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Coupling of MEMS gyroscope application with wavelet analysis for detection of airframe oscillations in flight conditions

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Abstract:
The gyroscopes established one of the fundamental reference for attitude and heading in aerospace applications. The information about angular velocity gives input not only for autopilot, but also damping devices, as yaw or pitch dampers for example. The MEMS gyroscopes (Micro Electro Mechanical Systems) are much less reliable than their laser or fibre optic cousins. Nevertheless, availability and low price of MEMS components cause growing area of application in avionics for General Aviation aeroplanes. This paper presents certain results of flight data analysis registered during flight testing campaign of the new class aeroplane – experimental low power single engine turbo-prop utility I-31T. The researches were focused on identification of oscillation modes, distinctive for the new aircraft, such as engine precession, whirl or shimmy. The data came from three-axis MEMS gyroscope recorder, placed near to the aircraft centre of gravity. Wavelet transformation gives better precision in time domain than Fourier transformation, especially for signals of low frequency.

Key words: Flight-test, MEMS, load-spectrum, wavelet analysis, I-31T.

1. Introduction

The development in the field of aeronautical engineering is always connected with research activities of high-risk. The incessant rush in improving of introduced solutions is entailing desire for their immediate implementation from one side, on the other, however, we are dealing with the quite natural conservatism firstly putting the protection of human life. The awareness of the great responsibility accompanied designers from the very beginning – Wright brothers, while manufacturing their aeroplane, known later as No.1, considered strength of each element to cope with the weight 5 times greater than mass of the pilot [18]. The methodology of research has been established and proven starting from ground static and stiffness tests to testing in flight. Within the decades, they were supplemented by many other, today inevitable, tests, such as flutter, vibration, fatigue to mention only few, most important. The whole array of tests and trials before putting a new aeroplane to the market has the only one goal – to eliminate all unwelcome features, may affect badly on her future career. In the course of the technological progress, the metrologies advance, giving wider cognitive abilities through more accurate and more extensive registration abilities, as well as practically any form of processing and presenting results. On the other hand, however the benefit of progress is giving rise to negative side effects in the form of extending the time of research works, and hence their cost, the number of different systems and the need for their mutual harmonizing. As a result, the number of new aerospace vehicles is decreasing constantly, comparing to the rising costs of development. So called 14th Augustine's law gives an excellent illustration [2], telling in subversive manner about the escalation of U.S. Air Force airborne research programs: *In the year 2054, the entire defence budget will purchase just one aircraft. The aircraft will have to be shared by the Air Force and Navy, 3.5 days each per week except for leap year, when it will be made available to the Marines for the extra day*. The simplification of metrologies, measurement software and hardware and the tests at large would seem reasonable in the light of budget optimizing. Nevertheless, one may be wrong, forcing the simple „back to the roots" solution. Although, whenever paper and pencil should lay on the desk. Test planning should follow towards the search for new applications of advanced but simple in general metrologies in unexplored areas. A significant indicator for the new application would be a number of

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parameters and number of samples measured during the test. The methods utilizing a reduced number of entry parameters become crucial for total time of the test program, especially in-flight. As an example one may recall a group of “bootstrap” methods [16].

One of the most important information recorded during the flight, furthermore not only in the development phase, but also during the entire life of the structure, is flight loads spectrum of the whole airframe and individual parts as well [21]. Early attempts of flight loads recording in organized manner are dated as soon as the dawn of modern aviation [7]. Familiarity with aeroplane accelerations gives not only information about the load factor the structure is exposed to during sustained or instantaneous manoeuvres. The coupling of the load magnitude and exact aeroplane attitude in the time history enables to find a load spectrum, inevitable for preparation of long-term ground fatigue tests. The essence of such data might be underlined by the fact that their importance does not terminate when the fatigue durability tests of the new structures were completed successfully. There may come time for revisiting the data when the aeroplane would serve for many years and problems of ageing will appear [11].

Increasing the sampling frequency of the measurement device gives ability to register not only low-cycle flight loads, but also faster spectra, such as vibrations originated by propulsion or turbulence, also aeroelastic response of the structure. Proper comparison of this data with the results of Ground Vibration Tests (GVT) makes ground for identification of resonance.

