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DEVELOPMENT AND FLIGHT RESEARCH OF NON-INTRUSIVE AIRBORNE SYSTEM OF PILOT PSYCHOPHYSIOLOGICAL STATUS MONITORING

Mironov A.D., Nakvasin A.Y.
State Scientific Centre of the Russian Federation
GROMOV FLIGHT RESEARCH INSTITUTE (LII GROMOV)
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Abstract

Systems continuously monitoring crew member psychophysiological status implemented in the advanced aircraft avionics suit will become effective measure of flight safety promotion, as more than 70% flight accidents are connected to «human factor». Standard recording equipment on modern aircraft records up to several hundred different indexes for monitoring flight parameters and on-board equipment technical state, but the status of the key element in accidents prevention – pilot is still beyond the scope of standard recording. It is connected to high processing complexity of implementing polygraphic methods of pilot psychophysiological status continuous monitoring on board the aircraft, as generally they were developing as laboratory research methods. During experiment preparation and realization these methods assume special conditions provision and direct involvement of highly-qualified specialists, which does not allow transfer of the primary methodology without deep adaptation to production aircraft cockpit for mainstream use.

The given report considers some aspects of development and flight tests in Flight Research Institute of non-intrusive airborne system of pilot psychophysiological status monitoring, that allows to conduct monitoring independently without the necessity of sensor installation on pilot's body and outfit and without introduction of additional tasks for the pilot, as well as other non-specific, not connected to common working load impacts.

1 General Introduction

Professional activity of the crew in heavy transport category aircraft runs in severe physical and information environment, which except for other operative factors, is defined by continuous staying in flight and growing fatigue because of noise and vibration exposure in enclosure. In long duration flight the probability of the situation aggravation increases due to weather conditions variation along the flight route and technical failures. Moreover, there are strict requirements for the pilots imposed by modern aircraft control concerning data processing and decision speed, especially when two or more complicating factors work simultaneously. In such cases there is a high risk of critically adverse crew psychophysiological status development during the flight because of the fatigue and stress. Investigation materials of several flight accidents in 2004-2008 [5,6], received from Interstate Aviation Committee (IAK) in the area of aviation psychology and human factors, showed that adverse pilot psychophysiological status in the context of his current functional reliability evaluation in most cases manifests itself in the initial phase of accident development as attention tunneling and difficulty in flight data processing. Further comes destruction of flight parameter perception integrity or in other words mentation fragmentarity. For example during the roll with asymmetric thrust reverse, pilot insistently tries to prevent the aircraft overrunning to the runway shoulder, however he does not monitor thrust rating and runway speed. The last stage of air accidents development is characterized by acute stress reaction, accompanied by either pilot's complete functional freezing or by inadequate chaotic activity outburst. Escalation to emergency or catastrophic situation can be excluded only by prevention of crew psychophysiological status transfer to the phase of critical attention tunneling and difficulty in data processing. But it is prevented by preliminary accumulated fatigue and perhaps persistency of sustained passive perception of flight information in monotonous environment.

In cases under consideration [5, 6] pre-flight medical monitoring procedure didn't diagnose prerequisites for dangerous pilot psychophysiological status alteration in the forthcoming flight, as at the moment of examination all the monitored parameters were normal. Also insufficient efficiency of normalized duty time system and pre-flight medical monitoring system became one of the main reasons for resonant air crash of flight 3407 Colgan Air in Buffalo, New York, February 12, 2009. The results of its investigation revealed the leading role played by the factors of both pilots' chronic fatigue and accumulated sleep-debt.

It is a common fact, that transport pilots working time often contradicts natural sleep-wakefulness pattern, especially during long-lasting flights involving time zone change. Also, psychological pressure on the crew is generated by the awareness of possible flight accident drastic consequences, the reason for which is often a combination of unforeseen and uncontrolled phenomena. With insufficient efficiency restoration (especially against the sleep disorder background) it can cause chronic fatigue and stress and also result in cumulative fatigue which they often conceal during pre-flight medical examination.

Cause analysis of many air accidents brings out clearly that control of stress and fatigue factors only by conservative methods (by common pre-flight medical examination and crew flight and duty hours normative regulation) very often turns out to be ineffective, as it does not consider objective individual and group statistics of pilot psychophysiological status variation under the influence of real workload in flight. This information, in return, is not available without usage of airborne system of crew psychophysiological control and risk management technological system, connected to fatigue and critically adverse psychophysiological status.

