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Abstract

Purpose – This paper aims to describe the idea behind and design of a miniaturized distributed measurement system based on a controller area network (CAN) data bus.

Design/methodology/approach – The intention of the designers was to build a light and modular measurement system which can be used in remotely piloted aircraft systems and ultra-light aircraft during flight tests, as well as normal operation. The structure of this distributed measurement system is based on a CAN data bus. The CAN aerospace standard has been applied to the software as well as the hardware comprising this system. PRP-W2 software designed for PCs is an additional component of the proposed measurement system. This software supports data acquisition from a recorder unit and allows for preliminary data analysis, as well as data conversion and presentation.

Findings – The system, complete with a high-speed data recorder, was successfully installed on board of an MP-02 Czajka aircraft. A research experiment using the system and oriented on airframe high frequency vibration analysis is presented in the final part of this paper.

Research limitations/implications – This measurement system allows analysis of high-frequency vibrations occurring at selected points of the aircraft. A data set is recorded by three-axis accelerometers and gyroscopes at frequencies up to 1 kHz.

Practical implications – The use of a miniature and lightweight modular measurement system will, in many cases, be faster and less expensive than full-scale measurement and data acquisition systems, which often require a lengthy assembly process. The implementation of this class of lightweight flight test systems has many advantages, in particular to the operation of small aircraft. Such solutions are likely to become increasingly common in unmanned aerial vehicles and in other light aircraft in the future.

Originality/value – The introduction of high-frequency multi-point measurements on the board of small and miniature aircraft.

Keywords UAV, RPAS, CAN bus, Distributed measurement system, Ultralight aircraft

Paper type Technical paper

Nomenclature

Definitions, Acronyms and Abbreviations

ADC = air data computer;
AHRS = attitude and heading reference system;
CAN = controller area network;
CWT = continuous wavelet transform;
FDR = flight data recorder (file format);
FFT = fast Fourier transform;
GPS = global positioning system;
IAS = indicated air speed;
IMU = inertial measurement unit;
MEMS = micro electro-mechanical systems;
RPAS = remotely piloted aircraft system;
RPM = rotation per minute;
TAS = true air speed;
UAV = unmanned air vehicle; and
UL = ultra light.

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Introduction

Flight tests play key role in proving airworthiness of planes. Unfortunately, some categories of flight tests have limited application in ultra-light (UL) and remotely piloted aircraft system (RPAS) systems because of weight limitations and the complexity of data collection systems (Bakunowicz and Meyer, 2016; Blachuta *et al.*, 2014; Brzozowski *et al.*, 2017; Majka, 2014; Nowak *et al.*, 2014; Kopecki and Rzucidlo, 2016). Another challenge is the flexibility of systems in terms of signal redundancy, multiple measurement points (Krichen *et al.*, 2017), capability and integration issues (Chudy *et al.*, 2013; Kopecki *et al.*, 2016; Majka, 2017). Moreover, flight test costs are increased by the necessity of complex processing and interpretation of collected data, as well as limitations driven by regulations (Szewczyk *et al.*, 2017; Rzucidlo *et al.*, 2016). Bearing this in mind and capitalizing on experience obtained during previous in-flight tests, a distributed measurement system dedicated for UL and RPAS aircraft classes has been designed (Kopecki *et al.*, 2013; Rydlo *et al.*, 2013; Rzucidlo,

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2013; Kopecki and Rzucidlo, 2014). The following high-level requirements for the system have been considered:

- easy integration on the board of the aircraft to reduce the effort required in the flight tests preparation phase;
- a modular structure to provide flexibility and adoptability dependent on flight tests type and customer needs;
- a single lightweight module, to avoid interfering with the center of gravity of the aircraft in a significant way;
- low power consumption with an independent power supply not requiring alteration of the aircraft electrical installation; and
- reduction of data processing time by providing dedicated software capable of interpretation tasks such as measuring correlations between measured variables.

General description of the PRP-W2 measurement system

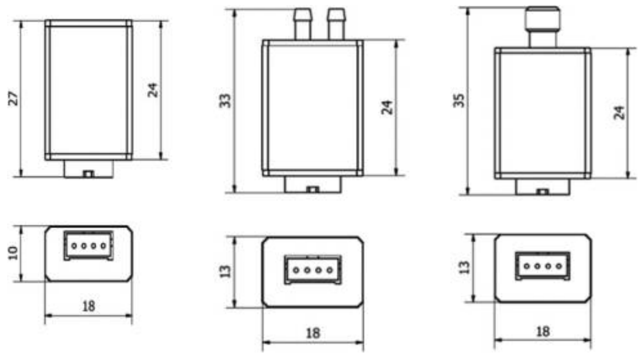
To fulfill the requirements of adoptability and easy integration, a decision was made to design the system with a modular structure (Figure 1). First, modules must be simple to integrate, which is why in most cases a single connector structure is used. This connector is used both to provide the module with power and to enable data exchange between modules. The next design decision was driven by the weight requirement, so each module was limited to a total size of 20 × 20 × 40 mm (Figure 2). This was a key design limitation, as the integrity of electronics had to be carefully considered. Moreover, these dimensions were inclusive of protective casing which is used to limit the environmental impact on each module, making the electronic unit design yet more complicated. All of the modules weigh no more than 6 g except for the global positioning system (GPS) module which weighs 9 g (without external antenna).