The gyroscopes belong to the group of sensors widely utilized for low and high cycle loads recording. MEMS accelerometers in 1990s found their application to air-bags activation systems in automotive. But they become widespread in household and hobbycraft electronics due to their small size and relatively low price. The aerospace industry absorbed them as well, especially in avionics for General Aviation light aeroplanes [14], [24] or systems onboard of RPAS [10], [19].

This paper presents a preliminary study of acceleration spectrum flight data analysis with continuous wavelet transformation [1]. The airborne measurement device based on MEMS gyroscopes and was placed on board of a light turboprop utility aeroplane. Several examples with unique frequency representations of different flight states have been presented to illustrate the method.

2. Aeroplane and flight testing

The measurements took place on the I-31T aeroplane (Fig. 1), the advanced modification of the I-23 *Manager* aeroplane [5]. Both crafts were designed in Institute of Aviation, Warsaw, Poland. The origins of the aeroplane reach back to early 1990s. The light, piston engine powered, high performance, equipped with advanced avionics aeroplane belonged to the chain of Small Air Transport System. Following worldwide crisis in General Aviation sector caused that only sole prototype has been built. But the idea to build a transportation system in Europe with door-to-door operation time less than four hours left in minds and became one of the core directions in the aviation development today [23], being focused on personal aeroplanes propelled by small engine units [17]. Introduction of low power, below 200kW, turbine engines for propeller propulsion gave opportunity to create a prototype of a new aeroplane class, reconciling handling and performance of a light General Aviation aeroplane with economy and simplicity of turbopropeller engine.

Fig. 1. I-31T aeroplane during one of the test flights.

The I-31T aeroplane has been designed and manufactured as one of several technology demonstrators in large, international, collaborative European project ESPOSA (Efficient Systems and Propulsion for Small Aircraft) co-funded by European Commission with the 7th Framework Program [9]. The concept of a new aeroplane class has been proven during the flight test campaign led by Institute of Aviation, Warsaw together with Rzeszów University of Technology. But the fundamental remark for similar future initiatives says that this class of aeroplanes must not be developed by ordinary conversion of previously piston driven aeroplanes into turbine. The design should be dedicated for the propulsion exclusively to share all benefits of the new propulsion.

Flight test campaign of the new I-31T aeroplane covered all items described in CS-23 requirements, inevitable to prove conformity [6].

Certification test flights were organized in rather classic, conservative manner, bearing in mind the simplicity of the aeroplane. The main recording of the flight parameters has been left for the eye and hand of the Flight Test Engineer (FTE), who was accompanying the test pilot side-by-side during the flight. Independent recording devices were used supplementary for certain measurements of rather scientific nature, e.g. temperature distribution.

The measurement data analysed in this paper came from the flight data recorder (FDR) installed on board, inside the cabin, close to the centre of gravity, which enables to record following parameters with sampling frequency of 50Hz [15]:

- accelerations a_x, a_y, a_z;
- angular velocities p, q, r;
- orientation angles;
- static pressure;
- GPS navigation data (10Hz).

The recorder is an advanced modification of the device designed and manufactured in Rzeszów University of Technology for flying laboratory based on PW-6U glider [3] used in second edition of Advanced In-Flight Measurement Techniques (AIM2) project.

The FDR was put into operation before the flight by FTE and switched off after landing. The data set recorded on SD memory card, was transferred on PC hard disk and processed in dedicated software commercial as well as created in house.

Besides the independent, impartial data recording by the FTE and FDR, the opinions of the test pilots about the handling and other feelings were collected in the disciplined manner [12].

3. Measurements results and discussion

This paragraph deals with several examples of cycle load spectrum analysis recorded during test flights. The emphasis has been laid on the movement of the aeroplane on the ground, due to the fact that these recordings initiated presented research.

Landing and ground manoeuvres

The I-31T aeroplane operated from concrete runway surfaces. Her approach and landing qualities were assessed at the 4 to 5 grade in the Cooper-Harper scale [12]. The aeroplane has a wing loading of 115kg/m^2, which locates her in the upper range in the class. This implies a high approach and landing speeds. Additionally, high effectiveness of elevator and marginal longitudal stability, decreased by a long nose of the new propulsion, require higher pilot's concentration. The flare phase is rather figurative. To summarize, the aeroplane is characterized by short landings in a "carrier-like" style.