Since 2011, after 3407 Colgan Air flight air accident investigation, there has been the growth of activity in aviation community concerning promotion of risk control technology, connected to pilots fatigue. Resolution of the 37th session of ICAO Assembly puts «flight safety improvement» and particularly crew fatigue control as one of three main objectives for the nearest future. Within the last three years ICAO Counsel has accepted amendments № 35, 36, 37-A to International standards and Recommended practice in Part I Annex 6 «Aircraft operation» [1], which introduce in Chapter 1 corrected definitions of «Fatigue» and «Fatigue Risk Management System (FRMS)», and in Chapter 4 point 4.10. – «Fatigue control» with Annex 7 – «Requirements to FRMS». ICAO has also developed manuals for operators [2] and regulatory authorities [3] on FRMS implementation.

The given regulatory documents actualize development for the serial operation of crew status control technical means as hardware of risk control technology, connected to fatigue and negative psychophysiological conditions. The authors of this report put forward for consideration several aspects of development and flight tests of experimental non-intrusive airborne system of pilot psychophysiological status monitoring in Flight Research Institute.

2 Method

2.1 Applied measurement method

In modern psychophysiology a wide range of signals and calculated parameters, which indicate the current organism subsystem status are used for human functional state (FS) measurement in laboratory environment. In professional publications there is a wide range of study materials connected to this topic, instrumental basis for which are such methods as: electrocardiography and pneumography, functional magnetic resonance imaging, encephalography, electromyography of different muscle groups, and also methods based on galvanic skin reaction and blood biomedical measurement change analysis. In a separate group there should be placed a human operator (pilot) FS measurement methods suitable not only for laboratory study but also for standard aircraft flight. Such methods shouldn't require measuring equipment allocation on pilot's body and outfit, shouldn't impose subtasks and change usual procedures in the cockpit, and generally, shouldn't have nonspecific (not connected to typical pilot workload) impact. Commonly such methods are called non-intrusive, this group includes FS speech diagnostics, ballistocardiography[7], ocular and eyelid movement reaction analysis through video image, posturography in sitting position[4] etc.

Each currently used method has its own individual restrictions. For that reason researchers specializing in human operator FS measurements tend to use several biological signal sources simultaneously, thus enhancing message comprehension and measurements reliability based on them. Such method is used in modern polygraphy (including so called «lie detector» research methods).

Polygraphic measurement methods implementation on the aircraft inevitably cause difficulties connected to a large number of measuring equipment integration into modern aircraft equipment closed system. It should be also taken into account that during experiment preparation and performance these methods suggest special conditions provision and high-qualified specialists direct involvement, that does not allow to transfer the primary methodology without profound adaptation to production aircraft cockpit for mainstream use.

Within the development in Flight Research Institute of risk management technology connected to pilot fatigue and critical negative psychophysiological status occurrence, there have been worked out and now being flight-tested and developed experimental techniques and hardware for psychophysiological crew status non-intrusive monitoring during long-term flight. This method is non-intrusive (sensors are placed in the pilot seat), self-contained (measurement arrangement and data collection are automatic and do not require presence of a high-qualified specialist on board), has a low implementation cost. The closest analogs with similar signal measurement principle are used in space medicine area at RF SSC-Institute of Biomedical Problems RAS (research team directed by R. Baevsky)[7], and in N.N. Burdenko Research Institute of Neurosurgery of the Russian Academy of Medical Sciences (research team directed by O. Maksakova) [4]. The major differences are: sensor type and analysis technology used.

Application of this method in flight training will allow to reveal potentially hazardous pilot psychophysiological status in prospect, and if applied systematically, to estimate the crew technique mastering level and crew proficiency general level. It can be used during new aircraft system tests for crew workload specification and for ergonomic research and in perspective for real-time crew guidance and standard flight data recording.

The hardware of the method under consideration is pilot status monitoring system–(PSMS), which records a vast scope of pilot body biomechanical signals, including those generated by breath and heart function (biomechanical cardiogram analog), and also can record pilot motion behavior level in the pilot seat.

