Impact of Changing Quality of Air/Fuel Mixture During Flight of a Piston Engine Aircraft with Respect to Vibration Low Frequency Spectrum

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Knowledge about the source of vibrations on a plane is an important prerequisite for modelling adequate response/isolation of initially discovered vibration. The following paper shows results and analysis from changes in low-frequency vibration spectrum located in the engine of Lasta airplane. Due to different working states and various conditions of engine, changing of vibrations is transmitted from the engine to pilot seat, as a consequence of changing quality composition of air/fuel mixture, while testing on a flying plane equipped, with piston propelled propulsion group. Test-measure systems used for researches in vibration dynamics characteristics are shown. Values of vibrations are shown in relation to engine working parameters changes. Research results show that knowledge of engine vibrations gives a wide options for an evaluation of response from piston propeller propulsion group on impact from changing quality composition of air/fuel mixture in the engine leaning process.

Keywords: *piston propeller propulsion group, engine leaning, vibrations, frequency analysis*

1. INTRODUCTION

Correct work and managing plane propelling propulsion group is of huge importance due to two reasons. The first reason regards obtaining the plane declared performances and the second one regards safe working condition i.e. avoiding working conditions that can cause damage or eventually disaster. In monitoring engine condition the measuring of vibrations and analysis of engine vibration spectrum are of great significance.

Monitoring work and analysing changes in engine working conditions are based on attaining huge number of its working parameters requiring a large number of sensors. Based on engine working parameters and its vibrations it is possible to establish contribution made to disorder in working condition of engine parts via changes of vibration spectrum. Using vibration analysis is important to establish contribution of vibrations on improper work of particular engine part. But before that it is needed to verify that recorded vibration signal is a relevant indicator for working irregularity.

L. Barelli, G. Bidini, C. Buratti, R. Mariani, [1] have confirmed that variations in a cylindar charging pressure while valve is open, contribute to generating vibrations on engine, and furthermore this confirmis that engine vibration signal is an excellent indicator for variations in the cylinder charging pressure.

J. Pečinka & J. Kamenický [2] have determined the model for vibration calculation on crankshaft-propeller of engine Avia M337 with three-pointed propeller V506 and after that compared it with results established on workbench testing.

S. Liu, F. Gu and A. Ball [3] have defined detection technique how to establish the beginning of cylinder valve malfunction on the engine Shanghai Diesel Works model 4135D, based on engine head vibrations measurements. It is confirmed that vibration characteristics in time and frequent domains are very useful in establishing working engine conditions. Similar to this, deBotton C, Ben-Ari J. & Sher E., [4] have confirmed the existence of few irregularities connected to anomalies/inconsistencies on the spark plug, spark timing and change in the spark plug clearance, based on analysis of signals from engine vibrations.

C.P. Ratcliffe and D.F. Rogers [5] have analysed vibrations, fuel economy and temperature of exhaust gases on 6 cylinder engine Continental IO 520 BB installed in Beech Bonanza plane. Research has been initiated by the occurence of engine vibrations caused by unbalanced mixture of fuel and air in cylindres. Conducted are parallel evaluations of engine tests with different fuel injectors. The main measured parameters are amplitude and vibration frequency on engine specific fuel economy and relative temperature of exhaust gases as per each cylinder separetely. Given are evaluated results for measured parameters of engine working conditions and engine vibrations, as their mutual relations for two different types of fuel injectors.

Listed researches clearly show that vibration analysis on piston-propeller propulsion plane group should focus on differences that appear in relation to specific vibration spectrum of propulsion group. With this analysis, it is possible to establish contribution from

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changes in work of some components to vibration spectrum of propulsion group, and furthermore on observed part of plane structure.

While doing flight testing and determination of normal working parameters on some planes of the type Lasta S. Dobrosavljević, S. Jovanović i A. Đurić verified the existence of vibrations on pilot's seat at specific working state of engine [6].