One of many landings, at three points and quite "hard", on wet runway with centreline lamps touched by the front wheel during roll-off finished with *shimmy* vibrations of the front undercarriage, which ceased when the aeroplane came to a halt completely.

Shimmy occurs when a wheel oscillates at often large amplitudes about its vertical axis about which the wheel rotates. For light aeroplanes it is common for front gears with one wheel and manifests itself as a limit cycle oscillation with a frequency range typically 10-30 Hz. The most common reasons are inadequate torsional stiffness, torsional freeplay, wheel imbalance, etc. It is normally countered by careful design or use of dampers. The I-23 aeroplane, progenitor of I-31T, has been equipped with shimmy damper during her flight test campaign, but it was removed and no complaints has been recorded so far. Indeed, a quick maintenance after this particular shimmy incident revealed an excessive freeplay in front steering mechanism.

The FDR on board of the aeroplane recorded data on attitude of the aeroplane, navigational parameters and information from the accelerometers and MEMS gyroscopes. The sampling frequency reached 50Hz and it allows for detection and analysis of phenomena at 25Hz or less.

The vibration of the aeroplane during roll-off, caused by shimmy of the front gear, were clearly recognizable by the plane crew and felt on the background of other motions of the aeroplane. Therefore, it might be assumed, the FDR should also register them in a certain manner, e.g. oscillations of angular velocities or linear accelerations.

In the first step, several recordings of different landings including final approach, flare, touch down and roll-off were investigated. The crucial moment to distinguish the moment, the aeroplane leaves the air and starts to ride on the ground is identification of wheel contact with the pavement. The main gear contact was identified by analysis of n_z change in comparison to change of altitude and ground speed (Fig. 2 A-B, G). The touch of the front gear is better visible after continuous wavelet transformation (CWT) of all three components of acceleration n_x, n_y i n_z (Fig. 2 D, F, H). But the most repeatable results, regardless of the landing quality were obtained for the n_x component.

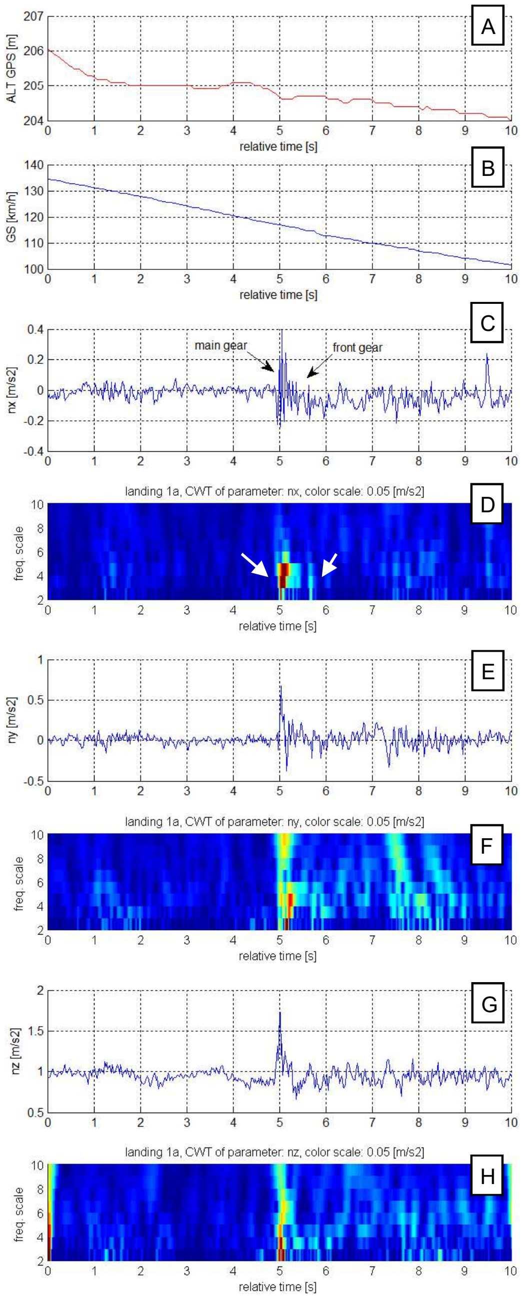

Fig. 2. CWT analysis graphs for main and front gear touch down moment detection (landing No.1a). Charts present respectively: A – altitude [m], B – ground speed [km/h], C – n_x [m/s²], D – CWT analysis of C, E – n_y [m/s²], F – CWT analysis of E, G – n_z [m/s²], H – CWT analysis of G, in time domain span 10 [s].