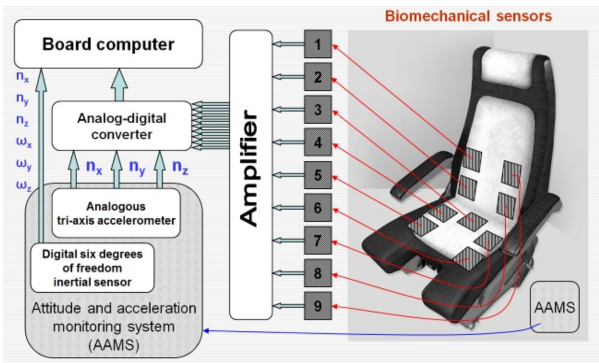

Fig.1. Structure of one of the implementation variants of the pilot status monitoring system with biomechanical sensors in the pilot seat.

As PSMS application experience on flight simulator shows, pilot heart rhythm and respiratory activity can be studied with the only Biomechanical Signal Sensor (BMSS) put in pilot seat. Yet during the flight there may appear measurement conditions (including ones connected to plane longitudinal and lateral-directional dynamics), whereby one channel for physiological monitoring estimation can be insufficient.

Pilot motion behavior study, as orientation phenomenon, requires minimum three measurement points in the seat for pilot motor action orientation estimation, such as pilot body general center of pressure (GCP) travel. Moreover, during the flight the pilot body is influenced by vibration and fluctuating accelerations, connected to occurrence of aircraft pitch rate, yaw, roll and load factor in the perturbed atmosphere zone or during maneuvering. In order not to associate erroneously these «external» accelerations with natural pilot motion behavior, several measuring channels for acceleration and angular velocity recording in close proximity to pilot seat should be allocated. In PSMS this problem is solved by attitude and acceleration monitoring system (AAMS) (Fig.1.) with analog module (accelerometer) and digital module (inertial system). Duplication of information on the local acceleration is provided for additional synchronization monitoring of biomechanical signal and inertial system channel recording.

2.2 Signal analysis

Recorded information analysis is carried out regarding individual and group statistics of pilot psychophysiological status index changes in several flights. During test flights acceleration, vibration in pilot seat location area and aircraft attitude were monitored. For monitoring of experimental procedure and pilot actual motion behavior video recording system was installed.

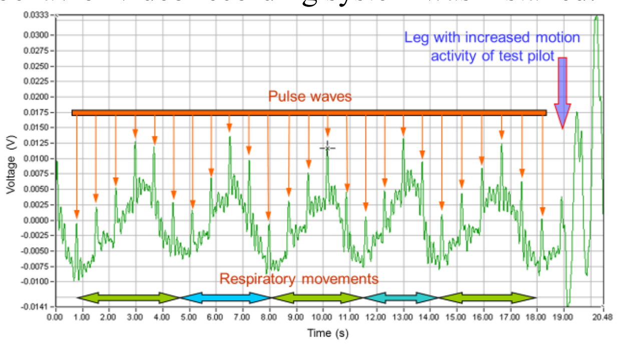

Fig.2. Recording area of the pilot seat main sensor signal after processing and adjustment in view of the local overload and vibro acceleration in the pilot seat area (there are marked 25 cardio pulses, 5 breath cycles and beginning of the area with the pilot enhanced motion behavior).

Fig.2. demonstrates recording area of the pilot single biomechanical channel signal in the low motion behavior status. At 20 sec. interval clearly seen are 5 breath cycles with 15mv scope and 25 cardio pulses with 10mv scope, that gives a good understanding of the system sensibility, considering full dynamic range of biochemical signal measuring scope, which makes 5000mv at given equipment alignment, and low noise level – 0,075mv.

At the end of the recording area there is an impulse of pilot enhanced motion behavior (PMB), which makes impossible pulse and breath physiological detection. In addition to that motion behavior parameters are also used as pilot psychophysiological status information source [4]. As a result, pilot status estimator has two working modes– for high and low PMB, in each of them the system allows to define several pilot status independent calculated rates simultaneously (partly by basic polygraph principle implementation). In low PMB mode cardiac rhythm, breath and heart rate variability (HRV) indicators and different pilot functional status indicators, based on HRV diagram analysis[7] are available. In high PMB mode energy, stability and entropy of dynamic process, connected to travel of pilot body center of pressure on the seat during physical activity is estimated [4].