Communication interfaces and power

A growing market of micro electro-mechanical systems (MEMS) sensors is providing constructors with a reliable source of measurement signals, and even sampling frequencies of above 1 kHz. This leads to one of most important decisions that were made. Each module has its own microcontroller unit which is responsible for collecting data from the MEMS sensor (in reality a block of sensors). The microcontroller unit also contains a digital data bus to exchange data with other modules, and auto diagnostic functions to inform modules on failures that may affect data reliability. Other measurement modules such as GPS and air data computer (ADC), as well as analog and digital measurement units, are also equipped with their own microcontrollers and communication interfaces.

Figure 1 PRP-W2 measurement system: general view of the set of modules

Figure 2 Dimensions of the PCDL-01, PCAD-01 and PCGP-01 modules (in millimetres)



Based on the previous experience of authors with controller area network (CAN) buses, a decision was made to use one as source of data exchange. This is because of reliability proven by many years of automotive usage and growing presence in aviation (e.g. the CAN aerospace standard) (Stock, 2001) and simplicity of the physical layer (only 2 lines CAN_H and CAN_L are needed to transfer data). The limiting of the number of connector pins to only four also enables usage of a small-size connector.

To meet the requirement of an independent power supply for the measurement system, 5VDC was chosen to use as a primary supply voltage. This power supply is used in power banks for charging devices from USB ports. Typical current consumption per module does not exceed 60 mA @ 5VDC. The complete PRP-W2 measurement system consists of the following modules:

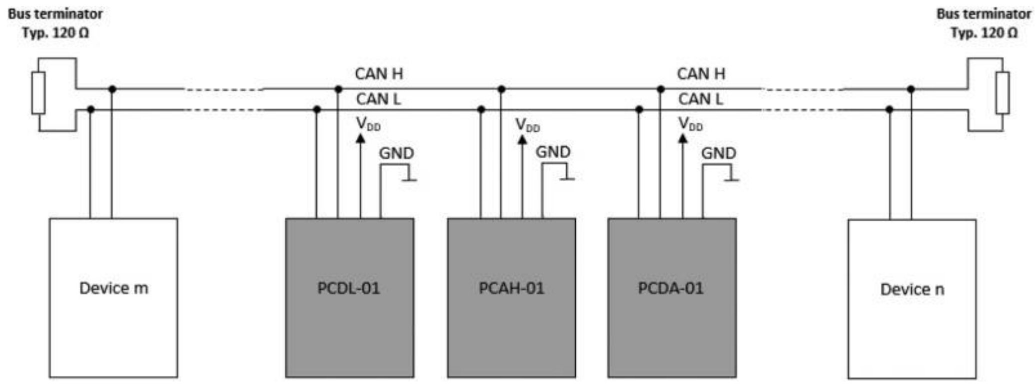
- PCDL-01– data logger;
- PCDA-01– ADC;
- PCAH-01– AHRS (attitude and heading reference system);
- PCAI-01– analog input measurement module;
- PCDI-01– digital input measurement module;
- PCGP-01–GPS receiver module; and
- PCIM-01–inertial measurement unit (IMU) module.

Structure of the measurement system

With a modular structure assumed, and the redundancy of modules plugged into the CAN bus, it was very important to distinguish which data are driven by which module. To achieve this, individual identification of modules based on the CAN aerospace specification was used (Figure 3).

Each module is factory calibrated to provide accurate data without the need for individual calibration (Sipos *et al.*, 2012). This includes temperature calibration to reduce the effect of temperature change on measurement units. The impact of temperature calibration is critical, e.g. when calculating AHRS

Figure 3 Example configuration of modules including the PCDL-01 data logger, PCAH-01 AHRS and PCDA-01 air data computer



solutions of orientation angles from the MEMS gyros and accelerometers.

Software for data analysis

PRP-W2 is a specialized software tool for advanced analysis of flight recorder data. It was created by and for aviation engineers to facilitate working effectively with large amounts of data from flight tests. In designing the software, emphasis was put on the processing speed for large data volumes, convenient presentation of data and an easy and intuitive graphical user interface.

General description of PRP-W2 software

Figure 4 presents the main window of the application. The key feature of the application is the decoding of data recorded by the miniature PRP-W2 registration system. Once data are decoded, they can be visualized as graphs or exported to other data formats. One format is a simple *.TXT file, so that the user can further process data in other common applications such as MATLAB or Excel. Another option is to save the data in *.FDR format so that the user can reproduce the flight in an X-Plane application. This facilitates analysis of the correlation between recorded data and a physical interpretation represented through a 3D visualization. In Figure 5, we can see