T. A. Loomis. J. A. Hodgdon. L. Hervig i W. K. Prusacyzk [7] confirmed that continuous exposure to increased vibrations have negative impact on psychophysical condition of a pilot or other plane crew, increasing body fatigue, decreasing ability for right judgment and taking adequate command actions in regarding flight requirements. Increased vibration levels have dynamics loads as a consequence.

Based on previous experiences obtained while researching and vibration analysis on planes while in working process, Brian D. Larder [8] confirms that in regarding investments the greatest possibilities for new benefits are in research vibration area incurred on propulsion group, and it is the most important source of vibrations.

Working conditions can be split in to two groups: wanted and unwanted. In wanted working conditions, while in flight, engine working parameters are controlled by the pilot and/or plane automatic systems, as for the sake of obtaining necessary pulling forces for demanding flight requirements. In unwanted working conditions, while in flight, engine working parameters appear due to failing or engine malfunction. Every engine disruption has to be written in frequent vibration spectrum, because there is no breakdown in mechanical sytem without upfront warning signals.

Relaying on methods and results of listed researches, authors of this paper have implemented research procedure for establishing impacts from changes in quality of fuel and air mixture on piston propullsion engine to engine vibration spectrum.

Research results on the route from the engine to the pilot seat will be presented in subsequent papers by this group.

2. LEANING OF PISTON ENGINE EQUIPPED PLANE

Leaning of piston engine equipped plane means the process of using depleted and enriched fuel-air mixture to achieve optimal fuel economy and engine working conditions.

Leaning the fuel air mixture is one of the most important yet most misunderstood operations in the operation of an internal combustion powered airplane. There is a good deal of misunderstanding of the conditions under which leaning is desirable, and even required, and the proper technique for reaching the desired fuel air mixture [9].

Engines are more efficient when they are supplied with right mixture of fuel and air. Flying with an over rich mixture may induce spark plug fouling, which may shorten the life of the spark plugs. Right leaning also results in a smoother engine running, and a cleaner combustion chamber that has less likelihood of preignition cousing sometimes accumulation of carbon deposits [10].

Operating on the lean side of peak exhaust gas temperature (EGT) involves leaning the engine until the EGT reaches a maximum and starts to decline. Theoretically, it is the area of the combustion regime that corresponds to best economy (most miles per gallon). Lycoming recommends cruise operation at peak EGT, which is the point where the best economy range starts.

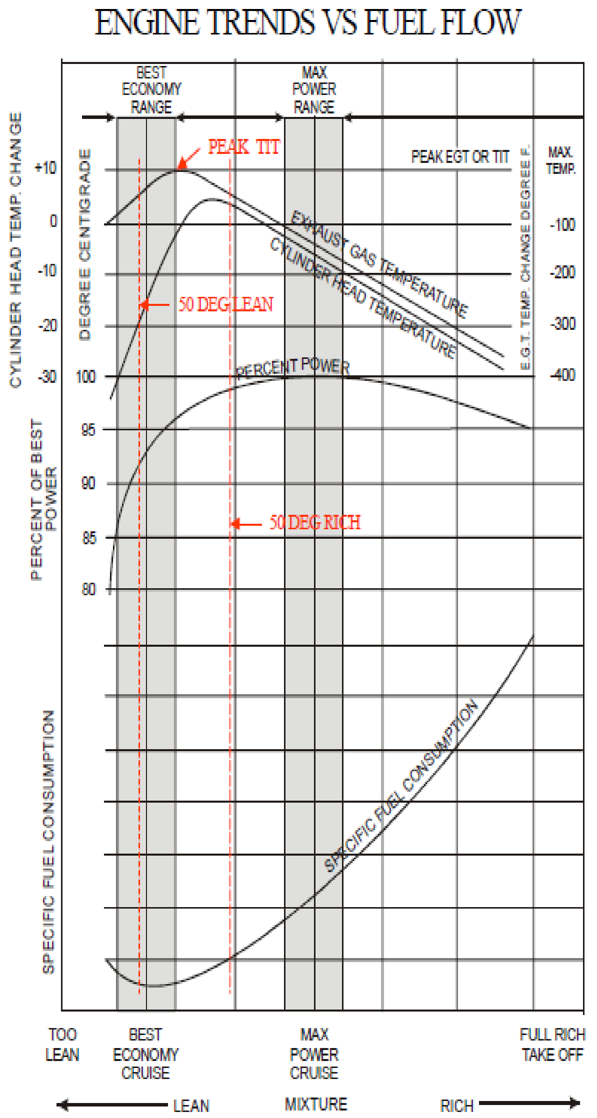

Figure 1. Engine trend versus fuel flow [11]