There is always short term vibration along the longitudinal axis (Fig. 2 D), which concentrates close to the value of 5 on frequency scale (that means 10Hz, according to Fig. 3). The frequency as well as amplitude of n_x oscillations are not correlated with n_z component, which denotes the "hardness" of the landing. Therefore CWT analysis of n_x may be sufficient for effective touch-down identification with accuracy of 50ms. The colour shade in Fig. 2 D, F and H denotes vibration amplitude. Dark blue is equal to "zero" and purple – limit amplitude, defined as colour scale in CWT charts.

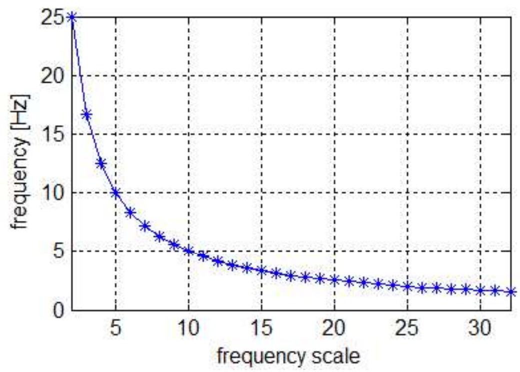

Fig. 3. Complex Morlet wavelet dependency between central frequency and frequency scale.

The landing analysed in the Fig.1 (landing no.1a) may be assumed as regular one with smooth touch-down. During roll-off there were no disturbing phenomena. Shimmy vibrations appeared during the roll-off recorded in landing no.2a. This kind of oscillatory movement is hard to identify in acceleration and angular velocity time plots, however they manifest as high frequency occurrence (frequency scale 2 to 10) from 2nd to 7th second in CWT chart of n_y. In the 4th second there is short braking action of the pilot (Figs. 4 B-C, 5 C-D), that caused unexpected increasing of amplitude. When the aeroplane groundspeed was below 75kph (Fig. 4A), the vibrations of high amplitude occurred, clearly visible as change in acceleration along y axis (Fig. 4D-E). Resembling characteristics may be found on time plots as well as on CWT charts of n_z (Fig. 4F-G) and velocities p and r (Fig. 5A-B and E-F). The analysis of n_x load and angular velocity p reveals two attempts of braking action initiated by the pilot between 11.5s to 13s, and following from 18.5s to 24s. Each breaking increased the amplitude with maximums recorded in 12.5s, 19s and 23s respectively. In the second 23 vibrations of n_y reached 1m/s², remaining n_x and n_z had amplitudes lower by half.

