MEASURING AND MODELLING THE LONGITUDINAL MOTION OF PARAGLIDERS

Andras Nagy*, Jozsef Rohacs*
***Budapest University of Technology and Economics**
Department of Aircraft and Ships
nagyan@rht.bme.hu; jrohacs@rht.bme.hu

Keywords: *paraglider, in-flight measurement, flight dynamics, motion analysis*

Abstract

Nowadays, the use of paragliders in leisure and sport activities is increasing, as well as their application as powered unmanned air vehicles applications. The paraglider designers need more precise models and validation of their CFD – based simulation technologies.

This paper introduces a so called 2D physical model developed for foot launched paragliders. This model can be used to investigate the longitudinal motion of the pilot-wing 2 mass oscillating system. The measuring system includes a 3 axes accelerometer, a GPS unit for positioning, the force measuring built in carabiners, a data recorder unit, and a ground based data analyser. the force measuring unit. The force on carabiners of the paraglider, the speed and course over ground, the altitude and the actual acceleration around 3 axis can be measured and stored by this system and the flight path can be reconstructed in 3 dimension.

The paper describes the measuring system, the measuring methods and the 2D physical model and shows the test flight results.

1 Introduction

Paragliding is becoming more and more widespread nowadays. It is used for leisure and sport activity all around the world and this technology as powered unmanned aircraft has started to use by industry.

The designers and manufacturers of paragliders are used the CFD-based methods and experimental flights for reaching the best flight performance. They need more precise and validated models.

Unfortunately, the measurement of paraglider is a rader difficult task. For example, there is no fix point on the whole structure; the pilot and the wing are able to move virtually individually.

Generally, from the flight dynamics and control viewpoint, there are several major differences making the paraglider motion simulation more complex then the fixed-wing aircraft motion (following to [1]):

- the separation between the center of gravities of the canopy and the payload produces swing motion,
- changing thrust induces a considerable pitching motion,
- relative pitching and yawing motions exist between the canopy and the payload,
- the canopy is a tailless flying wing,
- directional control is done not through rolling motion but through yawing,
- added mass of the canopy must be taken into account as in an airship.

These difficulties are appearing during the measurements of paraglider performance, too. Only some papers [2, 3] deal with developing the measuring systems for the paragliders.

This paper introduces a – so called 2D physical model developed for foot launched paragliders. This model can be used to investigate the longitudinal motion of the pilot-wing 2 mass oscillating system.

For measuring the longitudinal motion of a real sized paraglider in flight, an on-board measuring system and ground based data analyser have been developed. This system consists a 3 axes accelerometer, a GPS unit, the force measuring elements built into the carabiners and a data recorder unit. The speed and course over the ground, the altitude and the actual acceleration around 3 axis can be measured and stored by this system and the flight path can be reconstructed in 3 dimensions.

In this paper the measuring system, the measuring methods and the 2D physical model are described and the test flight results are shown.

2. 2D Physical model of paragliders

The powered paraglider is composed of a canopy and a payload with a propelling unit. As usually the canopy is connected with the payload at two points.

There are few models developed specially for describing the paraglider motion. The models are started from the 6D rigid body models, in which the relative motion of canopy and payload is neglected.

Some researches aimed to explore the differences between 6DOF and 9DOF model of paraglider [4]. Based on these investigations it can be said that the motion of paraglider can be described by 6DOF model precisely enough. The difference between the 6DOF and 9DOF model is the joint built between the canopy and the pilot. This joint adds additional three-way rotation into the system.

The reference [1] has introduced an interesting model in which the canopy has six degrees of freedom (DOF) and the payload has two DOF of pitching and yawing motions relative to the canopy. Friction at the connecting points between the canopy and the payload is taken into account.

The physical model used in this paper is a simplified 2D variant of a 6DOF model. This model has been applied to investigate not only the longitudinal, but the transversal motion of paraglider, too.