For optimum service life, Lycoming suggests operating 50 degrees F rich of peak EGT. On an engine like the TIO-540- AE2A, this translates into a difference in cruise fuel economy of approximately 2-3 gallons per hour compared with peak or lean of peak operation.

Operating lean of peak results in substantial reduction power output, more than 8% from that is obtained with best power fuel flow. If leaning is initiated at 75% of power and continued through 50 degree F lean side of peak, the actual power output at that point will be approximately 69%. No wonder the indicated fuel flow shows a dramatic reduction. Although the fuel economy seems attractive, the aircraft cruise speed suffers [11].

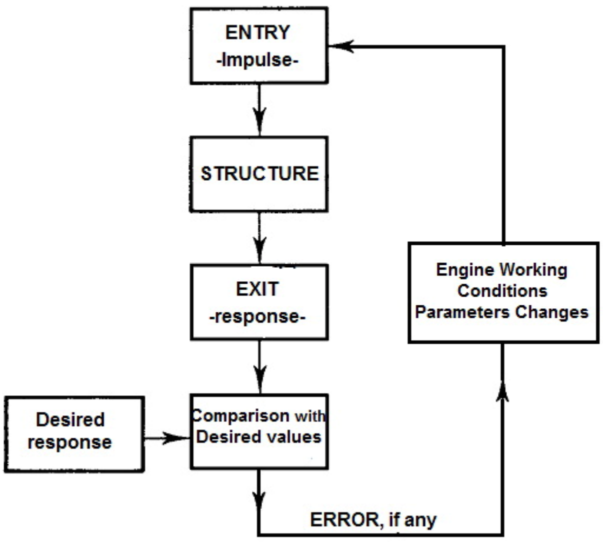

Figure 2. Changes in airplane structural vibrations impacted by changes in engine working conditions

Changes in engine working conditions have impact on vibration spectrum change, as well as on engine itself and on a pilot seat (Figure2).

3. SELECTION AND INTEGRATION OF EQUIPMENT FOR TEST-MEASURING ON THE PLANE

All measurements are completed on the first prototype of the plane Lasta [12] in Technical Testing Centre of Serbian Army (TOC) at Batajnica Airport. The Lasta plane is single engine low-wing metal construction, with two classical no-ejection seats positioned one at the back of another. Retracting landing system of tricycle type allows take-off and landing from concrete and arranged take-off – landing grass runways. The plane was designed against standard CS 23 and equiped with modern electronics that allows GPS and radio navigation. The plane is 7.97 m long and 3,16 m high, wing span of 9.71 m, wing area 12.9 m^2. Propulsion group makes single six cylinder piston engine "AVCO-LYCOMING" AEIO-540-L1.B5D and two-pointed propeller "HARTZELL" HCC2YR-4CF/FC 84756. Minimum flaying speed is 105km/h maximal speed is 340 km/h [13].

Measurement of low frequncy vibrations on the Lasta plane has been realised with multichannel digital system NetdB12-01 Metravib. This is a multichannel digital system for measurements of vibrations and noise which has an internal battery power and a recorder. The outlook of the system is shown on figure 4, and technical characteristics are shown in Table 1. It is equipped with dedicated software dBFASuite for data processing in real time.

For vibrations measurements was used uniaxial piezo accelometers B&K 4383P.

While the experiment was in progress, measurements were performed of engine working parameters, plane flight parameters using monitoring system, analysis of working engine MVP-50P of manufacturer Electronics International.

While preparing the experiment, time synchronisation was completed between MVP-50P with and acquisition system NetdB12-01Metravib.