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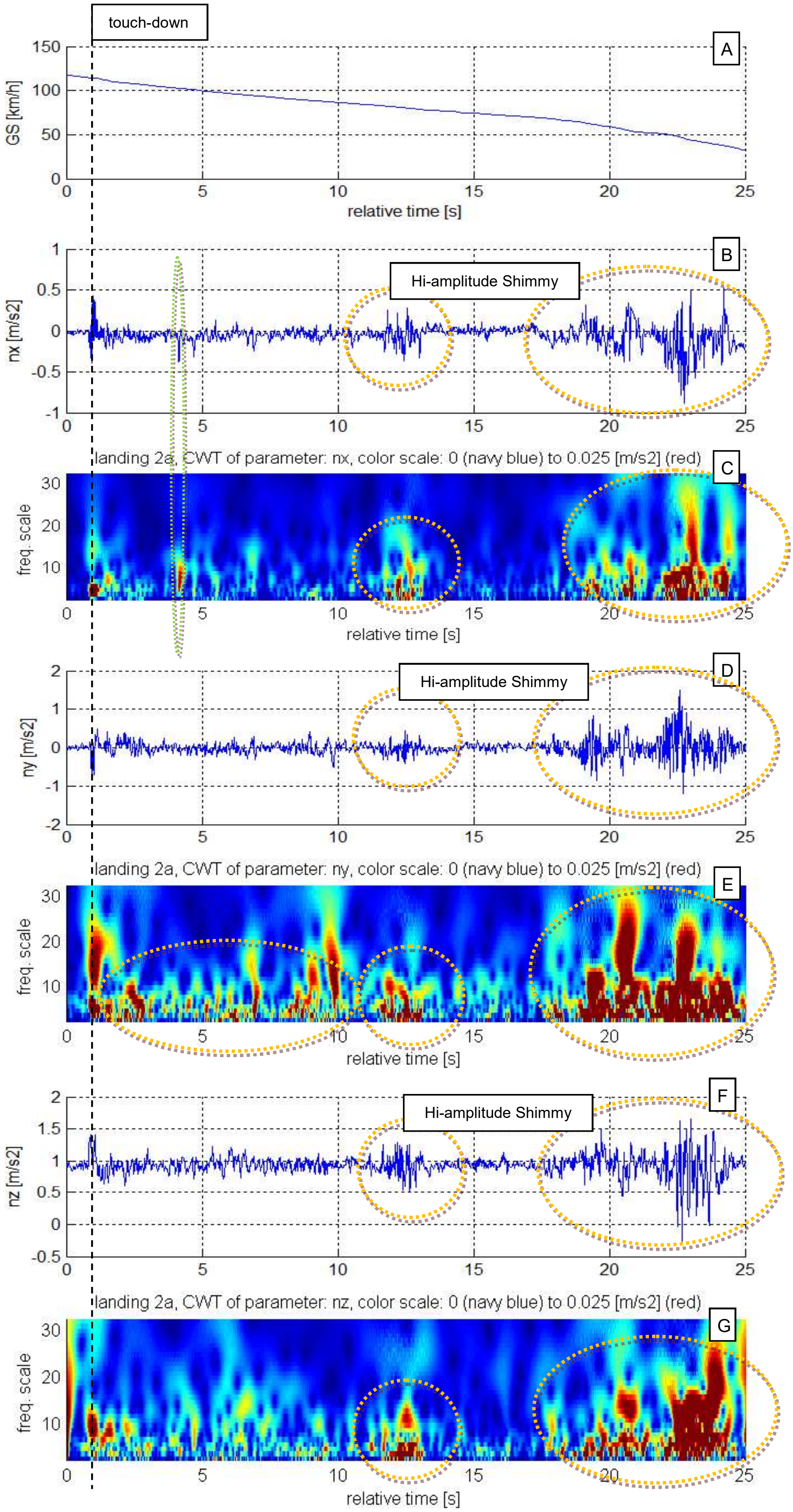

Fig. 4. Load factors analysis, recorded during the roll-off with shimmy vibrations of the front gear (CWT analysis with amplitude normalised), landing no. 2a.