2.1. Longitudinal model

In simplified longitudinal model applied here the canopy – lines – pilot system is modeled as rigid body, the canopy is not flexible. In most cases – when the paraglider is in normal flight condition and the canopy does not lose its stability - this approximation is enough.

The markings used in the equations 1-5 of the longitudinal model described on Figure 1.

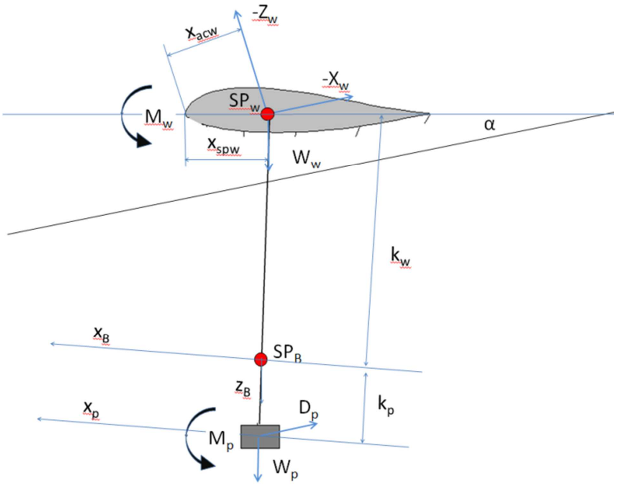

Fig. 1:
Designations used for longitudinal equations

Equations used in the model are the followings:

$$X_{SP} = X_w + X_P + (m \cdot g)_b$$
$$Z_{SP} = Z_w + Z_P + (m \cdot g)_b \qquad (1)$$

$$M_{SP} = Z_w \cdot (X_{SPw} - X_{ACw}) - X_w \cdot k_w +$$
$$Z_P \cdot (X_{SPp} - X_{Acp}) - X_p \cdot k_P + M_w + M_p \qquad (2)$$

$$X_{SP} = m \cdot (\ddot{x} + \ddot{q} \cdot \dot{z})$$
$$Z_{SP} = m \cdot (\ddot{z} - q \cdot \dot{x})$$
$$M_{SP} = I_y \cdot \ddot{\theta}, \qquad \dot{\theta} = q_E \qquad (3)$$

$$\begin{bmatrix} \dot{X}_E \\ \dot{Z}_E \end{bmatrix} = EB^T \cdot \begin{bmatrix} \dot{X}_b \\ \dot{Z}_b \end{bmatrix}$$

$$L_w = -\left[C_{Lw} \cdot \frac{\rho}{2} \cdot v^2 \cdot S_w\right], \quad C_{Lw} = f(\alpha)$$
$$D_w = -\left[C_{Dw} \cdot \frac{\rho}{2} \cdot v^2 \cdot S_w\right], \quad C_{Dw} = f(\alpha) \qquad (4)$$

$$L_p = -\left[C_{Lp} \cdot \frac{\rho}{2} \cdot v^2 \cdot S_p\right], \quad C_{Lp} = f(\alpha)$$
$$D_p = -\left[C_{Dp} \cdot \frac{\rho}{2} \cdot v^2 \cdot S_p\right], \quad C_{Dp} = f(\alpha) \qquad (5)$$

As it can be seen the equations (1) – (5) really describe a simple longitudinal model of vehicle motion. Here the air forces are computed based on the variation of lift and drag coefficient in angle of attack.

2.3. Transversal model

In the transversal model the paraglider has been modeled as rigid body like at the longitudinal model.

