

POTENTIAL CONNECTIONS OF COCKPIT FLOOR - SEAT ON PASSIVE VIBRATION REDUCTION AT A PISTON PROPELLED AIRPLANE

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Original scientific paper

Improving aircraft pilot comfort requires continuous work in decreasing vibrations in the seat. In order to determine the suitability and potential of cockpit floor - seat connections we conducted an experiment where measurements were taken and seat vibration analysis conducted. Vibrations parameters were measured for maximum engine and propeller speed. This analysis indicates that passive vibrations damping or cockpit floor - seat connections functionality depends on flights profile and vibrations frequency. The connection in question was behaving like a vibration multiplier on the 3rd and 4th harmonic as well as on the 3,5 sub-harmonic in individual flight modes on basic propeller rotation frequency, however, it behaved as a vibration silencer on all other frequencies. Analysis of the experimental data has shown that it would be justified to start improving the self adaptive unit for active vibration reduction for pilot seats.

Keywords: aircraft seat, flight modes, Lasta airplane, piston engine, vibration reduction

Potencijal veze pod kabine - sjedište za pasivno prigušivanje vibracija na sjedištu klipno-elisnog zrakoplova

Izvorni znanstveni članak

Povećanje udobnosti pilota zrakoplova zahtijeva kontinuiran rad na smanjivanju vibracija koje djeluju na sjedište pilota. U cilju određivanja pogodnosti i potencijala veze pod kabine - sjedište pilota za pasivno prigušenje vibracija, proveden je eksperiment s mjerenjem i analizom vibracija na sjedištu. Parametri vibracija su izmjereni za režime leta zrakoplova s maksimalnim brojem okretaja motora i elise. Ova analiza ukazuje da kvaliteta pasivnog prigušenja vibracija, odnosno funkcionalnost veze pod kabine - sjedište, ovisi o režimu leta zrakoplova i frekvenciji vibracija. Na pojedinim analiziranim režimima leta veza pod - sjedište ponaša se kao multiplikator vibracija na 3. i 4. harmoniku, kao i na 3,5 poluharmoniku osnovne frekvencije okretaja elise, dok se na ostalim analiziranim frekvencijama ova veza ponaša kao prigušivač vibracija. Analiza ovog eksperimenta pokazala je da je opravdano započeti razvoj vlastitog prilagodljivog uređaja za aktivno prigušenje vibracija na sjedištu pilota.

Ključne riječi: klipni motor, prigušivanje vibracija, režimi leta zrakoplova, sjedište pilota, zrakoplov Lasta

1 Introduction

During an aircraft's flight the cockpit is exposed to both vibrations and noise. Long-term exposure to elevated levels of vibration adversely affects the physical condition of the pilot and increases body fatigue, reducing the ability to make correct judgment and take appropriate actions while in charge of the flight [1].

The most effective means for decreasing the vibration level on an aircraft is to reduce or eliminate the source of the vibration. The alternative to the effective decrease of the vibrations that affect and act on the pilot's body is to reduce or isolate the source of the cause which in most cases is the seat.

Vibration that exists on the pilot's seat represents a seat construction response to an excitation of the existing sources of vibration on the plane. The planes equipped with the piston propelled group have a number of different vibration generating sources.

Vibrations that appear on the engine are in a relation with working regimes and technical conditions of the engine. By carrying out a vibration analysis we can determine the contribution of disorder in any working engine component. Prior to this, however, it is necessary to confirm that the monitored vibration signal is a good indicator of some phenomenon in the engines operations. In experiment [2] it was proven that the variation on the cylinder pressure loading contributed to the generation of engine vibration at the time of the valve opening. This indicated that the vibration signal measured on the engine is a good indicator of pressure variation appearance.

From the above results, we can see that such information of the vibration characteristics that has an effect on the pilot's seat is of great benefit.

Research on the C-130J Hercules [3] aircraft was based on determining the vibration that is transferred to the crew of the aircraft. Based on research data it has been proven that vibrations in the cargo sections of the aircraft exceed previously established levels, they can cause discomfort and tiredness.

Experiment [4] shows research of vibration characteristics carried out on military aircrafts, propeller type, WC/C-130J, C-130H3 and the E-2C Hawkeye. It accentuated the influence of vibration which happens on BPF (blade pass frequency) and PRF (propeller rotation frequency), which influence the crew of the aircraft. Paper [4] proved that WC/C-130J aircraft's crew felt vibration which appears on BPF of 102 Hz.

Results of the research carried out have been analysed and the characteristic identified of vibrations that have affected the aircraft seat is the frequency range of 1 Hz to 200 Hz.

Passive vibration reducing techniques currently used in aviation provide moderate vibration reduction in a narrow range of vibration, for example absorber, seat cushions, stiffening elements and buffers [5]. Therefore, in paper [6] it is recommended to use a seat suspension system and active vibration reducing control on a helicopter seat, with the purpose to decrease vibration transfer from floor to the seat.