Figure 4 Main window of the PRP-W2 application

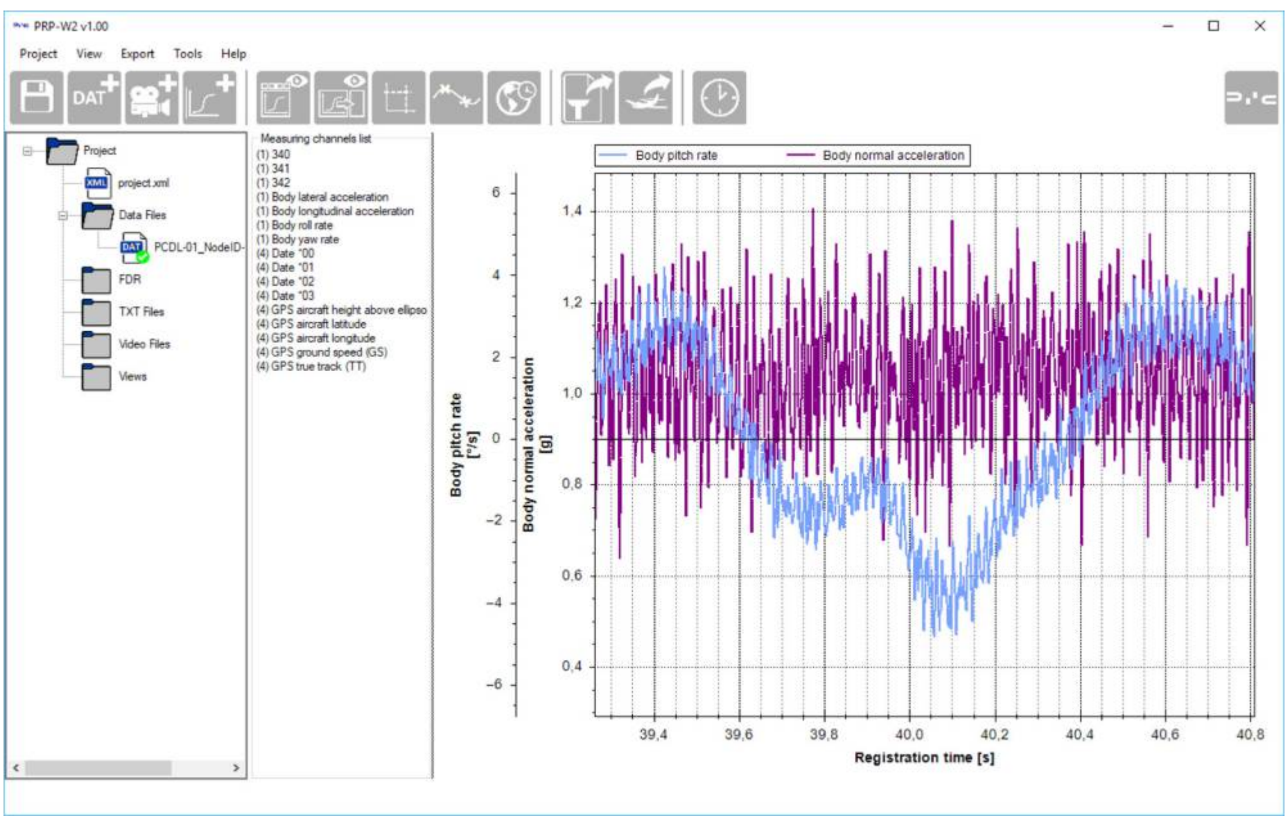
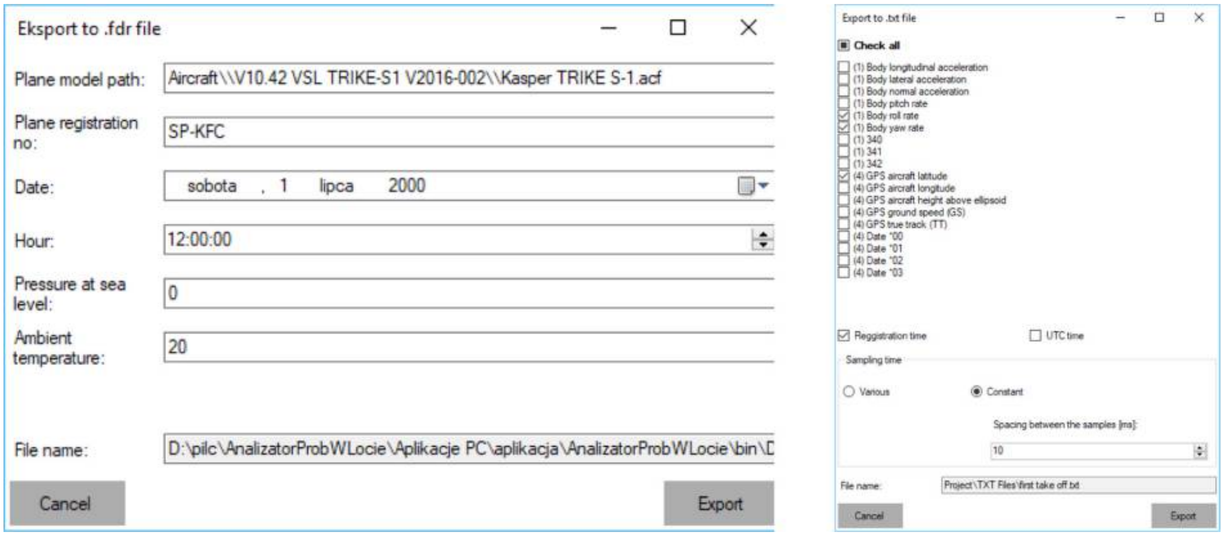


Figure 5 Windows for Export to X-Plane *.FDR file (left) and *.TXT file (right)



both the export to *.TXT format window and the export to *.FDR format window.