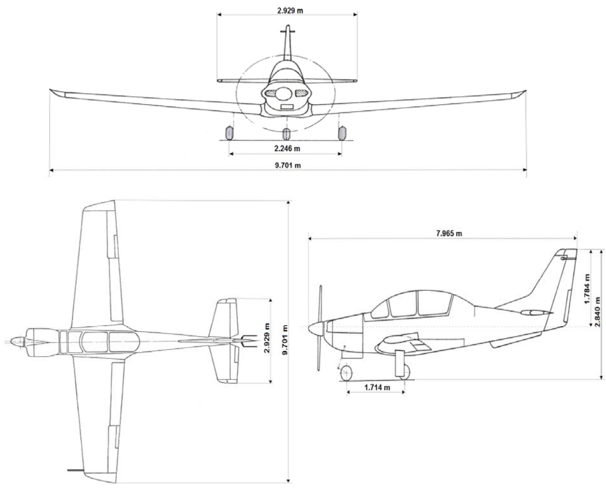

Figure 3. Lasta airplane in three projections

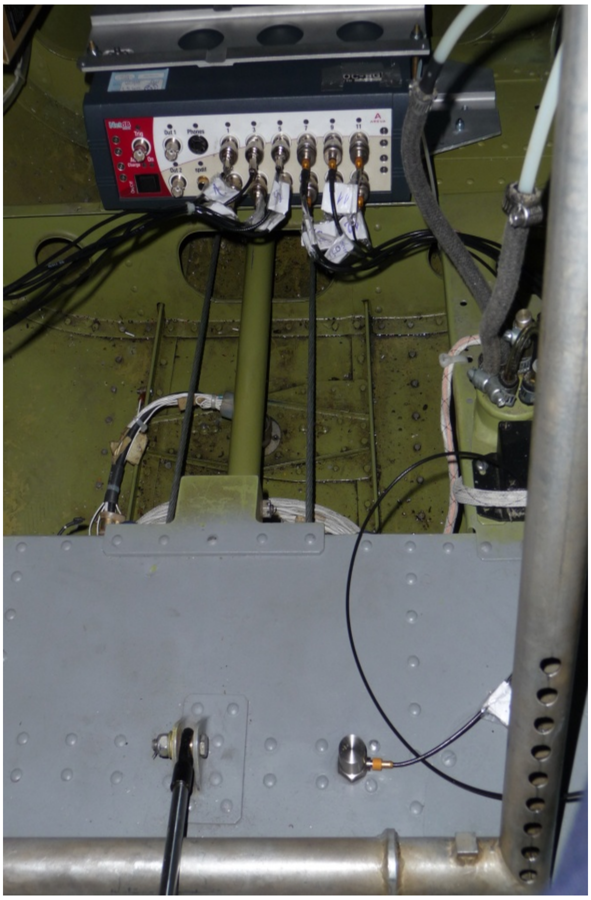

Figure 4. Acquisition system NetdB12 mounted on the aircraft fuselage

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) +20db: 141 mV (100 mV RMS)
CHP	>105 dB RMS full scale

4. METHODOLOGY AND PROCEDURES IN VIBRATION TESTING ON A PLANE

Vibration measurement results should correspond to the actual state of plane vibrations. This can be done by organising measurement of low frequncy vibrations on a part of the plane structure through some dependant steps. Low frequncy spectrum means a range of frequencies from 1 Hz to 100Hz. Low frequency vibration spectrum of technical systems expresses a range that has largest impact on the structure fatigue and failure, as well as plane crew fatigue.

The first phase is research preparations (pre-testing), the second phase is research itself, and the third and most important is processing and analysing of the research results (post-testing).

Figure 5 shows phases in the process of low frequency vibration testing on aircraft Lasta.