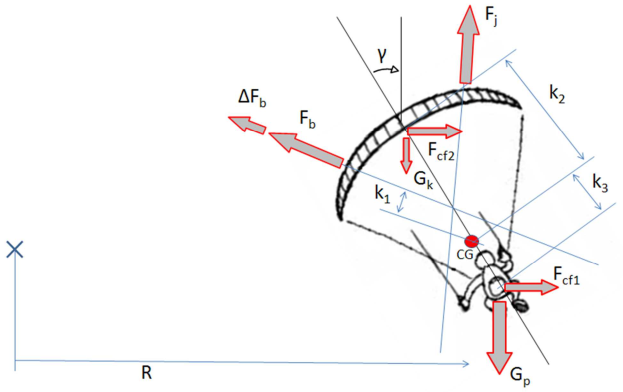

Fig. 2:
Schematic of transversal model used

The moment equilibrium applied to the centre of gravity (CG):

$$-M_{\Delta F_b} - M_{F_{cf1}} + M_{F_{cf2}}$$
$$+M_{G_p} - M_{G_k} = 0 \qquad (6)$$

Detailed description of equation 6:

$$-\Delta F_b \cdot k_1 - \frac{G_p}{g} \cdot \frac{v^2}{R} \cdot k_3 \cdot \cos(\gamma) +$$
$$\frac{G_k}{g} \cdot \frac{v^2}{R} \cdot k_2 \cdot \cos(\gamma) +$$
$$G_p \cdot \sin(\gamma) \cdot k_3 - G_k \cdot \sin(\gamma) \cdot k_2 = 0 \qquad (7)$$

where:
k_1 - the distance between the lift force generated on wing and the CG
k_2- the distance between the CG of canopy and the CG of body
k_3 - the distance between the CG of pilot and CG of body
G_p- weight of pilot
G_k- weight of canopy
v - velocity
R - turn radius
γ - bank angle

To solve the model, several values have to be measured come from Equation 7.

3. In-flight measurement system

In order to satisfy the requirements, the measurement system has to measure and record as follows:

- the resultant force of left and right wing separately,
- the flight track in 3D,
- the actual acceleration (G force)

The data acquisition has to be robust and data are stored safely in order to make the system reliable. It is important because test flights hard to repeat, some flight conditions are rare and the situation can be unique.

3.1. Description of the hardware

The measurement system is fully developed and built on the department. Its block diagram can be seen on Fig. 3.

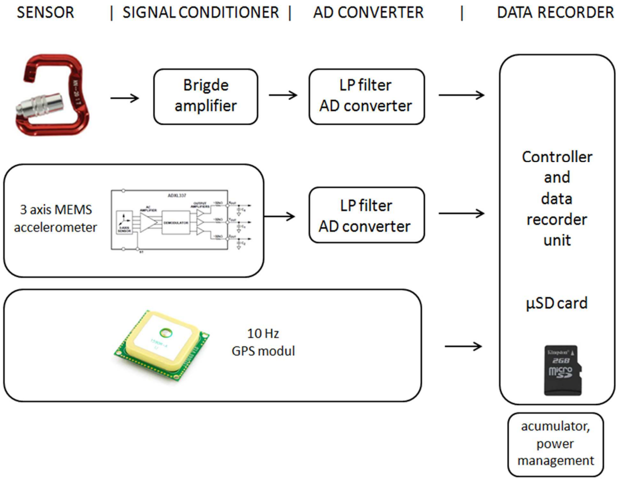

Fig. 3
Block diagram of the measurement system

The force measurements realised by strain gauge glued to carabineers. The sensor prepared can be seen on Fig. 4.

Fig. 4:
Carabineer with strain gauge

Carabineers used are typical paraglider equipment, manufactured by GIN. On the bottom and the top side, proper places are designed for the belting of pilot's harness and the paraglider. The strain gauges are manufactured by KYOWA, have nominal resistance 120 Ohm and thermally compensated for aluminium.

Carabineers have to be prepared for installing the gauges. Its surface is anodised which has to be removed before gluing. The installation finished with a protective cover insertion.
In order to proper processing the raw signal of the strain gauge, it is usually built into Wheatstone bridge. The bridge is widely used to measure extremely low changes in resistance. The signal given from the bridge has to be amplified, for which there are several solution. In the measurement system described here a precision instrumentation signal amplifier from Texas Instrument is used, type is INA125 [5]. This integrated circuit contains everything what are needed in an application like this. It contains very a low offset voltage amplifier and voltage reference circuit for supplying the bridge with precise voltage.