Additional functions of PRP-W2 software

PRP-W2 has been constantly developed and improved since its inception. In addition to the features mentioned above, PRP-W2 provides many other useful solutions, for example:

- creation of simplified data views, which can be particularly useful when a quick analysis of the suitability of data for deep analysis is required;
- synchronization of time data samples with universal time, based on the GPS system;
- calculation of selected signal functions such as minimum value, maximum value, sampling frequency, mean and others;
- signal scaling; and
- Fast Fourier transform analysis.

In-flight experiments

One of the research tasks recently carried out by a team of researchers from the Department of Avionics and Control Systems, Rzeszów University of Technology, was to analyze the vibration and oscillation of an airplane using wavelet methods (Bakunowicz and Rzucidlo, 2017). Such analyses have also been carried out in other research centers but have applied to aircraft of other classes (Naruoka *et al.*, 2009; Lichota *et al.*, 2016). Standard measurement equipment installed on the MP-02 airplane allowed recording of accelerations in the longitudinal and lateral axes of the aircraft only. This was possible with maximal frequency of 16Hz and only at a poor quantization level. Marketed measuring instruments, in particular accelerometer assemblies, enable measurements at frequencies above 500Hz – a requirement for accurate testing. Unfortunately, almost all the existing hardware solutions investigated were concluded to be problematic for the installation and operation of UL aircraft, because of the following:

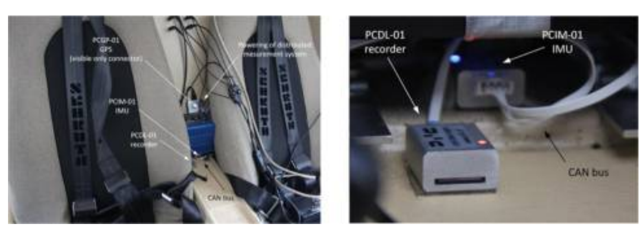
- the need to work with a personal computer (no loggers for fast and lossless recording of large data streams);
- problems with synchronization of acquired measurements to relative time and selected time reference (e.g. GPS time);
- power consumption requiring the use of relatively large and heavy power supplies;
- dimensions, weight and wiring that impede installation on the aircraft; and
- the need to involve the crew in the measurement process.

On board installation

The modified MP-02 Czajka airplane (Figure 6) owned by the Department of Avionics and Control Systems at the Faculty of Mechanical Engineering and Aeronautics of the Rzeszów

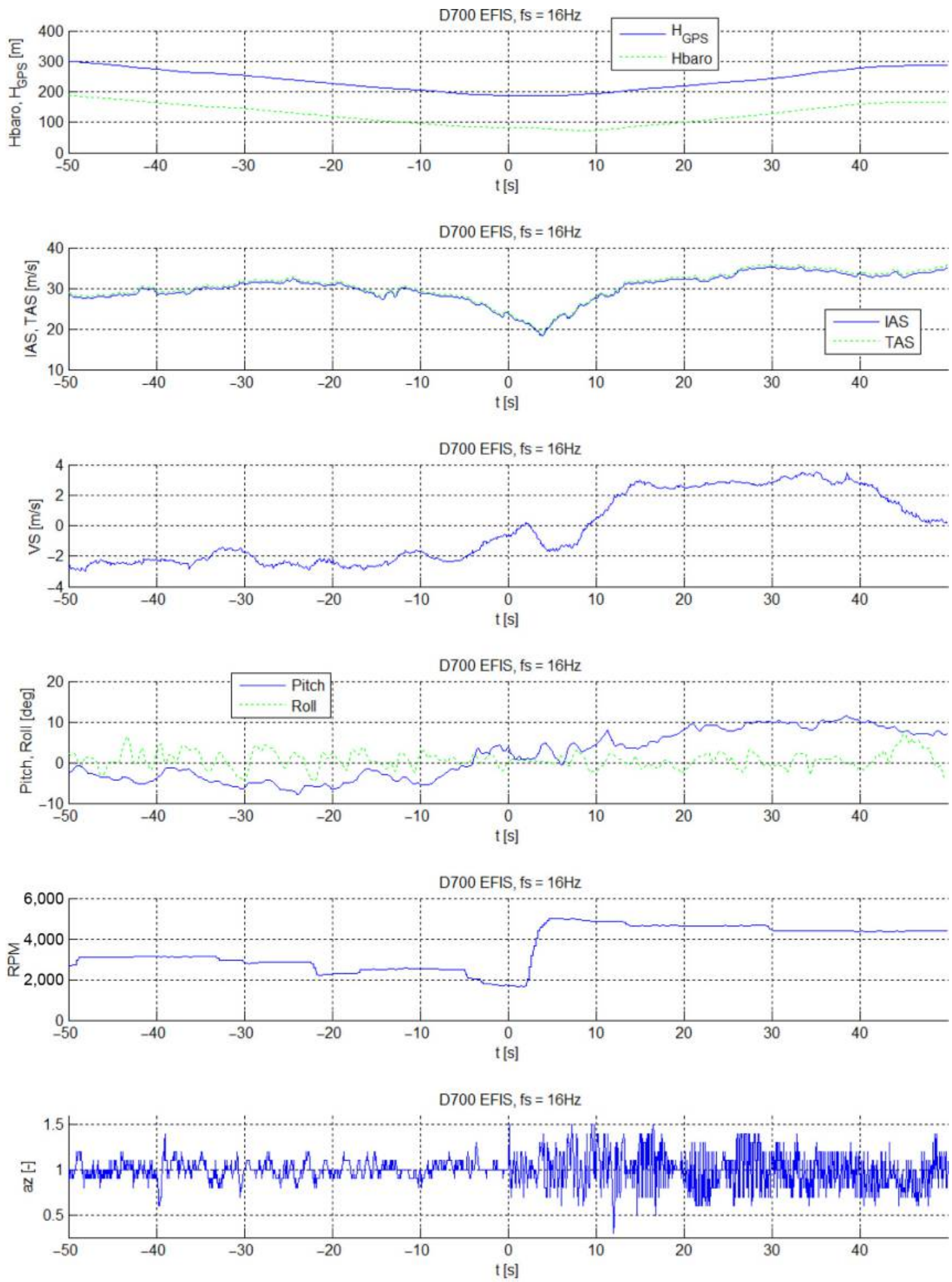
Figure 6 General view of the MP-02 experimental aircraft (left) and its cockpit (right)