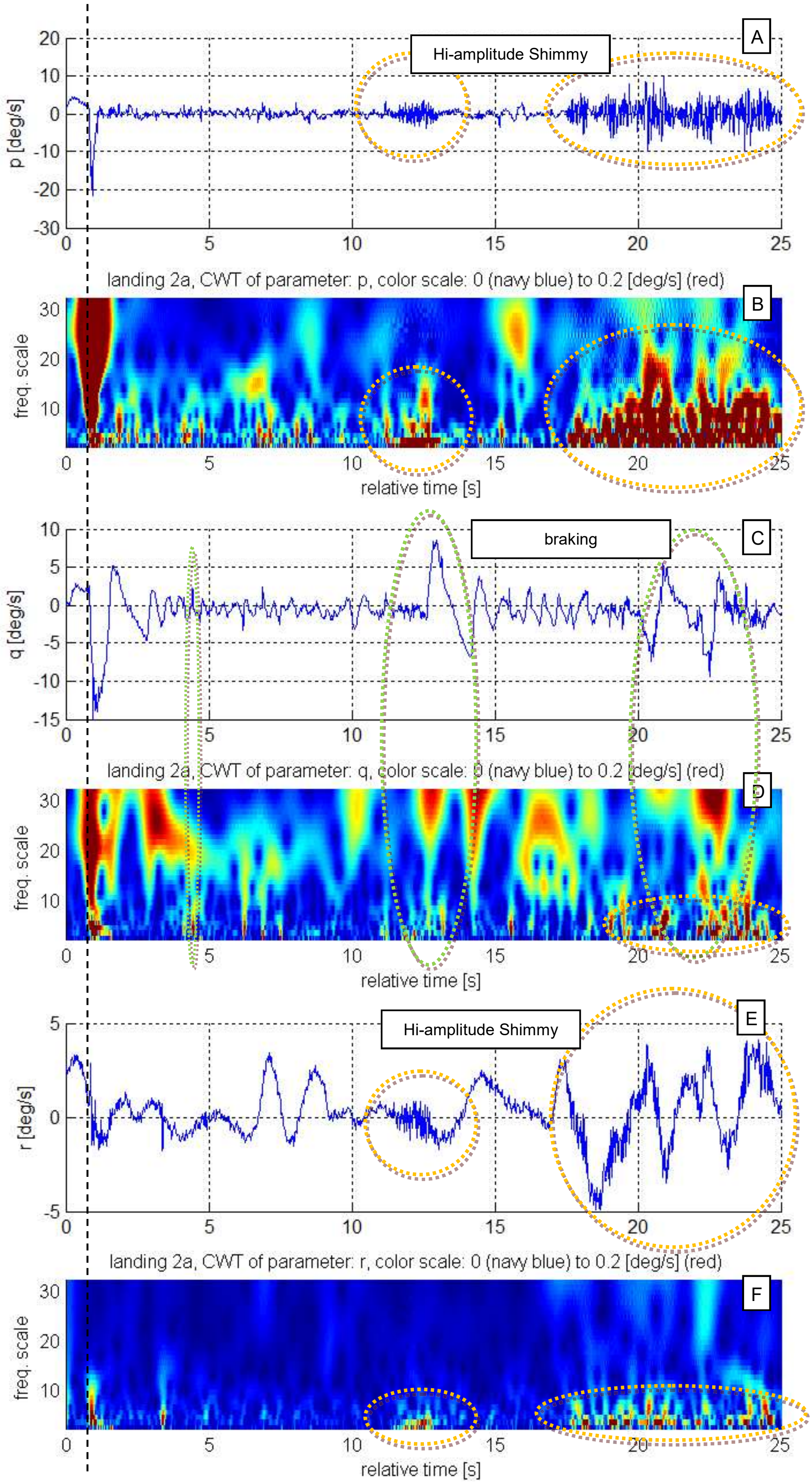

Fig. 5. Angular velocities analysis recorded during the roll-off with shimmy vibrations of the front gear (CWT analysis with amplitude normalised), landing no. 2a.

One may notice, analysing CWT charts of n_y and *p* in Fig. 4 E, 5 B, that between seconds 2 and 14 the spectrum is dominated by vibrations with frequencies 3 to 4 (normalised). According to the Fig.3, it represents frequencies between 12 and 17Hz. In second 17 and further, when the aeroplane groundspeed decreased below 60kph, high amplitude vibrations of n_y and *p* arouse gradually, having frequencies in middle of the scale between 10 and 20, that represents frequencies of 5Hz and 2.5Hz (Fig. 4E, 5B). The other accelerations and angular velocities were affected similarly, but with mush less effect (Fig. 4-5). After second 24, when the aeroplane groundspeed decreased below 40kph, the vibrations ceased. The pilot claimed, that the only possible solution to damp the vibration was to halt the aeroplane. Rolling with the groundspeed higher than 40kph caused increasing of the amplitude.

It should be underlined, any other landing in the set of 20 recorded did not contain similar characteristics during roll-off.

The vibrations described above and recorded by FDR represent the effect of interaction between shimmy oscillatory movement of the front gear and the rest of the airframe, an finally the FDR itself. Therefore this spectrum (frequencies and amplitudes) does not represent the behaviour of the undercarriage, and cannot be applied directly. Moreover, the shimmy vibrations belong to the oscillatory movements with more than one degree of freedom. But concerning the effects of shimmy vibrations on the rest of the airframe, the spectrum in this form would give useful information about frequencies and “severity” of the vibrations.