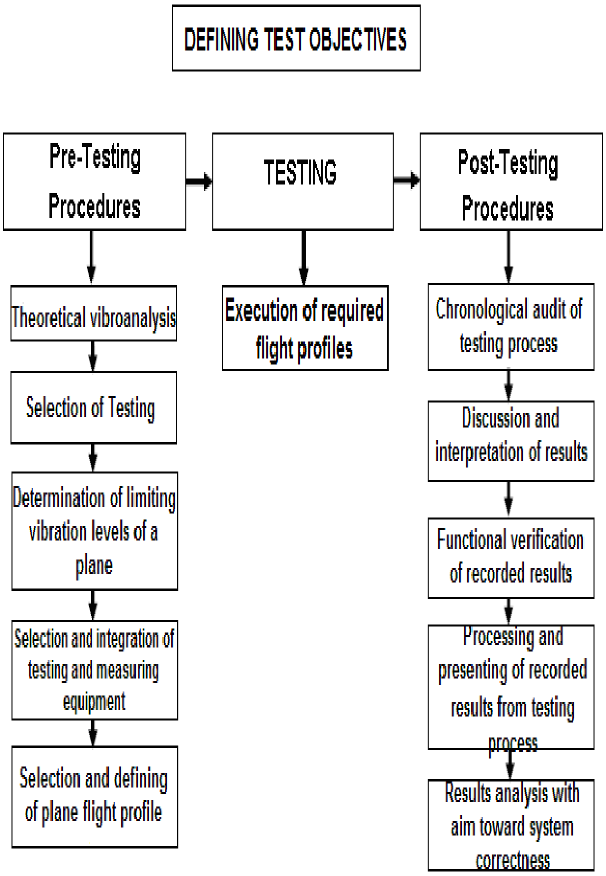

Figure 5. Phase in process of vibration testing on aircraft Lasta [14]

The aim of testing is to establish impact from changes in engine working conditions on low frequency vibration spectrum show on the engine, and establish the critical vibration regime to the continuation of determination, i.e. if there is possibility to lower vibrations level transferred on pilot the seat and then on the pilot's body.

In this paper one part of wider vibration investigation on the plane Lasta is shown. Elaborated is the part which reflects on the impact of leaning fuel/air mixture on piston engine toward low frequency spectrum on a flying plane. Installation position for accelerometers, is shown in Figure 6.

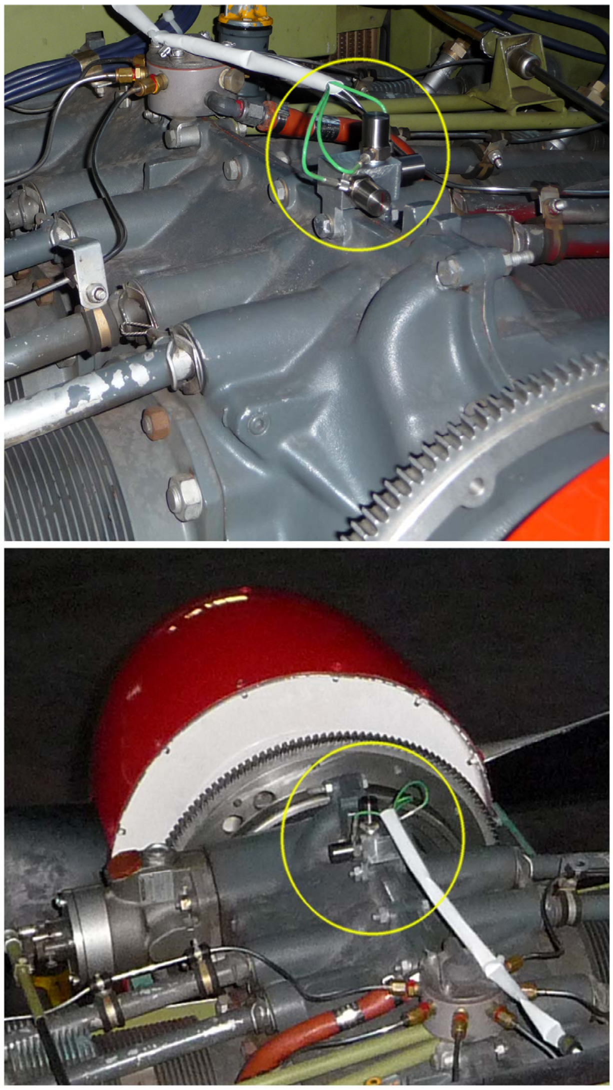

Figure 6. Installation position for accelerometers on the engine

5. TESTING RESULTS AND ANALYSIS OF MEASURED VIBRATIONS

Shown are the results of vibration measurements on an engine and the engine parameters while the plane is in flight at an altitude of 1500 metres, as per the following engine working regimes:

- leaning process in a working regime 2450 RPM and fuel charging pressure of 23.6 InHg;
- leaning process in a working regime 2350 RPM and fuel charging pressure of 20.8 InHg.