Figure 7 Installation of the PCDL-01 recorder and measurement units in the MP-02 cockpit (left), detailed view of PCDL-01 and PCIM-01 units (right)



University of Technology is an experimental design. It was equipped with a flight control system developed through the LOT research project (Basmadji *et al.*, 2012). The avionics installed on the aircraft includes a D700 integrated display system. It allows the recording of multiple flight parameters and navigational data as well as operating parameters with a frequency of 4Hz in emergency record mode and up to 16Hz in user programmable mode.

Figure 8 Flight parameters recorded during landing and take-off without stopping



Note: May 17, 2017, runway 08 EPRJ, recorder D700, f_s = 16Hz and Q = 1027.09hPa

The PRP-W2 system has been configured for research purposes in cooperation with PILC Company. Additional MP-02 on-board equipment includes the miniature PCDL-01 logger and a network of miniature measurement modules (Figure 7), in particular:

- miniature air data computer PCDA-01;
- miniature GPS receiver PCGP-01; and
- miniature inertial measurement unit PCIM-01.

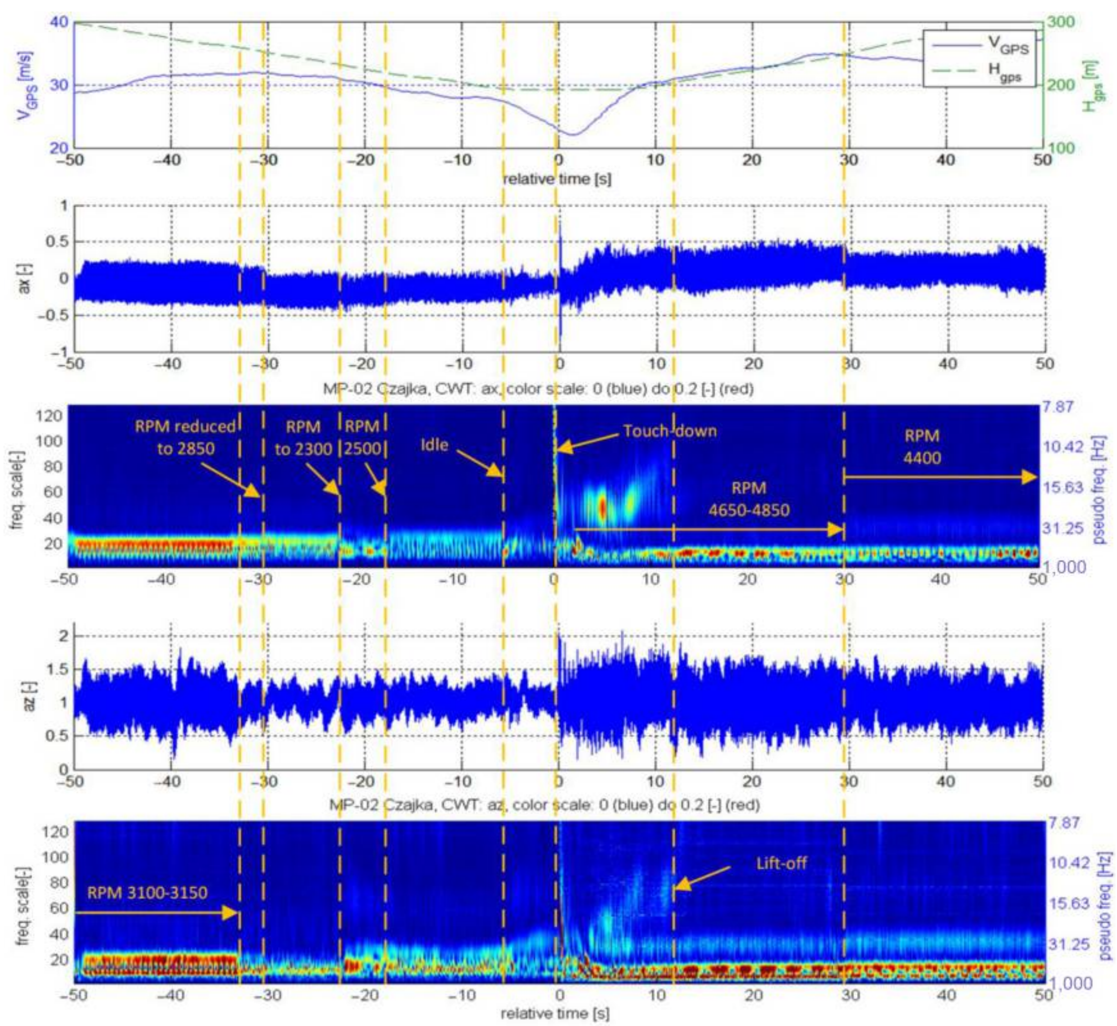
The devices operate according to the CAN aerospace standard, enabling measurement and recording of inertial quantities at a sampling frequency of 1 kHz. Navigation data are captured and recorded at a frequency of 10Hz, while the aerometric data sampling frequency is 100 Hz. Both the D700 and the PCDL-01 allow us to synchronize recorded data with a GPS time reference. In practice, this means the ability to synchronize data sets derived from two independent measurement and registration systems (Szpunar and Rzucidło, 2012; Lamonaca *et al.*, 2014; Hrbac *et al.*, 2015). The D700 system achieves precision in the time domain of 1/16 s. The PCDL-01 and PCGP-01 are designed to be accurate in synchronization with the GPS time-stamp to 0.001 s.