The schematic draw of the bridge amplifier can be seen on Fig. 5, while the developed and used unit can be seen on Figure 6. The output of the amplifier is a voltage, proportional to the force on carabineers.

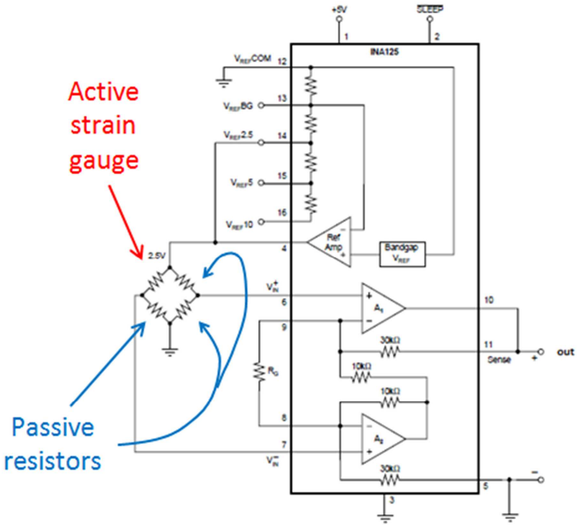

Fig. 5:
Bridge circuit with INA125 instrumentation amplifier.

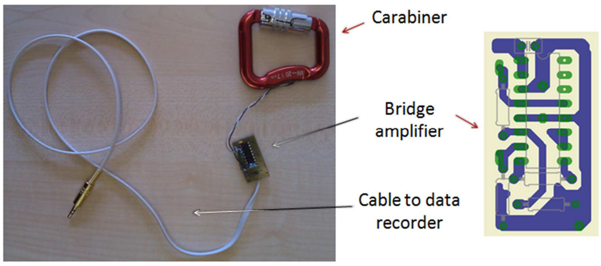

Fig. 6
Developed carabineer with bridge amplifier

In order to precisely measure the force on carabineers, the actual G force has to also be measured. For this task, a MEMS accelerometer unit type ADXL335 is used. Unfortunately, the position of the measurement unit is unknown in flight, because it is fixed to the pilot hanging under the paraglider. Despite its unknown position, the G force can be measured by calculating the resultant of the 3 axis. It is precise enough in the first approximation. The MEMS accelerometer has built-in signal conditioner circuit, so before the AD conversion its output signal only needs a low pass filter.

Another part of the measurement system is the GPS module, which is used to record the flight path in 3D. The GPS module used is manufactured by Locosys Technology, type is LS20030. It has 66 channel, 10 Hz update rate and built-in high gain antenna. It provides several data, from which followings are processed and stored: position (lat, lon), altitude, velocity and heading.

The data acquisition is controlled by a PIC microcontroller, which is part of the control and data storing unit. The type of the microcontroller is a PIC18F4523 from Microchip. It has built-in 10 input, 12 bit AD converter, which resolution is suitable to convert all of the analogue signals in this application. The microcontroller runs on 20 MHz external clock in order to provide enough stability.

Its tasks are:

- controlling the data acquisition process
- collecting and converting data from sensors
- processing the sentences come from the GPS module
- storing collected data on a micro SD card in the suitable format

Finally, the measurement system has to supply from a single cell Li-poly accumulator. The power management part of the circuit provides the proper voltage for each unit. It is based on the TPS61097-33 power management IC from Texas Instruments. The basic voltage level of the system is 3.3 V.

3.2. Description of the software

There are 2 different software, which have to be developed. Software is written for the microcontroller, the other is for PC.

The software of the microcontroller has to realise the tasks of the measuring system. It is written in MicroPascal, which is a development system from MikroElektronika [6]. It has several units and libraries which can be used in any projects.
In the measuring system the proper timing is one of the key elements, thus the software is written to use the GPS module as precision timer. The whole measurement process is timed by the GPS module, therefore the sampling frequency is 10 Hz. In every 1/10th seconds the GPS module send a GPS sentence, which is processed and stored together with the values come from the force sensors and the accelerometer. Between the 1/10th seconds, the system is sampling the accelerometer and the force sensor data ten times and compute them average, therefore the stored values are the average of the last 1/10th seconds. By this method, a basic noise reduction can be provided in addition to the low pass filtering.

