to use and it is also necessary to disconnect the lines from the riser in order to mount the force sensors. It takes a long preparation process and can cause the loss of safety certificate of the paraglider. Because of these disadvantages, the system described in [A6] can be used only in test flights.

Some studies investigate the paraglider with simulations, mainly motion and stability simulations. The well-known and widely used 6 DOF models are used mainly for investigating the longitudinal stability [A1, A2, A3], which modelling the paraglider as a rigid body.

In another study [A4] the flexibility of the canopy-pilot system was taken into account by developing and using a 9 DOF mathematical model. The additional degree-of-freedoms comes from a ball joint, which was placed between the pilot and the canopy into the centre of gravity (CG). These models are not widely used, thanks to its complexity and the big number of parameters required.

The simulation parameters can be estimated in several ways, for example in [A8] the cross section of the inflating canopy was investigated in wind tunnel. The variation of the cross section shape, the pressure in the canopy and the pressure distribution on the upper surface were investigated in [A8].

Parameters can be also determined by test flights. In [A9] simulations based on lifting line theory were performed, and the parameters were determined by the results of test flights.

2 Methods of the research

A more suitable model for the goals of the dissertation was developed, which is moderately complex. As mentioned before, the main goal is to investigate the stationer, balanced turn of the paragliders, which is free from dynamical effects. Therefore, instead of motion equations, static force equations were used to build-up the mathematical model. It enables to use simple equations, and thus the parameters can be evaluated easier.

In the model developed the paraglider is rigid, the forces which are taken into account can be seen in the Fig. 2. This is suitable to investigate the static, balanced turn of paraglider.

The turning mechanism of the paragliders is quite different from the conventional aircraft. The turn of a conventional aircraft is started by the deflection of the ailerons, which cause the banking of the airplane. After the desired bank angle is reached, the ailerons must be set back into neutral position and the angle of attack of the wing, which is necessary to reach higher lift force required by the turn, must be raised by using the elevator. The lift force in this situation has been increased by the increased lift-coefficient through the increased angle-of-attack.

On paragliders, there is no tail at all, and the control surfaces can be only deflected downward, hence the lift force increasing cannot be achieved by raising the angle of attack. The paraglider increases the lift force by raising the gliding speed in turn, which means higher gliding angle. Paraglider in turn moves on a spiral path, in which the gliding angle is increasing in the function of bank angle.