Sample results of vibration-oriented data analysis

Figure 8 depicts changes in altitude, speed, vertical speed, attitude, engine revolutions and the acceleration component a_z over a period of 50 s before and 50 s after touchdown, during routine landing and take-off without stopping (data from the D700 recorder). Data from this recorder include indicated air speed (IAS), true air speed (TAS) and rotation per minute (RPM) data. This set of data (excluding GPS altitude and a_z) is not accessible from the PRP-W2 recorder in this special purpose configuration. The acceleration information obtained from the D700 system is characterized by a quantization level of only up to 0.1 g_e (g_e - standard gravity constant: 9.80665 m/s^2), which in practice makes effective quantitative analysis of this parameter impossible.

When analyzing a set of data recorded by the D700 system (Figure 8), it is possible to identify the touchdown time in the a_z

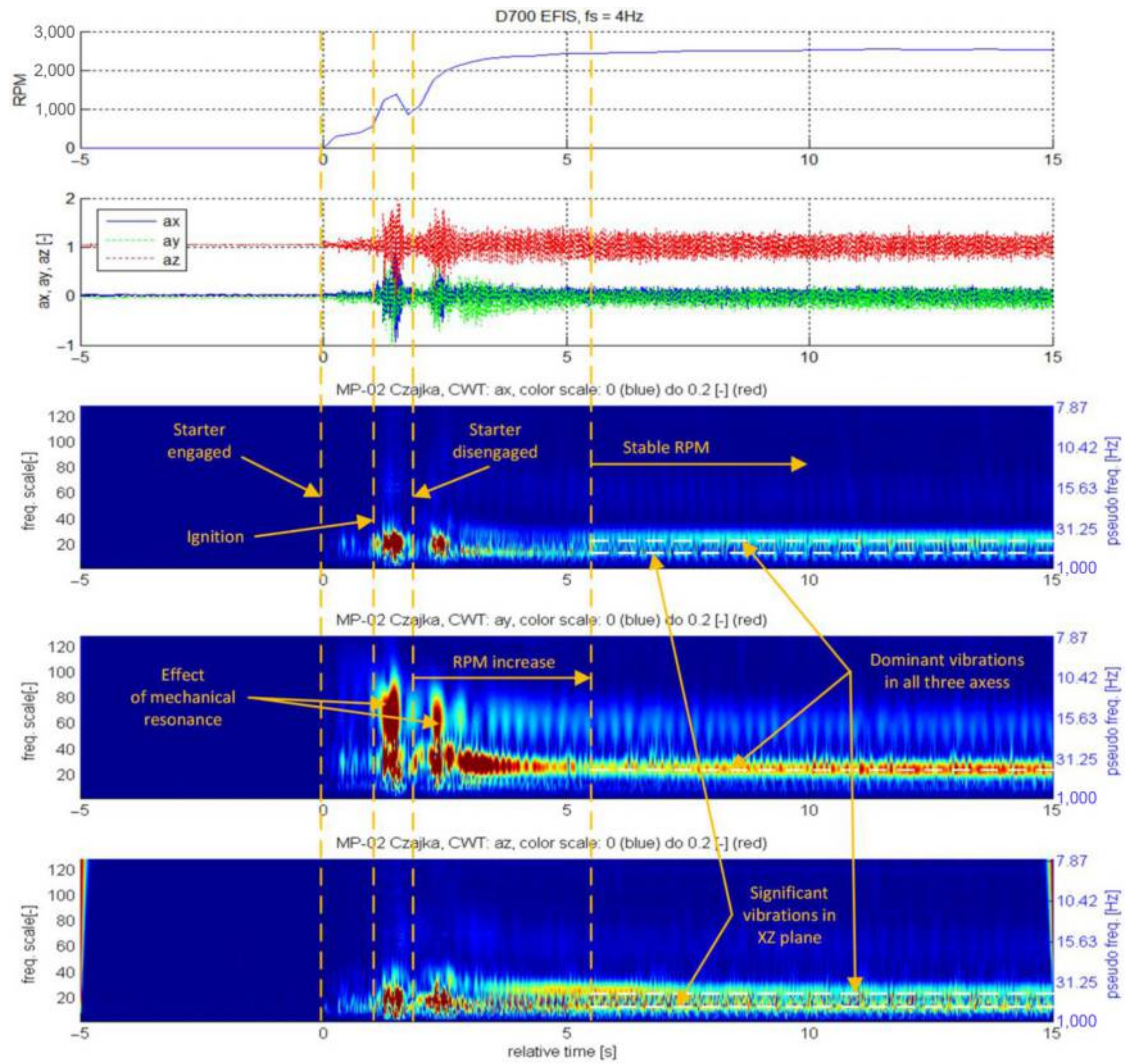
Figure 9 Flight parameters recorded during landing and take-off without stopping, and CWT of ax and az