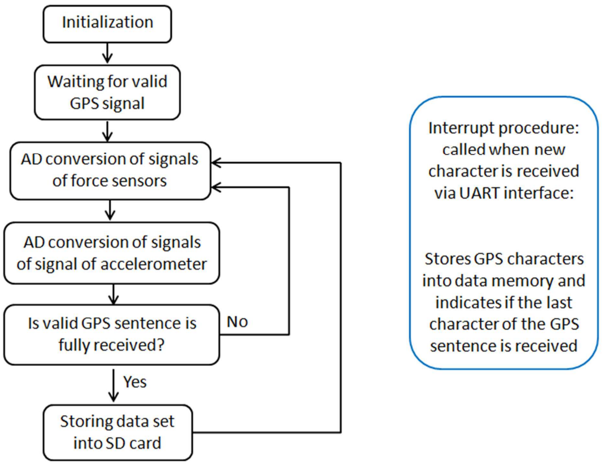

Fig.7:
Block diagram of software of the microcontroller

The software of the microcontroller has to also ensure the security of the stored data. It is important, because if interference disturbed the normal operation of the measurement system, the stored data would has to be protected. For this reason there is no file system developed on the SD card, the data storing is based on direct sector writing, therefore in case of malfunction, the data damage is restricted to the actual sector, but the others. The simplified block diagram of the software of microcontroller can be seen on Figure 7.

In order to recover the stored data from the SD card, PC software has to be developed. It is necessary, because as mentioned, there is no file system on SD card, thus the PC software has to read the SD card sector by sector.

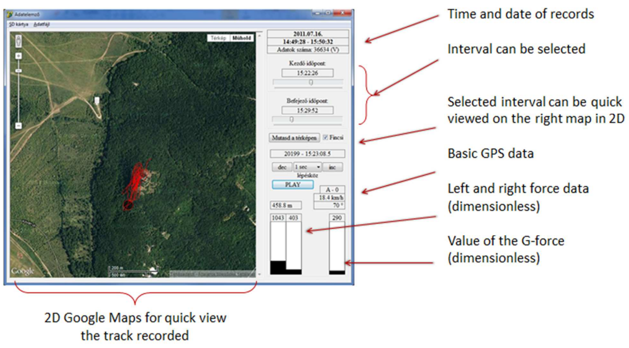

Fig.8
Screenshot of the PC software developed

On Fig. 8 the screen of PC program can be seen. It is only used to recover data from SD card and to inspect into data instantly.

4. Results of system tests and measurement flights

4.1. Test of the GPS and the accelerometer

In the first tests the modules of the system have been verified. The verification of the GPS module has been performed by flight with a glider. During the test, another GPS logger has been on board. Recorded data of the GPS logger and the GPS module of the measurement system have been compared in order to validate the accuracy of the module tested.

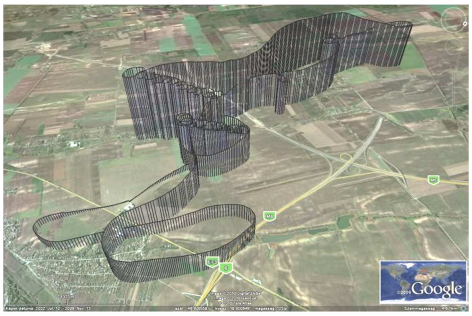

Fig. 9:
Flight path recorded during test of GPS

From results it can be said that the GPS module works as expected, the average difference is in the range of the accuracy of GPS.