Research [7] implies knowing the vibration characteristics for certain aircraft; it has also confirmed justification for development of vibration reductions, which have an effect on both the pilot and crew. An active

vibration reduction on a pilot's seat can also reduce the risk of resonant oscillation on all of the pilot's body parts. Chart 1 shows the resonant oscillation frequencies for individual parts of the human body [8].

An effective method for reduction and improvement requires detailed dynamic vibration characteristics like frequencies, amplitude, direction and location of influence [1].

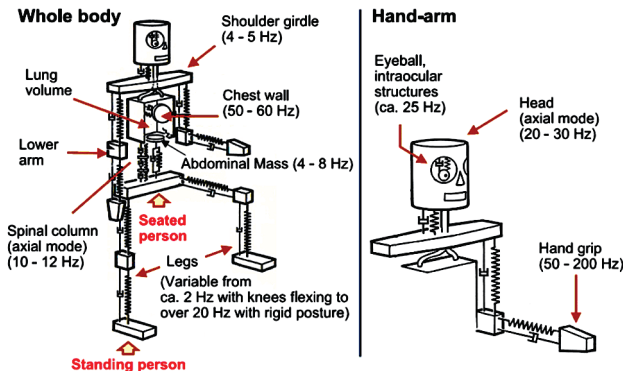


Figure 1 Mechanical models of the human body [8]

An experiment was performed during an actual flight in order to determine the vibration characteristics that affected the first Lasta prototype aircraft pilot seat. The main aim was to determine cockpit floor seat connection potential to reduce the transfer of vibration from construction to the seat alternatively to determine if there is a passive reduction of vibration on this connection.

It was also decided to perform a preliminary analysis of the validity of an adaptive device improvement for active vibration reduction on the Lasta aircraft's seat.

Vibration measurements were performed in the flight instructor's cockpit at the Technical Test Centre Belgrade on the Batajnica airport. Special attention was given to the airplane flight modes with a maximum engine and propeller speed. We analyzed the following modes: take-off, climb and acceleration in horizontal flight.

2 Theoretical analysis of the vibration on airplane equipped with piston propeller group

Excitation forces can have a continuous or periodical effect on the plane; they can also arise due to a sudden or impulse shock or random in time. The vibrations that occur on the plane, in addition to adverse effects on physical condition of the pilot, can cause dynamic stresses and strains in the airplane's construction, which can cause fatigue and damage, contact corrosion and noise [9].

Structural response and response of aircraft parts, depends on the mode and site excitation forces or displacements, and the dynamic characteristics of structures, such as the natural frequencies of oscillation, stiffness and their own vibration reduction. Vibrations with frequency near the natural frequencies, or when these frequencies become equal, for a single plane's part are very risky vibrations because resonance can occur, which in turn could result in a large increase in amplitude.

The dominant sources of vibration in planes with piston propeller group are propellers that generate

aerodynamic vibration, and in reciprocating ICE (internal combustion engine) that generates mechanical vibrations. Significant vibration level is generated on the PRF and its harmonic multiples.

In this paper we will use both terms PRF and engine crankshaft rotation frequency equally.

2.1 Vibrations generated by an ICE

Vibrations which appear during the ICE work process, are classified as mechanical vibrations.

Every ICE generates its own vibration spectrum. Vibration characteristics are specified by character and periodicity excitation. Engine's vibrations are consequences of the thermodynamic work cycle, piston and distribution mechanism, also the power and lubrication system.

Crankshaft rotation frequency is defined by formula (1):

$$f_1 = k_1 \cdot n_1, \text{ Hz} \tag{1}$$

where:

$k_1 = 1, 2, 3, \dots$ – harmonics order, with fundamental frequency for $k_1 = 1$,

n_1 – engine crankshaft rotation speed, s^{-1} .

The torque intensity on the engine's crankshaft is a function of gas pressure changes in the working cylinders. Engine cylinders pressure depends on fuel consumption and engine speed. It is a fact that engine can generate the same torque for a number of different working regimes. However, there is a corresponding engine vibration spectrum for every working mode [10].

Engine vibration may occur as a consequence of cycle-to-cycle variations, of cylinder-to-cylinder variations whereby the combustion in the cylinders creates different pressures and exhaust gas temperatures and cylinder head temperatures.

Piston engines are installed on aircraft frames through the elastic mount (shock absorbers), which prevents the equalization frequency vibration generated by the engine to the natural oscillation frequencies of the aircraft structure, thus protecting the plane from resonant vibration.

2.2 Propeller generated vibrations

Propeller is a constant source of aero dynamical vibration on the aircraft.

BPF is determined by formula (2):

$$f_2 = k_2 \cdot n_2, \text{ Hz} \tag{2}$$

where:

$k_2 = 1, 2, 3, \dots$ – harmonics order, with the fundamental frequency of rotation for $k_2 = 1$,

n_2 – propeller speed, s^{-1} .