BMSS sensor signal analysis effective instrument is the method based on wavelet transform[9], which transforms one-variable function (time) to a set of wavelet coefficients– bivariate function (scale and time). Fig.3. gives a demonstrative example of continuous wavelet transform appliance to corrupted biomechanical signal (in practice less resource-intensive discrete transformation variant is used). Conversion coefficients include complete information about original signal. Reciprocal of scale number characterizes relative «frequency» of short scan vibratory impulse – wavelet. For perception convenience, Fig.3 scale is reorganized into relative frequency logarithmic scale. It is possible to represent diagrammatically on the plane simultaneously all coefficients by presenting them as time-frequency coordinates.

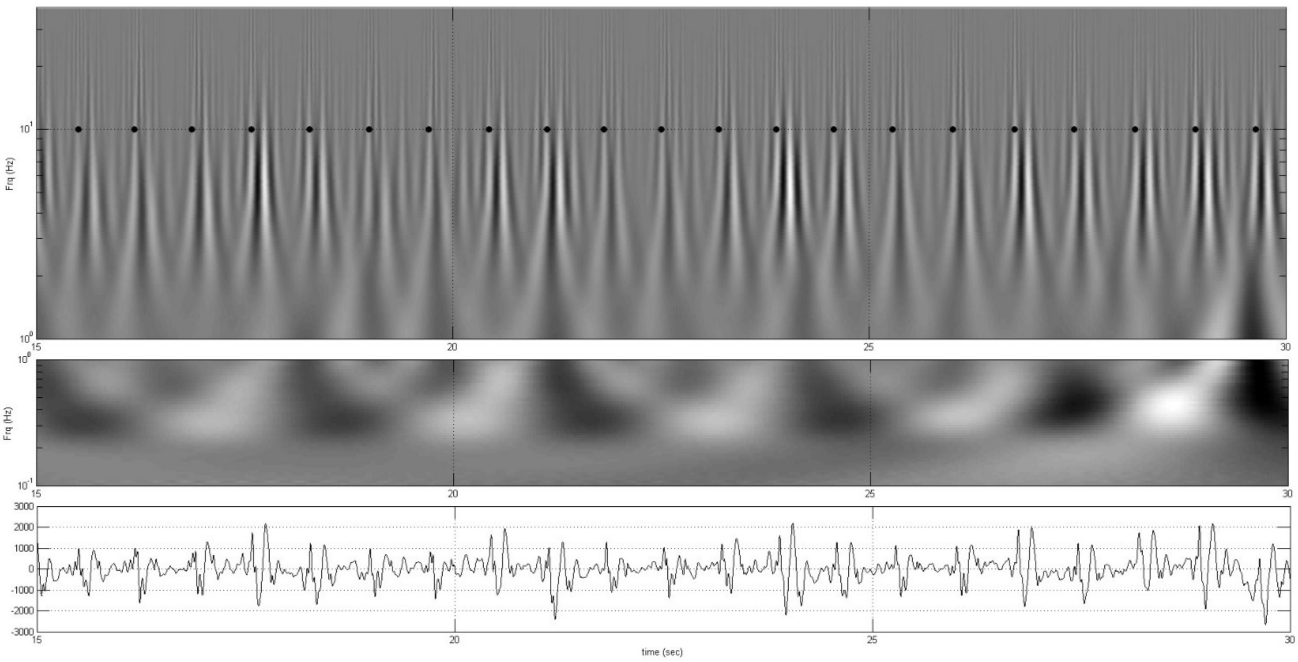

Fig.3. Analysis illustration of BMSS noisy signal section by means of Gaussian wavelet of order 4.

Top and middle diagram (Fig.3.) illustrates such surfaces as relative frequency and time plane projection parameters, where wavelet-coefficient figure at the point is marked by color of corresponded intensity(here in grey shade).

It is clearly seen that wavelet-analysis helps to identify in noisy degraded signal some aspects, that could be difficult to identify with classic spectral estimation methods. For example, in the middle diagram (Fig.3.), that reflects vibrations in a range of 0.1 – 1hz, 5 breath cycles are clearly seen and they are invisible on original signal diagram.

The upper diagram (range of 1 – 37.5 Hz) shows 21 impulses of similar time-and-frequency structure which are shown in seismic record diagram but do not look single-type. These impulses fall neatly with heart contraction marks recorded by certified electrocardiographic device (marked with black on the upper diagram). The wavelet coefficients are represented in two separate frequency ranges as weaker low-frequency component is rated separately for more contrast presentation in the diagram.