4.2. Test of the force measuring unit

The force measurement part of the measurement system has to be calibrated, the correlation between the raw data of the A/D converter and the force applied on the carabineers. The calibration has been performed on the laboratory of the Department. On Figure 10 one test platform for force measurement unit can be seen. The harness positioned to the same position like in-flight, and fixed onto a horizontal rod by ropes.

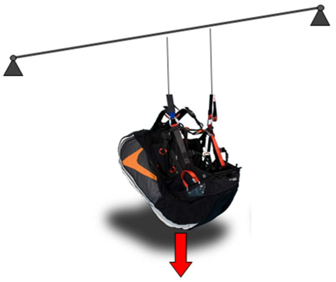

Fig. 10:
Schematic draw of the method of force measurement test

The system induced by a step pulse, and the response recorded by the measurement system. The results can be seen on Figure 11.

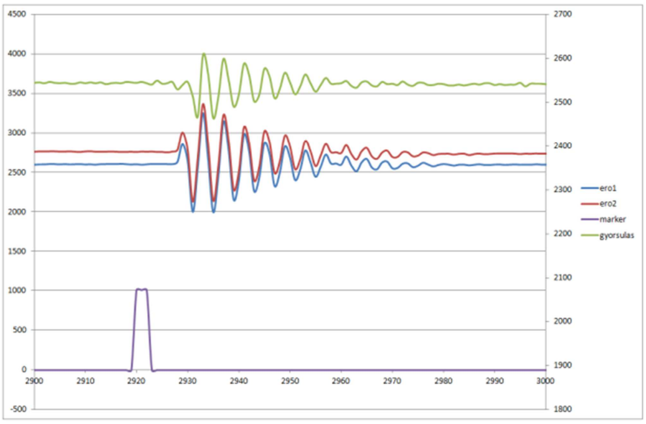

Fig.11:
Force measurement test results

It can be seen on the figure, that the response of the system to the step pulse is absorbed by the rod on which the system is hanged.

4.3. Results of test flights

The system prepared for flight test and experimental flight can be seen on Fig. 12.

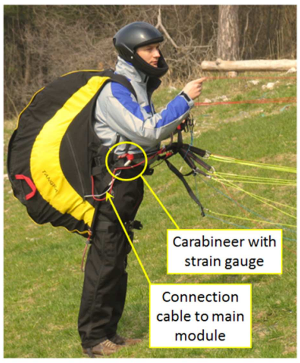

Fig. 12:
Measurement system prepared for flight

The weather in which the flight tests can be executed is important to be selected well. For take-off and long time fly, proper wind and thermal activity is necessary because the paraglider has not got propulsion. On the other hand for repeatable and smooth measurement, calm weather is required. The most suitable time for measurement is in summer or autumn near sunset. In this period, the wind is usually calm just enough for slope flying and the thermal activity is weak or not at all.

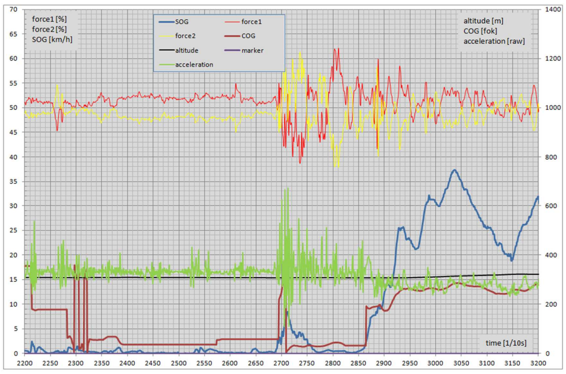

Fig.13:
Results of the take-off period of a test flight

On Figure 13 a take-off period can be seen. The first activity during take-off of paraglider is preparing the wing into state in which take-off is possible. This process can be observed in the diagram on Figure 13.

From recorded data the flight path can be reconstructed completely and can be visualized in Google earth software. This visualisation can be seen on Figure 14.