The main propeller task is to generate the traction force required for self rotation which is necessary for airplane flight. At the same time, the propeller is

subjected to periodic disturbance of pressure and generates aerodynamic forces and moments that cause propeller blade vibration. These forces and torques can show effect in different ways and can cause strain due to torsion and stretching (Fig. 2).

Fig. 2a shows how the blades flex in the direction of the aircraft flight due to the effect of pulling force. Due to the traction peaks blades bend forward, because of their effect on the propeller-aircraft system, the propeller is a flexible part of the system. The thrust force moves the aircraft in the direction of flight and also opposes the centrifugal force.

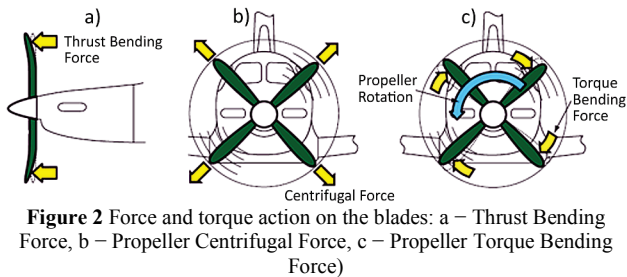


Figure 2 Force and torque action on the blades: a – Thrust Bending Force, b – Propeller Centrifugal Force, c – Propeller Torque Bending Force)

The most influential force which affects the blades is the centrifugal force; it affects the blades by stretching them from the hub to the blades tip (Fig. 2b).

The torque effect results in bending the blades in the back, opposite to the direction of propeller rotation (Fig. 2c).

Propeller response to different excitation force depends on its natural frequencies, vibration reducing and blade stiffness. Propeller vibrations can be reduced by regular periodic inspections and balancing. Vibration during the flight can be reduced by choosing a flight with smaller propeller step.

3 Experimental setup

The experiment was performed on the first Lasta aircraft prototype in the Technical Testing Centre Belgrade at the airport Batajnica [11]. Lasta is a low-wing, metal construction, tandem two-seat trainer aircraft, powered by a single piston engine propeller group (Figure 3).

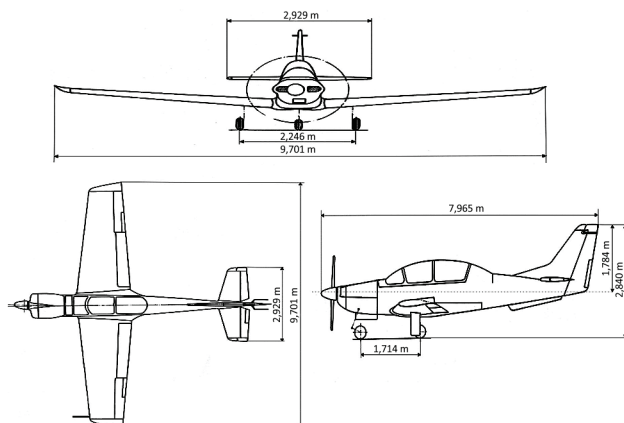


Figure 3 Lasta aircraft in three projections

The aircraft was designed and manufactured in the Republic of Serbia. Retractable tricycle type landing gear allows take-off from/to landing with concrete and

landscaped grass runway landing paths. The plane was designed by the EASA CS 23 and MIL-F-8785C standard and it is equipped with modern avionics that provides GPS and radio navigation. The power train consists of a six-cylinder piston engine "AVCO-LYCOMING" AEIO-540-L1.B5D and two-blade propeller "HARTZELL" HCC2YR-4CF/FC 84756. Minimal flight speed is 105 km/h and maximum is 340 km/h.

Vibration measuring is carried out with multi-channel digital acquisition systems NetdB12 - 01 Metravib which has an internal rechargeable battery and recorder. The device characteristics are shown in Table 1. The device is equipped with utility software dBFA Suite for collecting and processing data in real time.

For vibration measurements a uniaxial piezo accelerometer B&K 4383P was used.

During the length of the experiment engine and aircraft parameters were continually measured by Electronics International MVP-50P device that is utilized for monitoring and analysis in line. During the preparation for the experiment time synchronization of MVP-50P device was performed with acquisition systems NetdB12 - 01Metravib [12].