Note: May 17, 2017, GPS time 10:48:31.9 at relative time 0, runway 08 EPRJ, recorder PRP-W2, f_s = 1000Hz plot (0 s of relative time). The change in vertical velocity VS plays a secondary role in this analysis because of delays in the operation of the aircraft's vertical speed indicator. Barometric altitude, GPS altitude, spatial orientation (roll, pitch) and TAS and IAS speeds have little meaning in the process of identifying the moment of touchdown. The engine RPM, also shown in Figure 8, may be helpful in analyzing acceleration az, for example, to distinguish between vibration of the construction induced by the engine unit and that induced by external forces (e.g. reaction from ground, or atmospheric gusts). By observing a summary of the engine revolutions obtained from the D700 recorder with the continuous wavelet results of a_x and a_z acceleration obtained from the PRP-W2 system (Figure 9), we can see the potential of using correlated data sets from both systems. The spectrum of accelerations subjected to continuous wavelet transform (CWT) analysis has been limited to those below a frequency of 7 Hz (Figure 9), as there are no longer significant phenomena in the touchdown process below this frequency, and the slow-motion phenomena associated with aircraft movement are not as intense and visible here.

The touchdown on the EPRJ's airfield concrete runway is clearly visible both on the timeline and on the graphs showing the modified wavelet coefficients of the ax and az transformations. This event corresponds to the values of the oscillation amplitudes a_x and a_z, which exceed 0.2 (continuous wavelet graphs), with maximum values in the range of 15-30Hz. A detailed analysis of acceleration time plots in the touchdown zone (−1 to 1 second of relative time, Figure 9) shows that ax oscillations reach an amplitude close to 1, while az amplitude exceeds 0.5, specifically in the time range of 0-0.2 s. Vibrations with frequencies exceeding 30Hz are associated with the piston engine unit. Ten seconds after touch down, the chassis tires are

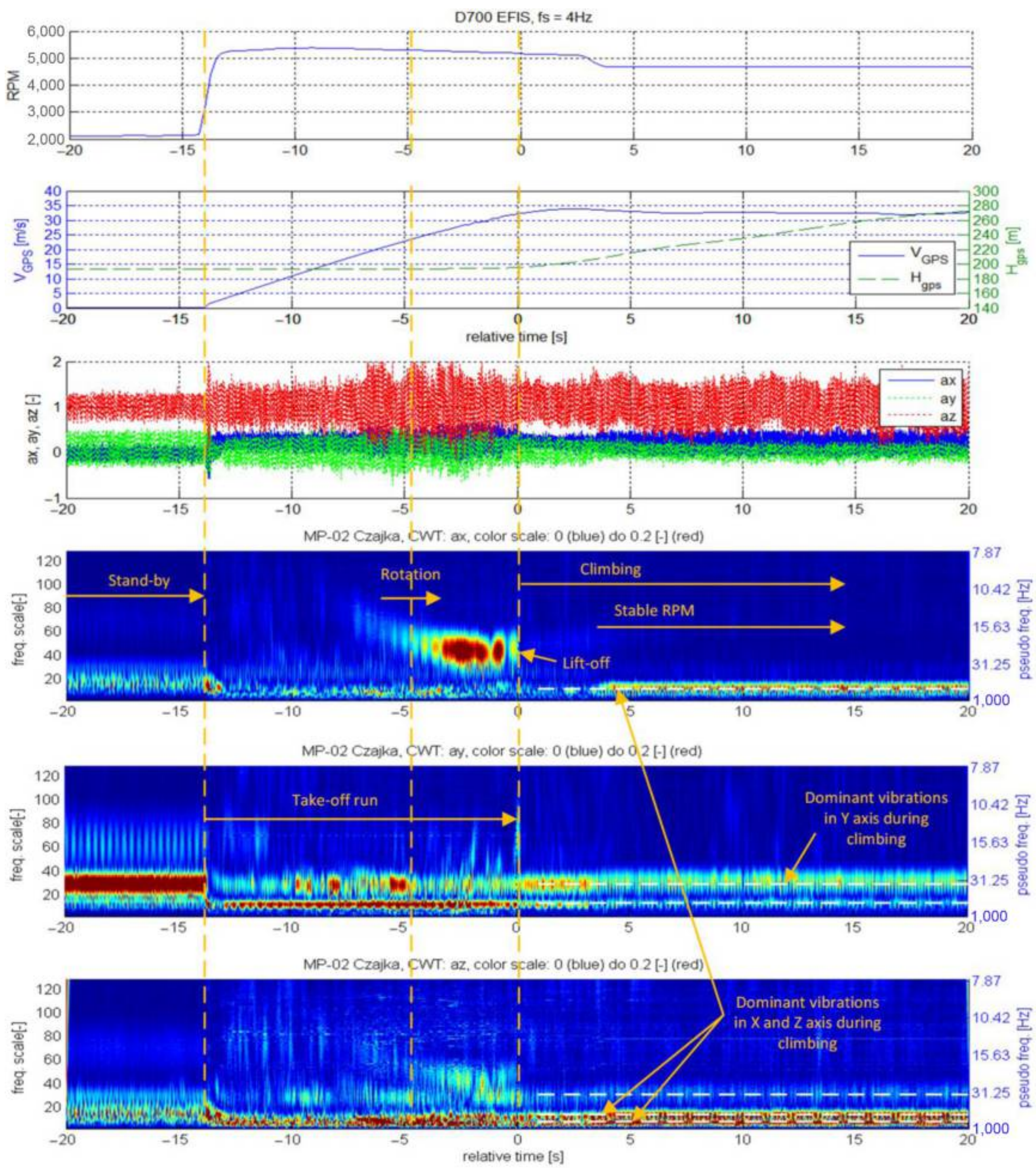
Figure 10 RPM (D700 recorder @4Hz) and accelerations (PRP-W2 recorder @1000Hz) recorded during engine start collated with CWT analysis of ax, ay and az