The Fig.6 presents the whole recording from the short “hoop” flight between two parallel runways. There are angular velocities *p, q, r* in the time domain (Fig. 6 B, E and H) starting from the short holding time before take-off and terminating at taxing to the apron (Fig. 6 A). This analysis does not present accelerations, due to troublesome interpretation of a vast number of oscillations.

In the Fig.6 take-off and touch-down were identified. It might be noticed in the CWT chart of *p* angular velocity (Fig. 6 C-D), when aeroplane is on the ground the spectrum is dominated by high frequencies from the engine. During roll on and roll off they are close to 3Hz, but there is no distinction between the engine itself and rolling. After lift off this band ceased and frequencies of 5Hz and higher are still visible (especially p, Fig. 6C), moreover, there is also band of 10Hz (for *q* and *r*, Fig. 6F, I). We presume the main source of the vibrations mentioned in flight is the engine and variation in *N1* revolutions. Unfortunately, at this level, further analysis seems to be rather complicated, due to the fact that sampling frequency of the FDR is only 50Hz, that means the highest vibration frequency possible to detect is 25Hz.

The frequencies below 3Hz contain a wide set of natural frequencies of weathercock and longitudal motions. In the Fig.6 G one may notice oscillations in pitch with mean frequency of 1.25Hz (velocity *q*). Their amplitude is increasing in moments of levelling off or when descent starts, but also during the approach to land. They may be explained as short period pitch oscillations. Similarly, dutch roll motion may be identified. In the Fig.6 J, there is a constant directional motion with mean frequency of 0.7Hz motion (velocity *r*), which is correlated with *p* oscillations of the same frequency (Fig. 6 D).

In the Fig. 6J there may be noticed also short period oscillations of *r* with mean frequency of 1.25Hz. We presume, the source would lay in gyroscopic moments caused by longitudal oscillations with similar frequency.

The aeroplane control may also have form of oscillations, especially when man-machine feedback loop is cauterised by short time constants [13]. Such behaviour may occur when pilot is focused on precise flight parameters, e.g. during precision approach and landing or following certain trajectory defined by dedicated flight instruments in both examples. While the aeroplane approaches the runway, the closer the threshold, the shorter the time constant, therefore the higher control frequencies. Although all landings during the flight test campaign were performed with reference to the external objects (not instrumental), the analysis revealed similar behaviour. In the Fig. 6D the roll frequency during take-off and final approach is close to 1Hz, but in the entire flight is much lower, about 0.3Hz.