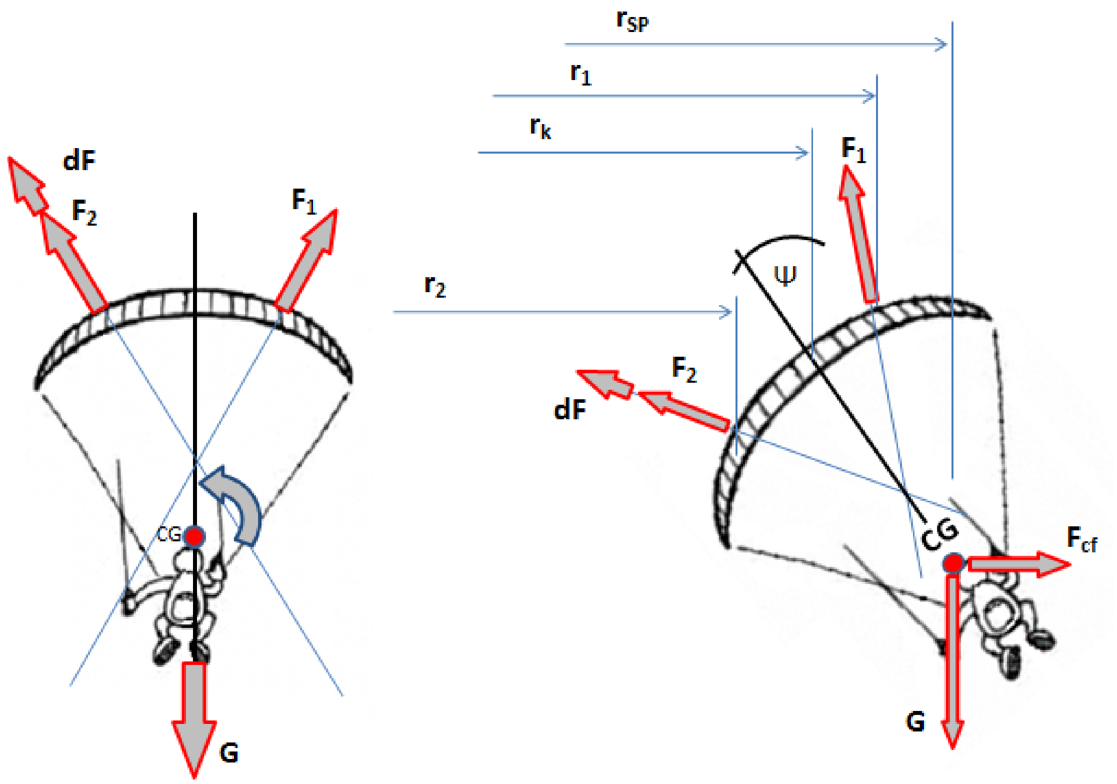

Figure 2: Considered forces on a paraglider in static, balanced turn

On the left side of the Figure 2, the paraglider is shown in strait flight, when the pilot pulls the left brake handle to start a left turn. It is another unique feature of paraglider: to make a left turn, the left brake must be applied, which results higher left wing forces (both lift and drag). This behaviour can be explained by considering the left wing force, which generates left moment around the CG[1].

The paraglider can be seen in static, balanced turn at the right side of the Figure 2. In this situation, the forces on the left and right wing are equal, which is required to maintain static turn. On the left wing (which is the inner wing in the turn) smaller forces are developed, because of its smaller speed in turn, therefore the left brake must be continuously applied in turn, otherwise the paraglider goes out from turn automatically.

[1] CG – Centre of Gravity

Further effect is the angle of attack difference between the inner and the outer wing on a spiral path. These 2 effects have been taken into account in the model developed in this thesis, and they determine the required break deflection.

The mathematical model was made in a Matlab© environment. The effect of parameters on the simulation was discovered by parameter sensitivity studies.

It was kept in mind when the measurement environment was developed that the simulation results have to validated by the results of the measurement. The measurement system developed is simpler and easier to use than the existing measurement systems in the literature, which is based on a Hungarian patent [B1], in which the author of this dissertation is one of the inventors (with 40%).

The measurement system consists of the followings:

a) force sensor
b) GPS receiver
c) 3 axis accelerometer
d) data acquisition, control and data storage module

By using these components, the measurement system can be used to measure the forces on the left and the right wing separately, while the turning radius can be also measured. The data collected are stored on a microSD card. In addition to the hardware development, software development was also performed. The PC software was written in Borland Delphi environment, while the software of the microcontroller in Mikropascal.

The force sensor is based on normal paraglider carabineer; therefore it is not necessary to dismount the lines of the paraglider.