Note: May 17, 2017, GPS time 10:37:26 at relative time 0, runway 08 EPRJ separated from the surface of the runway and the recorded vibrations transmitted through the fuselage onto the measuring system housing ceases.

Figure 10 shows the flight parameters recorded during engine start. The MP-02 airplane is equipped with a spark ignition gasoline Rotax petrol engine. It can be observed from the figure that relative time has a value of 0 for the moment the starter was switched on. Up until this point, no phenomena are visible on the CWT acceleration charts. On the time courses, only accelerometer noise is visible. According to the instructions for use, spark ignition occurs after exceeding 200 RPM. This value is exceeded around the first second, and this process is accompanied by strong vibrations whose amplitude in all three axes is close to $1g_e$. From the CWT diagrams, the frequencies of the strongest vibrations whose center frequencies are 50 Hz (for a_x and a_z) and 15 Hz and 25 Hz respectively for a_y. At around one second after there is a momentary RPM drop associated with the disconnection of the starter, followed by a smooth increase of revolutions up to 2,500. In the steady state of engine operation, vibrations with frequencies of 40 and 80 Hz dominate in the *x*- and *z*-axes, respectively, while in the *y*-axis 40 Hz vibrations are clearly visible.

Figure 11 RPM (D700 recorder @4Hz) and accelerations (PRP-W2 recorder @1000Hz) recorded during take-off collated with CWT analysis of ax, ay and az



Note: May 17, 2017, GPS time 10:43:16.5 at relative time 0

Figure 11 shows selected flight parameters recorded during preparation for the flight and during take-off of the MP-02 aircraft. While waiting for the start, the engine runs at 2,100 RPM. Similar to Figure 10, one can see the analogical character of vibrations in all three axes. After increasing the revolutions to over 5,100 RPM, the take-off run of the aircraft begins. It is accompanied by vibrations originating from the drive unit and vibrations arising as a result of the dynamic response of the chassis with the ground. The intensity and frequency of vibrations increases with increasing speed. This phenomenon is clearly visible in the x-axis on the CWT results. At the moment of the plane's liftoff, these vibrations abruptly cease.

Detection of the moments both of the aircraft touchdown (Figure 9) and liftoff (Figure 11) can be very problematic and imprecise, particularly if we refer only to the time series of such parameters as the altitude and speed of the flight. Time charts of accelerations, especially if recorded at high frequency, can enable precise localization over time of many selected phenomena related to aircraft operations. The additional CWT analysis of the recorded data is particularly helpful in this respect.

Conclusion

This paper presented work which has been done during both the development and test phases of the PRP-W2 measurement system. It was proven that the strict design requirements for the solution were fulfilled. The proposed system can be adopted and used even for such complex tasks as vibration analysis of UL aircraft, including potentially the creation of a vibration map of the airframe. Advanced vibration and oscillation measurements are also planned for the board of the experimental low power single engine turbo-prop I-31T aircraft using the present system. The lightweight nature and flexibility of the system means that it can be used in numerous advanced flight tests on objects that have not been able to be tested in this way until now.

Further plans are to test the system on Unmanned Aerial Vehicles (up to 5 kg) and also to use modules provided from PRP-W2 as source of information for control systems and not only the data acquisition systems.

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