Table 1 Characteristics of NetdB12 system – 01 Metravib

| Input channels | |
|----------------|--|
| No. channels | 12 BNC |
| Resolution | 24 bits |
| Voltage | AC / DC / AC ICP |
| Range | -20 db: 14,1 V (10 V RMS) 0 db: 1,41 V (1 V RMS) +20 db: 141 mV (100 mV RMS) |
| CHP | >105 dB RMS full scale |

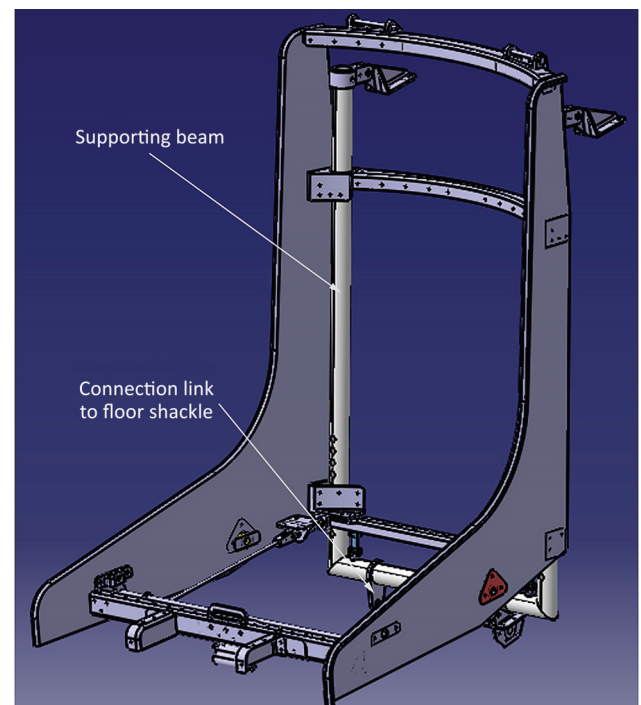


Figure 4 Seat frame model that was installed in the Lasta aircraft

Fig. 4 shows a seat frame model that is embedded in the Lasta aircraft.

Fig. 5 shows the fitting that is on the floor of the cockpit which binds the supporting beam of a seat. The back of the seat rests on two such supports.

There were three sets of accelerometers at the seat base for vibration measuring in *X*, *Y* and *Z* directions (Fig. 6a). The accelerometer for measuring *Z* direction vibration is set on the floor behind beams seat (Fig. 6b).

The designation used for the coordinate system with *X* as longitudinal, *Y* as lateral and *Z* as vertical axis. The results of the vibration measurement should match the real vibration condition on the construction part where it is measured. This is achieved by organizing the process of vibration measurement through several interrelated steps. The vibration spectrum is measured in the frequency range from 1 Hz to 200 Hz.

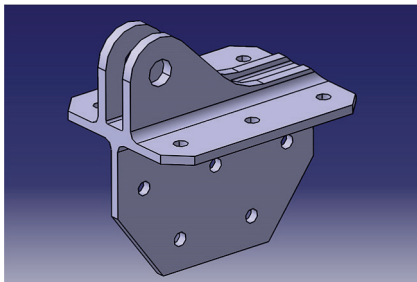


Figure 5 Binding seat fitting on the floor

First phase is a pre-test in which equipment and aircraft are prepared. In the second phase the experiment is conducted until the values are repeatable, and the third phase, which is the most important, being the post-test in which data is processed and analyses carried out of vibration on research subject. [13]

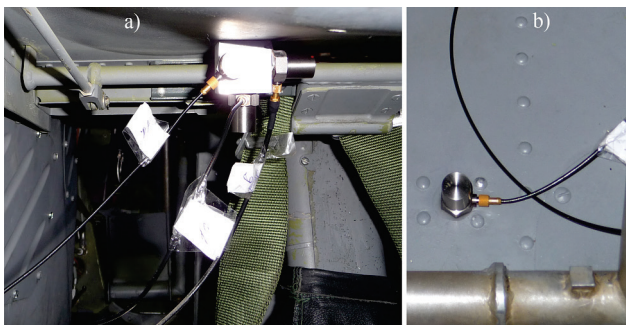


Figure 6 Accelerometer's position on the floor: a – Accelerometers on the seat base, b – Accelerometer on the floor

The subjects of the experiment are the pilot seat in the second cockpit (teacher's cockpit) and stiff pilots seat connection to the cockpit floor. The primary objective of this research was to determine the existence of a reduction in vibration level in the *Z* direction, which is transmitted from structure to the pilot's seat, and then to the pilot's body, i.e. if there is a passive vibration reducing on this connection. A secondary objective of the study was to define the range of vibrations that affect the pilot's seat in the aircraft, to provide a preliminary assessment of the feasibility of development of adaptive devices for active vibration reducing on the aircraft pilot's seat.

4 Results and discussion

The experiment was conducted in the aircraft flight modes which require maximum engine speed. Selected flight modes are: take-off, climb and acceleration to the aircraft top speed ($V_i = V_{i \max}$) at a height of $H_i = 1500$ m.

The reason for measuring the vibration in these modes of the aircraft lies in the fact that previous vibration studies on this aircraft revealed that the largest RMS (Root Mean Square) vibration acceleration is often related to the maximum engine and propeller speed.

In this paper there are tabulated vibration measuring results during the aircraft's flight with precisely defined program and required flight modes. The experiment was conducted through three flights with the same flight regimes. Measured vibration values were repeatable in all flight regimes in all three flights. According to the stated tests objective and selected aircraft flying mode, all measurements can be displayed in the time and frequency domains.