On the plane Lasta, while on other planes with piston propeler propulsion group, leaning is controlled by air/fuel mixture, while the position of engine acceleration lever reminds unchanged.

In the working regime of 2450 RPM leaning is completed in 6 decrements of fuel supplies into the engine. As per decrement fuel flow has been decreased by 5 l/h from starting 70 l/h to 45 l/h. On each working regime the engine was kept working at least one minute until the next leaning of fuel mixture.

Changes in engine fuel quantity supply, and changes in air/fuel ratio mixture combusted in engine, as a consequence has a change in exhaust gases temperature

(EGT) on all 6 cylinders and also a change in cylinder head temperature (CHT) on all 6 cylinders.

In Figure 7 are shown exhaust gases temperature of all 6 cylinders in the function of fuel flow change during leaning in the regime of 2450 RPM.

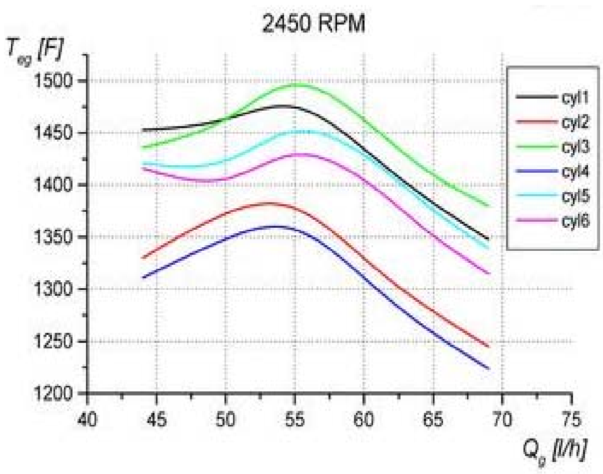

Figure 7. Exhaust gases temperature in function of fuel flow change during leaning process in regime 2450 RPM

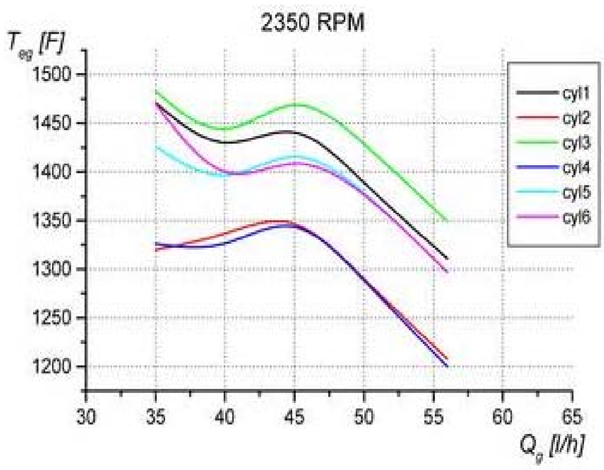

Figure 8. Exhaust gases temperatures in function of fuel flow change during leaning process in regime 2350 RPM

The same principle of leaning has been used in the engine working regime 2350 RPM. Engine fuel quantity has been evenly decreased for 5 l/h in each of the 5 steps from starting 56 l/h to 35 l/h.

In Figure 8 are shown exhaust gases temperatures from all 6 cylinders in the function of fuel flow change at 2350 RPM.

Curves of exhaust gases temperature in engine working regime 2450 RPM (Figure 7) confirm theoretical trends from Figure 1. Exhaust gases temperature is maximum at fuel flow of 55 l/h that presents ideal stoichiometric air-fuel mixture ratio.