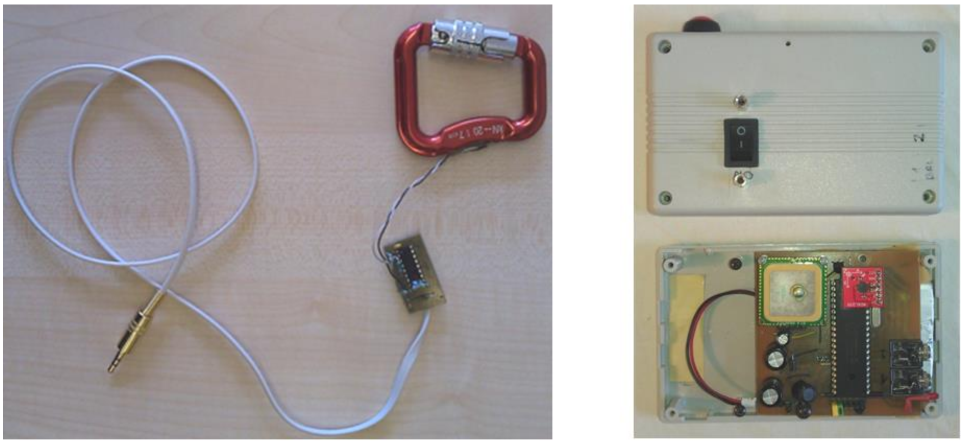

Figure 3: Force sensor developed (left) and the data acquisition system (right)

On Figure 3, the hardware elements of the measurement system can be seen. The entire system was developed at the Department. It can be observed that the size of the system is much smaller than the systems found in the literature, the structure is less complex and the hardware cost is significantly lower. The system is moveable, can be mounted on paraglider and allows more than 15 hours of continuous use.

3 Results

By using the measurement system and simulation environment, a specific paraglider was investigated (Nova Rookie S). At bank angles lower than 40 degrees, the test flights were performed by the author, while at higher bank angles the results are validated by using videos by [A16].

The results come from measurements were used to precisely determine the parameters of the simulation. One result of the simulation can be seen in the Figure 4, illustrating the relative force difference between the left and the right wings (ddF, Eq. 1) in the function of the static bank angle. This force difference must be eliminated by holding the brake handle down on one side, which results higher forces on that side. DdF in this model is positive in cases, when the inner wing (relative to turn) has smaller forces than the outer wing, so the inner brake must be continuously applied to maintain static turn.

It can be observed that to a specific angle the force different is increasing with the bank angle, which means that bigger and bigger brake deflection is necessary for a static state. After an angle (in this diagram it is about 43 deg) the brake deflection must be smaller for higher bank angles. When the blue line intersects the axis x (at about 67 deg.), no brake deflection is necessary, then after that point, brake deflection is necessary on the other (the outer) side.

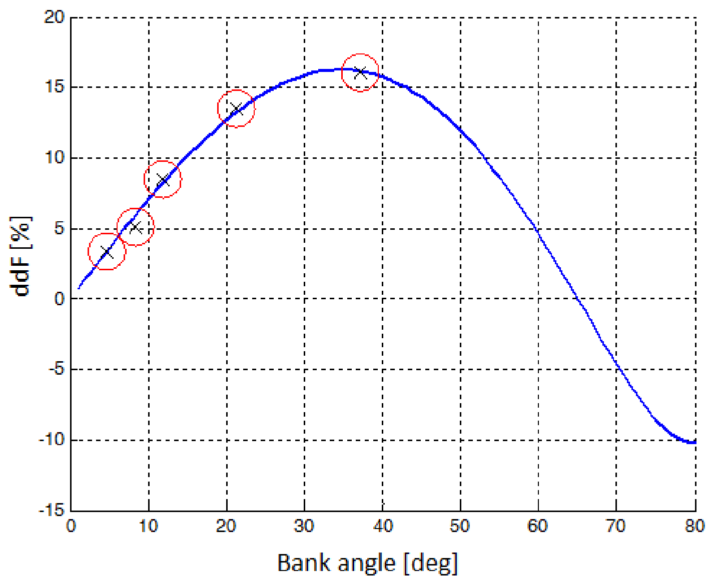

Figure 4: Force differences in turn between left and right wing

As it is shown on Figure 4, to the maximum of ddF(Ψ) function, the turn is stable, after that point, it starts showing instable behaviour.

$$ddF = \frac{AD_1 - AD_2}{AD_1 + AD_2} \cdot 100\ [\%] \qquad \text{Eq. 1}$$

In Eq. 1, the AD_1 and AD_2 are the force sensor data of inner and outer wings, respectively.

The results come from the simulation are quite similar to the flight experience, after a specific bank angle, the paraglider starts going into higher and higher bank angle autonomously. This effect causes several (sometimes fatal) accidents.