Also, the paper shows the averaged frequency spectra of vibrations which act on the seat and the cockpit's floor during the take-off, climb and acceleration to the top speed of aircraft flight at a height of 1500 meters. In all shown spectra in Figs. 7, 8, 9, 10, 11 and 12 we can see PRF and its harmonic multiplies. We can clearly notice existence of 1st, 2nd, 3rd. and 4th harmonic in all flight modes. During the engine operating at 2700 RPM, PRF is 45 Hz. Oscillation frequencies corresponding to 2nd harmonic are 90 Hz, 3rd harmonic frequencies corresponding to 135 Hz and 4th harmonic frequencies corresponding to 180 Hz.

The Lasta aircraft was built with a six-cylinder piston engine, and therefore the 3rd PRF harmonic coincides with the engine firing frequency. This plane's propeller is fitted with two blades, so the BPF coincides with the 2nd fundamental harmonic engine crankshaft rotation frequency. Matching 2nd harmonic engine vibration with aerodynamic vibration on the blade resulted in significantly increased levels of RMS acceleration on this frequency.

Mechanical vibration motor frequency and blades aerodynamic vibration overlap on all higher even harmonics too.

4.1 Vibration in take-off mode

Take-off mode can be separated in two phases. First phase is aircraft's run-up on the runway and continues until aircraft detaches. Second phase starts when aircraft detaches from the runway and it continues until aircraft reaches 15 meters above the ground.

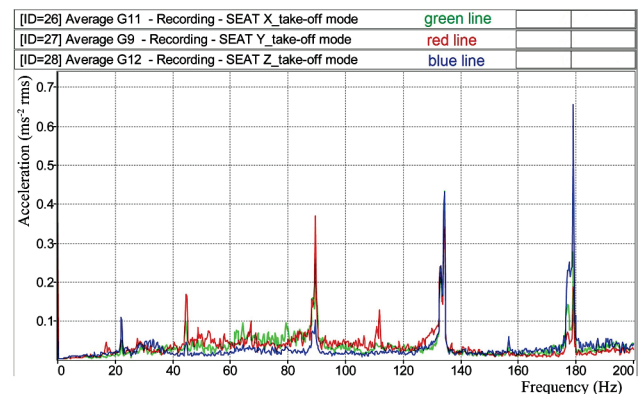


Figure 7 Averaged frequency vibration spectrums on the seat in take-off mode

In the take-off mode, the analysed frequency range of 1 Hz to 200 Hz exist acceleration peaks, starting from the largest on 4th harmonic, then 3rd harmonic, 2nd harmonic and the lowest in the fundamental PRF (Fig. 7).

To show the measured vibration a linear scale was selected on the abscissa and the ordinate, to quickly identify the most dominant vibration and their frequencies.

The measured pick values of acceleration in these harmonics, the axis directions of *X*, *Y* and *Z* are as follows:

The largest RMS acceleration on 4th harmonic is in the direction of the *Z* axis – 0,656 m·s⁻² RMS, followed by acceleration in the *X* and *Y* axes;

The largest RMS acceleration on 3rd harmonic is in the direction of the *X* axis – 0,434 m·s⁻² RMS, followed by acceleration in the *Z* and *Y* axes;

The largest RMS acceleration on 2nd harmonic is in the direction of the *Y* axis – 0,369 m·s⁻² RMS, followed by acceleration in the *X* and *Z* axes;

The largest RMS acceleration on 1st harmonic is in the direction of the *Y* axis – 0,169 m·s⁻² RMS, followed by acceleration in the *X* and *Z* axes (Tab. 2).

As a result of the aircraft taxing on the runway in the run-up phase a wide range of random vibration can be noticed. At the same time, in the run-up phase is slightly noticeable vibration reducing over tires and nose landing gear shock absorber. Since this vibration reduction is not large, and also the random vibration intensity, recognizing that air flight test item takes very short, this vibration analysis is performed in bulk for the entire take-off mode.

Table 2 RMS vibration acceleration values in take-off mode

| Accelerometer | Seat <i>X</i> | Seat <i>Y</i> | Seat <i>Z</i> | Floor <i>Z</i> |
|---------------|---|---------------|---------------|----------------|
| Frequency | Acceleration values m·s ⁻² RMS | | | |
| 22,5 Hz | 0,0534 | 0,0927 | 0,1020 | 0,1290 |
| 45 Hz | 0,0983 | 0,1690 | 0,0458 | 0,0704 |
| 67,5 Hz | 0,0706 | 0,0986 | 0,0292 | 0,1270 |
| 90 Hz | 0,2580 | 0,3690 | 0,1020 | 0,3960 |
| 112,5 Hz | 0,0343 | 0,1270 | 0,0218 | 0,0384 |
| 135 Hz | 0,4340 | 0,3400 | 0,4310 | 0,3320 |
| 157,5 Hz | 0,0304 | 0,0218 | 0,0598 | 0,0295 |
| 180 Hz | 0,2760 | 0,1880 | 0,6560 | 0,2710 |