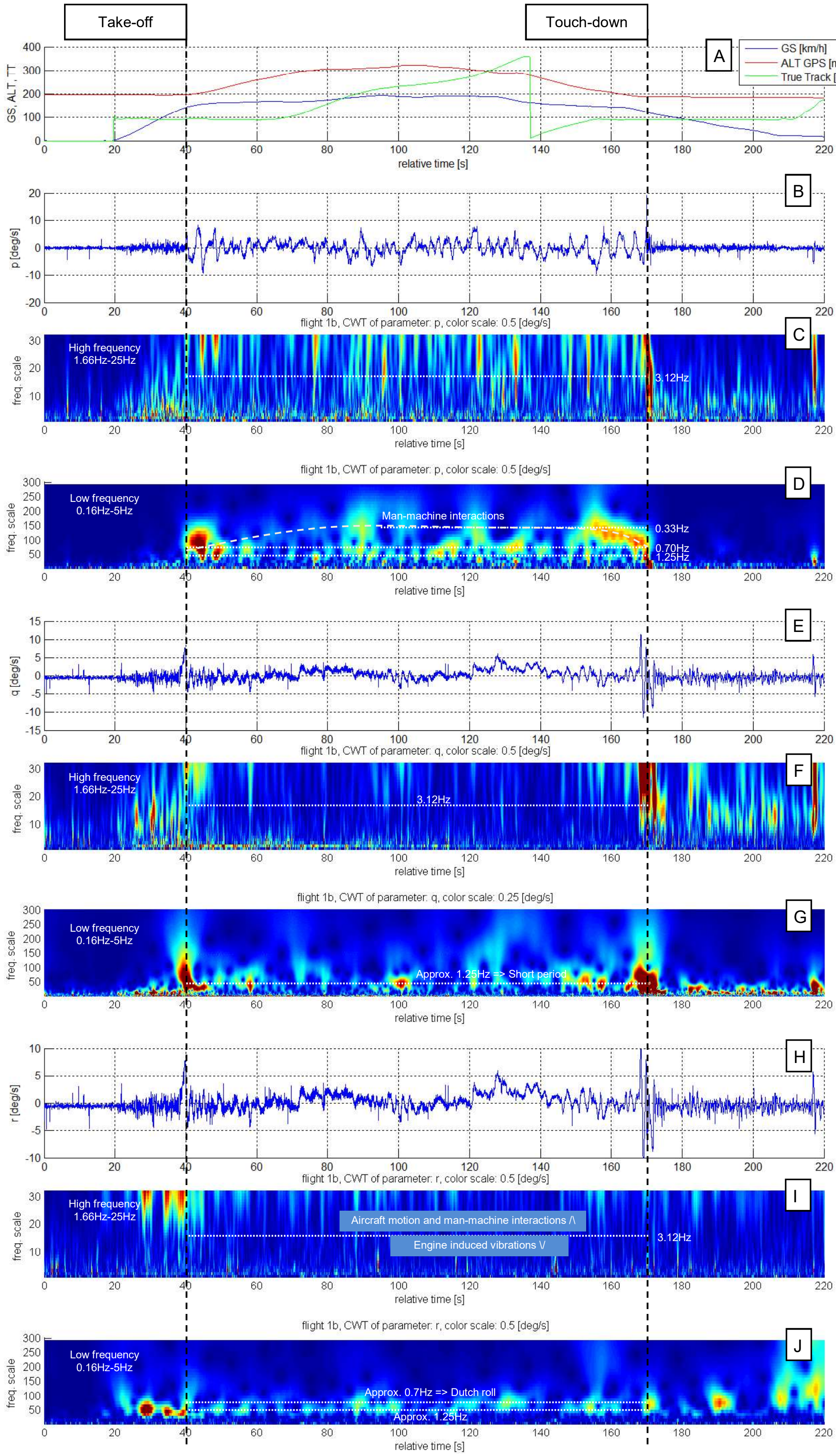

Fig. 6. Angular velocities analysis recorded during a short „hoop" between two parallel runways (CWT analysis with amplitude normalised) Flight no. 1b.

4. Summary

In the presented paper authors introduced examples of wavelet analysis of load spectra recorded with MEMS gyroscopes during the flight testing.

The wavelet analysis of accelerations and angular velocities supplemented with time plots of several other parameters, when appropriate, and having description of flight provided by the pilot, could be applied for aeroplane load analysis during the flight based on data from simple recorder unit.

The continuous wavelet analysis method makes easier the interpretation of high frequency vibrations of airframe induced by propulsion, undercarriage and the airframe itself, as well as the phenomena which take place in flight, such as dutch roll, short period oscillations, gyroscopic torques, but also man-machine interactions. There is also possibility to identify several longperiod phenomena, such as phugoids or gusts.

This paper introduces the method, which seems to be worthwhile for further development, especially towards higher frequencies. Regarding such phenomena, as flutter or comparison with Ground Vibration Tests (GVT) the recording device with at least 200Hz sampling frequency should be applied. The lowest eigenvalues for the I-31T aeroplane start from 8 – 9Hz and concern less probable modes. The eigenvalues connected with airframe deformation which may result in flutter start from 25Hz [7].

The results of analysis allow to identify also flight characteristics of the aeroplane. At this level we may not consider them as full handling qualities analysis due to the fact that several other parameters are still missing.

The other potential application of this method would be academic education. The courses of data analysis, handling qualities or flight testing seem to be still uncommon in aerospace engineering studies [22]. Rzeszów University of Technology has a flying laboratory based on Piper Seneca V aeroplane, equipped with additional devices on board, including FDR, similar to the described one [4], giving the opportunity to incorporate such analysis into study programme.

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