2.3 Measuring system location on board the aircraft

PSMS tests were conducted on a specialized flight test bed (FTB) developed on the basis of TU-154M. Equipment and interior of FTB crew cabin differ a lot from a production model. One of the most important for PSMS system tests is pilot work seat adapted design which caused the use of a special replaceable parachute pad as a BMSS sensor catch lock unit (Fig.4.).

Fig.4. BMSS seat sensor catch lock unit in TU-154M FTB left pilot seat.

PSMS system pre-prototype has a wide capacity range of adjustment and configuration of its components but its weight and overall dimensions do not allow locating all units in the crew cabin. Equipment for reinforcement, transformation, analysis and storage of PSMS system data as well as back supply during the test flights was located in the technical cabinet of 0, 6x0, 6x0,5 m dimensions (Fig.5.), and total weight of about 40 kg.

Fig.5. Location of PSMS system reinforcing, transforming, analyzing and storage equipment on board of TU-154M FTB

PSMS pre-prototype is not intended to be installed on product aircraft, it is used only on FTB for research of opportunities and limitations of this technique of noncontact pilot status monitoring. For product aircraft in LII a compact PSMS is being developed on the basis of microcontrollers.

3 Results

The main goal of system pre-prototype flight tests on flight test bed board was to evaluate biomechanical signal recording quality in the aircraft in the expected conditions of system operation.

During the PSMS system programme flights on TU-154M FTB the biomechanical signal statistics included the data on five monitored pilots with different anthropometric parameters that effected on position in the work seat. In particular, it is noted that for taller pilots with greater weight a deeper and closer seating is typical with constant rest on seatback. Shorter pilots often displace common seat pressure centre to the front and rarely fully lean on the seatback. Such feature is to be taken into account during the analysis of motion behaviour of pilots.

Fig.6 shows the example of initial recording of some board parameters and PSMS system signals (before correction and digital processing) during test flight with video shots of pilot motion behaviour in the work chair. Video recording system provides valuable information for analysis of formation biomechanics of pilot motion activity signal. Thanks to video records during the research we can divide the biomechanical signal into blocks of pieces with homogeneous specific features and close characteristics (for example, pieces direct with wheel steering, operation with control boxes, cockpit indication control or radio contact control).

Accelerometer test values registered in autosynchronous flow with BMSS signals by sufficient step-up of vibration level help to specify the start and end moments of taxying, run-out, ground-to-air transition at takeoff as well as touchdown at landing. Methods of biomechanical signal analysis that we possess do not allow to consider the modes of aircraft taxying, run out and roll-on (unlike the air cruise ones) as computational for conducting by PSMS system of pilot physiological index stable measurements because of extreme vibration and chatter.

During the flight moderately stepped-up vibration levels appear at flight stages with extended gears and high lift wing devices but at these modes the quality of signal registered by PSMS is satisfying. During the climb, cruise flight and at descend vibrational situation is friendly for BMSS sensors operation, and external electromagnetic fields thanks to PSMS system noiseless construction practically have no effect on signal noise level at all flight stages.

Without extra signal processing in Fig.7. on the appropriate scale, small amplitude respiratory process cycles are well observed. In case if signal noise vibrational term increases within fairly narrow limits, physiological components of cardiorespiratory process can be extracted by wavelet filtration methods [8,9]. In the BMSS signal section given in Fig.7. one of the diagrams (backseat left sensor channel) is at static “shelf” close to -1 mV level. This is caused by lack of contact between pilot lumbar and sensor surface in this section as pilot strayed his torso to the right, and the sensor stands at ease. It is clear that double amplitude of stand-at-ease sensor noise background lies within 0.4 – 0.5 mV limits.