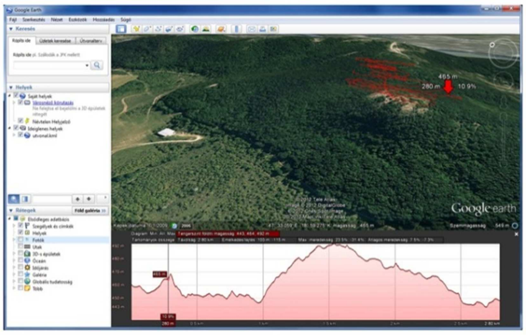

Fig. 14:
Flight path visualization in Google Earth

Based on reconstructed flight path, the turn radius and the wind speed can be determined. These data are required to use the equation described in chapter 2. The determination process can be seen on Fig. 15.

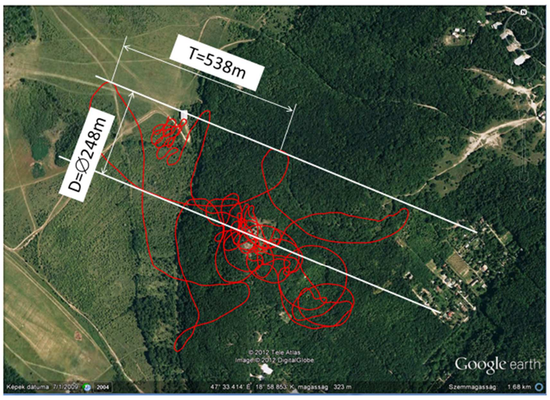

Fig.15.
Estimation of turn radius and wind speed from recorded flight path

From the result it can be said that the measuring system can be used to investigate the longitudinal and transversal motion of paragliders by in flight measurement. Based on results of test flights, in the turn seen on Fig 15. the turn radius is 124 meters, while the wind speed is 17 km/h and the constant airspeed is 35 km/h. With these values and the transversal model destcribed in 2.3, the moment which holds the paragider in turn is 28 Nm. Results show some deviation in measured values, hence further test flights are needed to clarify the results and decrease the deviations.

5. Conclusion

This paper has described a so called 2D physical model of the paraglider motion containing

- a simplified longitudinal motion of the rigid body canopy – lines – payload system, and
- the second part of model defining the transversal motion of rigid body paraglider system.

The model was developed for foot launched paragliders and it can be used to investigate the longitudinal motion of the pilot-wing 2 mass oscillating system

For further investigation and estimation of the model parameters a special measurement system was developed. The system integrates

- a 3 axes accelerometer,
- a GPS unit for positioning,
- the force measuring elements built in carabiners,
- a data recorder unit, and
- a ground based data analyzer.

The system measures and collects data force in carabiners of the paraglider, the speed and course over ground, the altitude and the actual acceleration around 3 axes, that allowed to reconstruct the flight path in 3 dimensional form.

The first results of experimental flights shown here, demonstrate that a pendulum-like motion is added to the "common" longitudinal motion of air vehicles.

Acknowledgement

The research is supported by the Hungarian National New Szechenyi Plan (TAMOP-4.2.2./B-10/1-2010-0009)

References

[1] Watanabe, M., Och, Y.: Modeling and Simulation of Nonlinear Dynamics of a Powered Paraglider, AIAA Guidance, Navigation and Control Conference and Exhibition 18 - 21 August 2008, Honolulu, Hawaii, AIAA 2008-7418C. Toglia,

[2] Gi-Bong Hur: *Identification of Powered Parafoil-Vehicle Dynamics from Modelling and Flight Test Data*, 2005

[3] Slegers, N. and Costello, M.,: *Comparison of Measured and Simulated Motion of a Controllable Parafoil and Payload System* AIAA, 2003, AIAA-2003-5611.

[4] M. Vendittelli: *Modeling and motion analysis of autonomous paragliders*, Technical Report n. 5, 2010

[5] B. Carter, T. R. Brown: Handbook of operational amplifier applications, Texas Instrument Application Note SBOA092A, 2001

[6] Mikroelektronika Inc: Pascal compiler for PIC microcontrollers User Manual, 2011

Copyright Statement