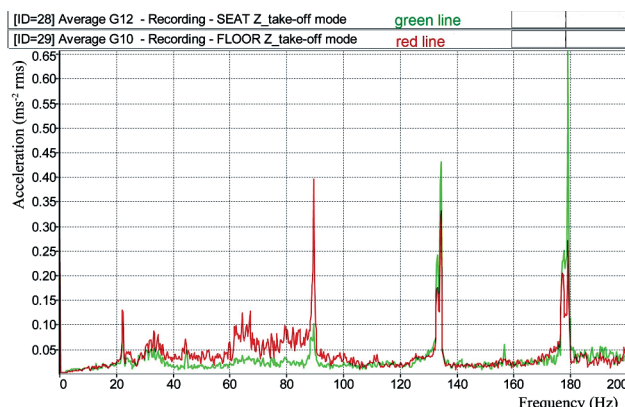


Figure 8 Averaged vibration frequency spectrums on the seat and floor in *Z* direction in take-off mode

In order to estimate the vibration reduction on the seat and the cockpit floor connection, in the *Z* axis direction and the take-off mode, Fig. 8 shows the frequency

spectrum of vibration in the *Z* axis direction on the seat and cockpit floor on which the seat is built-in.

RMS vibration acceleration in the *Z* axis direction on the seat is less than on the floor's 1st and 2nd harmonic, as well as 0,5; 1,5 and 2,5 sub-harmonics. At frequencies that match the mentioned harmonics and sub-harmonics vibration, seat-floor connection acts like a vibration absorber.

RMS vibration acceleration in the *Z* axis direction is bigger on the seat than on the floor on 3rd and 4th harmonic, as well as on the 3,5 sub-harmonic. At the frequencies that match the mentioned harmonics and sub-harmonic vibration, seat-floor connection acts as vibration multiplier.

Based on the above it can be concluded that the cockpit floor-seat connection's functionality depends on the frequency of vibration in the take-off mode in the direction of the *Z* axis.

There is vibration reduction on this connection on 1st and 2nd harmonic as well as on the 0,5; 1,5 and 2,5 sub-harmonic. The connection is not functional, i.e. there is no vibration reducing on the 3rd and 4th harmonic, as well as on the 3,5 sub-harmonic.

4.2 Vibration in the climbing mode

Climbing aircraft mode starts when the plane reaches the 15 meters height above the ground and lasts until it reaches the desired flight mode, usually horizontal flight.

In the climbing mode, the frequency range of 1 Hz to 200 Hz, there are acceleration peaks from the largest on 2nd harmonic, then 4th harmonic, 1st harmonic and the lowest on 3rd harmonic (see Tab. 3 and Fig. 9), and the maximum RMS acceleration values in these harmonics, the axis directions of *X*, *Y* and *Z* are marked in the Tab. 3.

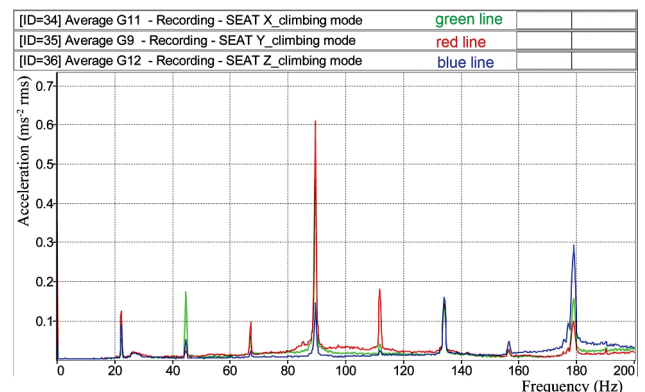


Figure 9 Averaged frequency vibration spectrums on the seat in climbing mode

Table 3 RMS acceleration vibration values in climbing mode

| Accelerometer | Seat <i>X</i> | Seat <i>Y</i> | Seat <i>Z</i> | Floor <i>Z</i> |
|---------------|--|---------------|---------------|----------------|
| Frequency | Acceleration value m·s ⁻² RMS | | | |
| 22,5 Hz | 0,0500 | 0,1230 | 0,0884 | 0,1330 |
| 45 Hz | 0,1730 | 0,0233 | 0,0513 | 0,1570 |
| 67,5 Hz | 0,0566 | 0,0956 | 0,0227 | 0,0840 |
| 90 Hz | 0,5660 | 0,6090 | 0,1440 | 0,7740 |
| 112,5 Hz | 0,0200 | 0,1810 | 0,0215 | 0,0374 |
| 135 Hz | 0,1200 | 0,1390 | 0,1590 | 0,0954 |
| 157,5 Hz | 0,0206 | 0,0244 | 0,0470 | 0,0230 |
| 180 Hz | 0,1560 | 0,0974 | 0,2920 | 0,3330 |

To assess vibration reduction on the pilot seat-cockpit floor connection, in the Z axis direction in the climbing mode, Fig. 10 shows the frequency spectrum of vibration on the seat and floor in the direction of the Z axis.