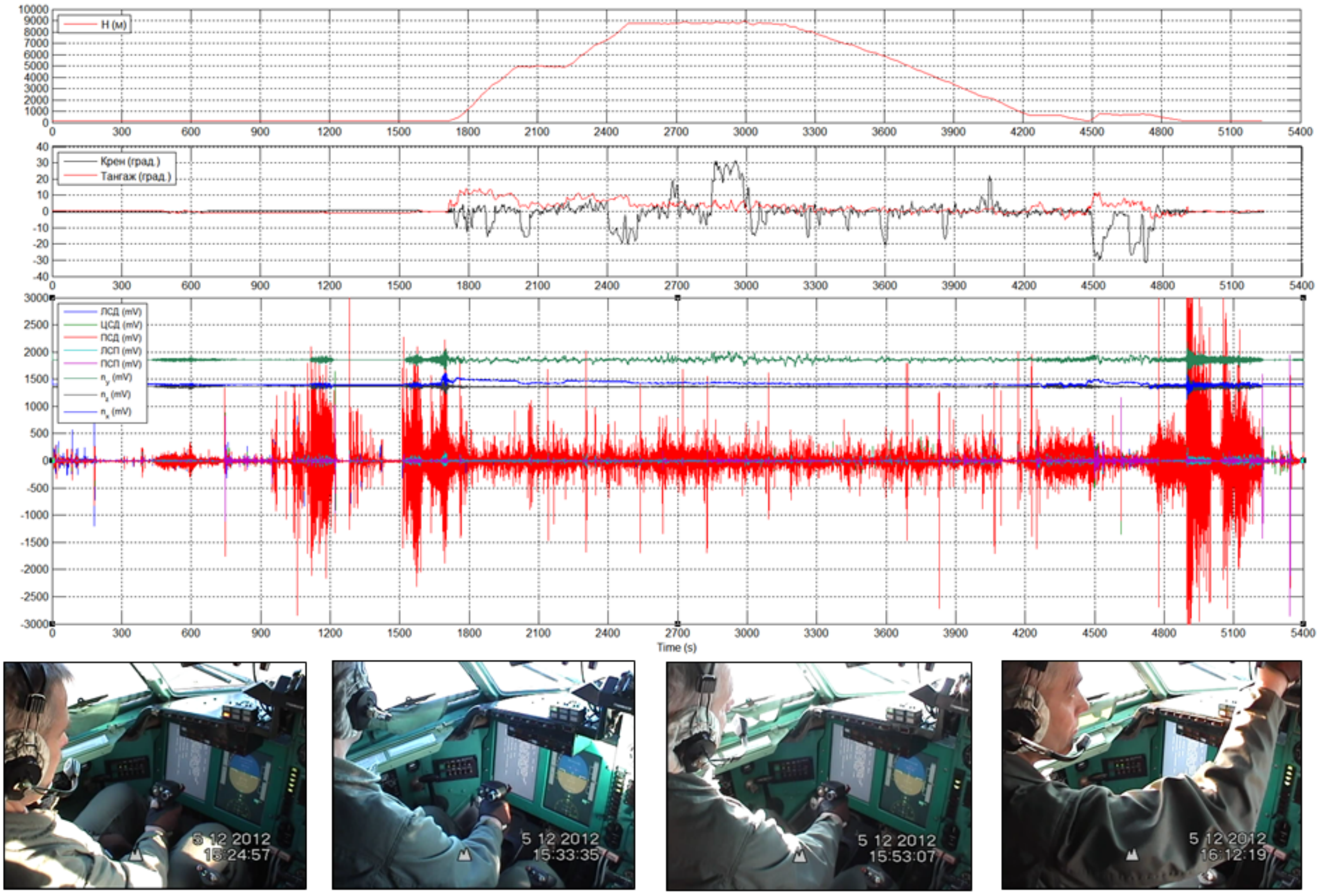

Fig.6. Original (before adjustment and digital processing) recording of some airborne parameters and signals of the pilot status monitoring system during the test flight with video recording shots of the pilot motion behaviour in the seat.