In the Figure 4, the measured points marked by circled crosses can be also seen. After the calibration of the simulation parameters, the results come from simulation and measurement are quite similar, only marginal differences can be observed in the diagram.

4 Thesis

The new scientific results I reached during my research activity and described in this dissertation were summarized in the following theses:

1. **I have analysed the history of paragliders and determined its features.**
    a. After a quite fast improvement in the principal features and performance parameters of paragliders, nowadays the performance of paragliders is on the same level, despite of the developments.
    b. Nowadays, the empirical methods used for developing paragliders have been changing and replacing with innovative, multidisciplinary, scientific methods.
    c. Due to the unique structure of the paraglider, the peculiarities can be described only by non-linear, high DOF equations, which numerous parameters can be determined by using specific measurement systems, measuring platforms.

2. **I have realised a measurement system, which is suitable to investigate the turning characteristic of paragliders on a qualitative way.**
    a. I have designed, manufactured and tested the hardware and software of a measurement system.
    b. The system measures the forces on the left and right wing separately by using integrated strain gauges on the left and right carabineers.
    c. The system contains a GPS module, by which the flight path can be reconstructed in 3D.
    d. The measurement system is based on Hungarian patent P12 00230, in which the author is a co-inventor.

3. **I have made a simulation method for investigating the stationer, balanced turn of paraglider**
    a. The simulation model takes into account the forces developed in turn on a static manner.
    b. The model considers the difference of velocity and angle-of-attack between the left and right wing.
    c. For realising the model, Matlab code is developed, which is validated by

flight tests for moderate bank angles, and by analysing of video footages for higher bank angles (up to 70 deg).

4. **By using the measurement system, I determined the simulation parameter for a specific paraglider (type Nova Rookie S)**
    a. The parameter fitting is based on the least squares method.
    b. The parameters for the specified paraglider are as follows:
        - C_F= 0,9
        - C_F^{α} = 5,6
        - Z_1 = 0,39 m
        - Y_1 = 2,7 m
        - k = 7,1

5. **By using the measurement system and simulation model, I have investigated the turning characteristic of paraglider for balanced turn and conclude the following behaviours:**
    a. At low bank angles, inner side brake deflection must be raised for maintaining higher bank angles.
    b. At moderate bank angles, inner side brake deflection must be lowered for maintaining higher bank angles.
    c. At high bank angles, outer side brake deflection must be applied.
    d. At bank angle, which divides the low and moderate banked turns, the aerodynamic force difference compensated by the brake deflection is maximal.
    e. At bank angle, which divides the moderate and high banked turns, the aerodynamic force difference compensated by the brake deflection is zero; therefore no brake deflection is necessary to keep the paraglider in turn.
    f. In the case of the investigated Nova Rookie S paraglider, the 5-d bank angle is 43 deg., while the 5-e angle is 68 deg.
    g. At moderate and high bank angles, the turn of the paraglider is unstable.

5 Application of the new results reached

New scientific results reached in this research can be used to compare the turning features of different paragliders in an objective, quantitative way. In paraglider classifications the results can be also used, by determining the parameters of the simulation for each paragliders in question, the maximum point of function ddF(Ψ) can be determined, which is a quite important feature in the point of flight safety.

The measurement and simulation environment can be used not only for sport and leisure paragliders, but for any other flying vehicles which has similar structure. For example, in the NASA X-38 project, the rescue recovery system used a flexible wing, very similar to a general paraglider to recover the rescue module gently to the ground in the last phase of landing. Unfortunately, this is not realized because of financial difficulties. In other applications, e.g. in military precision air delivery systems the parachute is replaced by a paraglider-like wing, which can glide into much more distances in order that the cargo plane avoids the enemy fire. The results can be used also for these kinds of paragliders (wings).

The full dissertation (in Hungarian) can be downloaded from the homepage of BME National Technical Information Centre and Library (http://www.omikk.bme.hu/en/). (After it is uploaded at the end of 2014)

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