As it can be seen from Tab. 3, RMS vibration acceleration in the Z axis direction on the seat is less than the floor at 1st, 2nd and 4th harmonic, as well as 0,5; 1,5 and 2,5 sub-harmonics. At frequencies that match the mentioned harmonics and sub-harmonics, seat-floor connection acts like a vibration absorber.

RMS vibration acceleration in the Z axis direction on 3rd harmonic and 3,5 sub-harmonics is higher on the seat than on the floor. At the frequencies that match the mentioned harmonics and sub-harmonic, seat-floor connection acts as vibration multiplier.

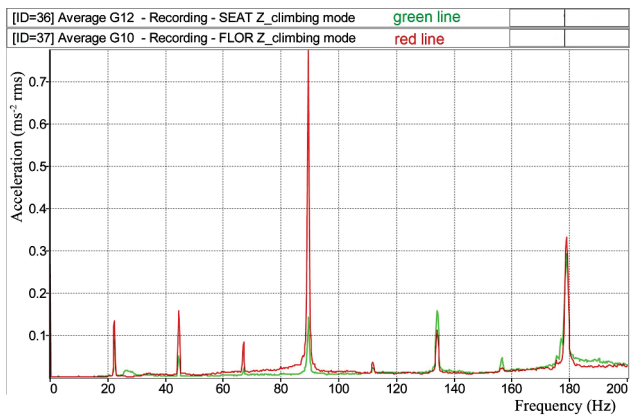


Figure 10 Averaged frequency vibration spectrums on the seat and floor in the Z axes direction in climbing mode

Based on the above we can conclude that the seat-cockpit floor connection functionality in the take-off mode and the direction of the Z axis depends on the vibration frequency. Vibration reduction on this connection exists on 1st, 2nd and 4th harmonic, as well as on 0,5; 1,5 and 2,5 sub-harmonics. Connection is not functional because there is no vibration reduction on 3rd harmonic and 3,5 sub-harmonic.

4.3 Vibration in the acceleration mode to the top speed of aircraft flight on the 1500 m height

In the acceleration mode to the top speed of aircraft at a height 1500 m, the frequency range of 1 Hz to 200 Hz, there are acceleration peaks from the largest on 2nd harmonic, then 3rd harmonic, 1st harmonic and the lowest on 4th harmonic (see Tab. 4 and Fig. 11), and the maximum RMS acceleration values in these harmonics, the axis directions of X, Y and Z are marked in the Tab. 4.

To assess vibration reduction on the pilot seat-cockpit floor connection in the Z axis direction in this flight mode, Fig. 12 shows the frequency spectrum of vibration on the seat and floor in the direction of the Z axis. As it can be seen from Tab. 4, RMS vibration acceleration in the Z axis direction on the seat is less than the floor at 1st, 2nd, 3rd and 4th harmonic, as well as 0,5; 1,5 and 2,5 sub-harmonics. At frequencies that match the mentioned harmonics and sub-harmonics, seat-floor connection acts like a vibration absorber.

RMS vibration acceleration in the Z axis direction at 3,5 sub-harmonic is higher on the seat than on the floor.

At the frequency that matches 3,5 sub-harmonic, seat-floor connection acts as vibration multiplier.

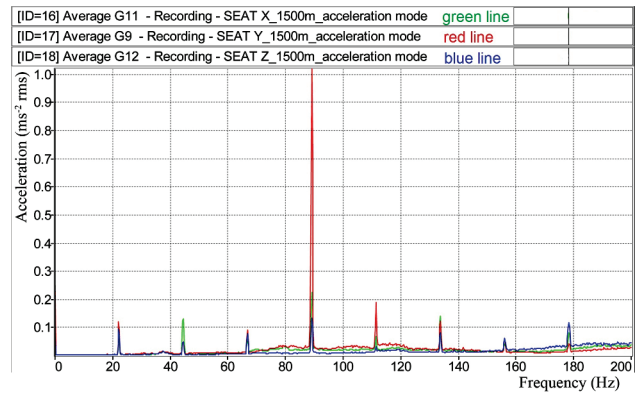


Figure 11 Averaged frequency vibration spectrums on the seat in acceleration mode to the top speed of aircraft flight on the 1500 m height