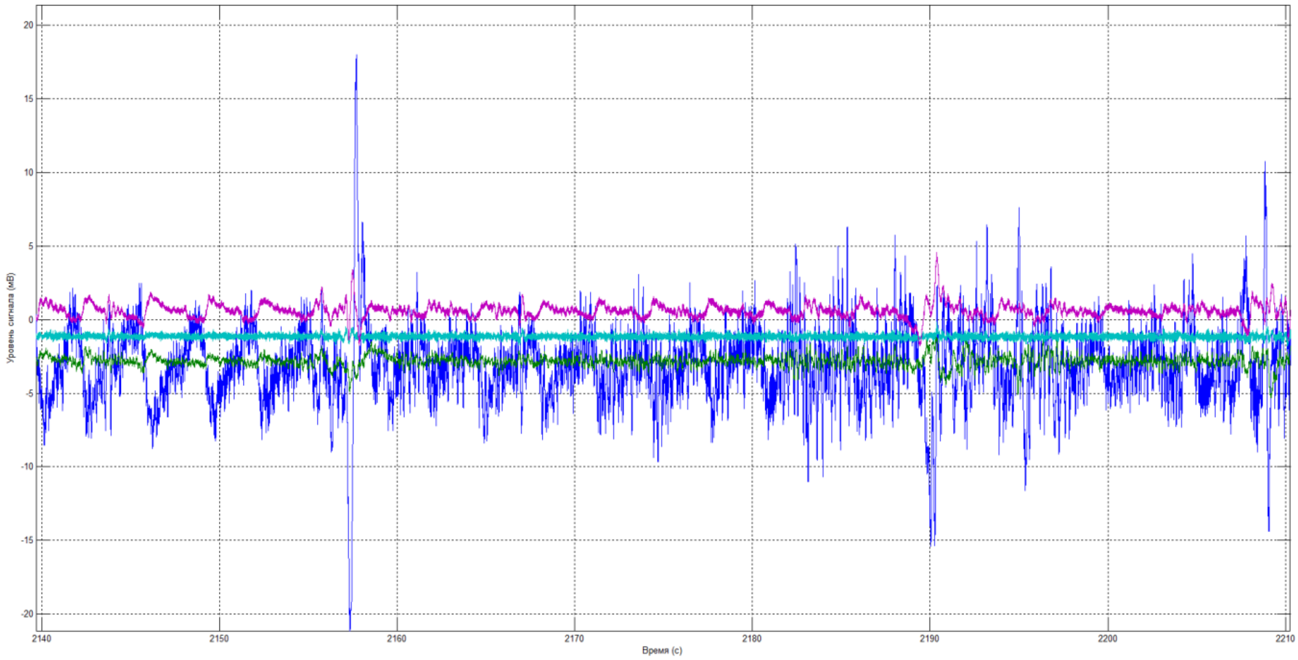

Fig.7. Signal of BMSS sensors in cruise flight.

Taking into account that physical range of measured signal amounts to 20000 mV effective system resolution in flight exceeds 40000 gradations of BMSS signal level and lies within the limits of 15-16 bits.

In the whole, the results of flight tests revealed that the quality of biomechanical signals registered by PSMS at all flight stages from ground-to-air transition to touchdown allows using them in computational algorithms of pilot status indicants. However, most human status indicators and indices [4, 7, and 8] implemented in the lab conditions demand adaptation to measurement conditions in the aircraft cabin. During the flight biological signal registered flow can be repeatedly interrupted because of spontaneous pilot body displacements or dynamic effects on aircraft in rough air. Those indicants of pilot functional status that demand strictly nonstop input biological signals during long time period cannot be considered reliable during aircraft on-board measurements. Indicant set used by the authors in this work allows the use of interrupted biological signals in calculations.

PSMS system flight test program did not include evaluation of information capacity of pilot psychophysiological status indices set because the sensibility of the implemented method does not allow to detect authentically the signs of fatigue accumulated by experienced test pilot during a short hour long flight along the route. Fatigue indicants used nowadays are informative in flight over 3 hours long, and differentiation of psychophysiological states with high and low levels of pilot body functional reserves is carried out on the basis of preliminary study of his individual standard.

PSMS tests were conducted together with other test programs, flight tasks of which did not suggest increase of flight duration over one hour. A set of two hour long flights with a ten minute break carried out by the same test pilot revealed at the end of the second flight a mild declination from initial level according to some common indicants.

Conclusions

The results of the first stage of PSMS system pre-prototype flight tests showed the practical feasibility of pilot psychophysiological status contactless onboard monitoring and opportunity of off line monitoring without installation of sensors on his body and outfit and without placing extra tasks for pilot as well as other nonspecific activities not included into standard workload.

The quality of biomechanical signals registered by PSMS together with state-of-art methods of their processing and analysis allows at all flight stages in expected operational conditions (excluding the movement along the runway) to use them in computational algorithms of pilot psychophysiological status indicants.

It is necessary to continue PSMS system flight tests to evaluate the information capacity of the set of pilot fatigue level indicants as well as definition of method reliability and stability at biomechanical signal measurement condition change (for example, when shaking level increases while passing the areas of disturbed atmosphere). It should be investigated also the opportunity of enhancing method sensibility to pilot functional reserve level change when the level of his fatigue grows.

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Contact Author Email Address

mailto: a_nakvasin@rambler.ru

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