Table 4 RMS acceleration vibration values in acceleration mode to the top speed of aircraft flight on the 1500 m height

| Accelerometer | Seat X | Seat Y | Seat Z | Floor Z |
|---------------|---|--------|--------|---------|
| | Acceleration values m·s ⁻² RMS | | | |
| 22,5 Hz | 0,0601 | 0,1200 | 0,0943 | 0,1370 |
| 45 Hz | 0,1310 | 0,0513 | 0,0470 | 0,1290 |
| 67,5 Hz | 0,0567 | 0,0900 | 0,0755 | 0,2350 |
| 90 Hz | 0,2240 | 1,0400 | 0,1330 | 0,7930 |
| 112,5 Hz | 0,0658 | 0,1870 | 0,0302 | 0,0346 |
| 135 Hz | 0,1390 | 0,1210 | 0,0810 | 0,1340 |
| 157,5 Hz | 0,0427 | 0,0545 | 0,0598 | 0,0364 |
| 180 Hz | 0,0815 | 0,0418 | 0,1150 | 0,2360 |

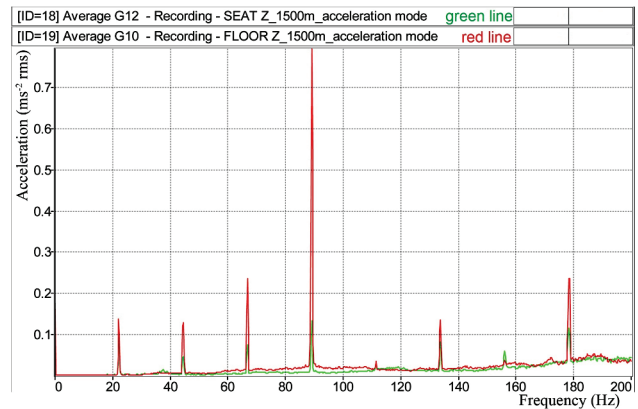


Figure 12 Averaged frequency vibration spectrums on the seat and floor in the direction of the Z axes in acceleration mode to the top speed on the 1500 m height

Based on the above we can conclude that the seat-cockpit floor connection functionality in the acceleration mode and the direction of the Z axis depends on the vibration frequency. Vibration reduction on this connection exists on 1st, 2nd, 3rd and 4th harmonic, as well as on 0,5; 1,5 and 2,5 sub-harmonics. Connection is not functional because there is no vibration reduction on the 3,5 sub-harmonic.

5 Conclusion

Vibration level measured on the pilot's seat depends on flight mode. In all flight modes the vibration level is the biggest on the fundamental PRF and its harmonic multiples and corresponding sub-harmonics.

In climbing and horizontal accelerating modes vibration on the pilot's seat is the biggest on the BPF at 90 Hz in the Y axis direction. At this frequency for two blade propeller BPF and 2nd harmonic of engine crankshaft rotation frequencies are the same.

In take-off mode the dominant vibration is 180 Hz in the Z axis direction. At this frequency 4th of harmonic mechanical vibration of the engine matches with double BPF value.

The largest RMS vibration acceleration measured in the acceleration mode to the top speed of aircraft horizontal flight ($V_i = V_{i \max}$) on the $H_i = 1500$ m height amounts to 1,040 $\text{m}\cdot\text{s}^{-2}$ RMS.

From the relationship between the level of vibration on the floor and seat vibration we can realize the cockpit floor-seat connection potential that in the Z axis direction can reduce vibration which affects from the floor to the pilot's seat. This connection's functionality and passive vibration reduction quality depends on the flight profile and vibration frequency.

In the take-off mode there is a vibration reduction on this connection at 1st and 2nd harmonic, as well as 0,5; 1,5 and 2,5 sub-harmonics. Connection is not functional, i.e. there are no vibration reducing on 3rd and 4th harmonic as well as 3,5 sub-harmonic.

In the climbing mode vibration reduction exists on 1st, 2nd and 4th harmonic as well as on 0,5; 1,5 and 2,5 sub-harmonics. Connection is not functional because there is no vibration reduction on 3rd harmonic and 3,5 sub-harmonic.

In the acceleration mode with horizontal flight the floor-seat connection reduces vibration on 1st, 2nd, 3rd and 4th harmonic as well as on 0,5; 1,5 and 2,5 sub-harmonic. The connection is not functional because there is no vibration reduction on the 3,5 sub-harmonic.

Existing floor-seat connection acts as a passive vibration absorber and reduces the amplitude of vibration on 1st and 2nd harmonic as well as on 0,5; 1,5 and 2,5 sub-harmonic in all analyzed flight modes. Since the vibration on this frequency most affects the pilot's fatigue this connection's potential for passive vibration reduction as well as measured vibration amplitudes values on this frequency enable safety exploitation of this aircraft in observed flight modes.

At certain analyzed flight modes floor-seat connection acts as a vibration multiplier on 3rd and 4th harmonic as well as on the 3,5 sub-harmonic.

Since the hand grip oscillation in certain conditions can be in the range between 100 Hz and 200 Hz, it is reasonable to begin the development of adaptive device for active vibration reduction on the pilot seat. The development of such a device should be done for the entire frequency range of 1 Hz to 200 Hz, in order to enhance the pilots comfort in all aircraft flight modes within the projected use of the aircraft.

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