Exhaust gases temperature in engine working regime 2350 RPM (Figure 8) does not have theoretical trend, instead it has got two temperature peaks (at fuel flow from 45 l/h and 35 l/h).

All vibration measuring can be shown in timing and frequent domain. Based on results shown in timing domain, it is not possible to get relevant data regarding changes of amplitudes at certain frequencies i.e. vibration levels on characteristics working frequencies of propulsion group elements. Vibrations are measured in frequency domain from 0 Hz to 200 Hz, in a such way that in parallel with vibrations on main frequencies there could be analysed higher harmonics and subharmonic vibrations of main frequencies.

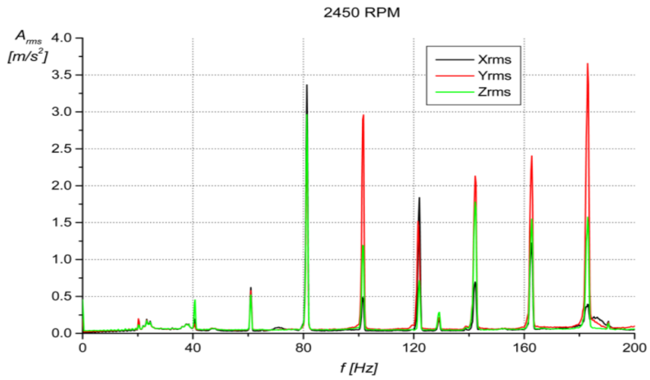

Figure 9. Averaged vibration frequency spectra in leaning process at 2450 RPM (fundamental frequency 40.83 Hz)

To show measured vibration, it has been chosen linear scale on both abscissa (X-axis) and ordinate (Y-axis) to achieve the quickest recognition of most dominant vibration and their frequencies [15].

Data were captured in the frequency range 0-200 Hz, using 801 point Fourier transforms with a Hanning window and a 50% overlap and frequency resolution of 0.25 Hz.

In Figures 9 and 10 are shown averaged vibration frequency spectrums from an engine during the leaning process in regimes 2450 RPM and 2350 RPM toward all three axis.

In further analysis of frequencies of 40.83 Hz and 39.16 Hz which are corespondengine shaft revolutions of 2450 RPM and 2350 RPM, will be called fundamental frequencies.

In Figures 9 and 10 it is easy to recognise that in the leaning process at both engine working regimes the dominant RMS of acceleration is on propeller legs crossing frequencies FPK (81.67 Hz and 78.33 Hz) in the directions of X and Z axis.

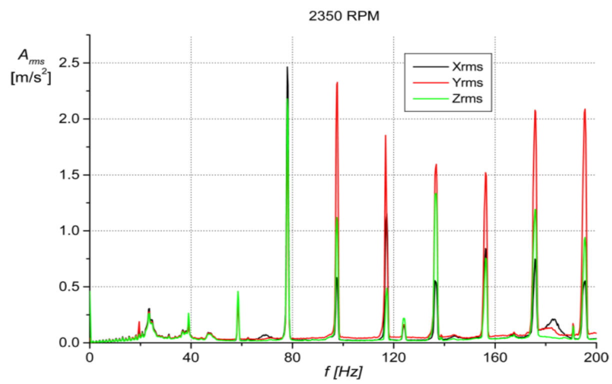

Figure 10 - Averaged vibration frequency spectra in leaning process at 2350 RPM (fundamental frequency 39.16 Hz)

In the Y axis direction, in both mentioned working regimes of the engine, RMS acceleration is dominant at higher harmonics and semiharmonics frequencies. Observed phenomena on the Y axis is characteristic of horizontal compact engine due to horizontaly positioned pistons.

Table 2 Values of measured RMS accelerations and characteristic parameters of a working engine

RPM	BPF	Fuel Flow	Max EGT	Max CHT	HP	Max A_{rms}
[o^{-1}]	[Hz]	[l/h]	[F]	[F]	[%]	[m/s^2 RMS]
2450	81,67	70	1379	423	67	X: 4.706 Y: 3.648 Z: 4.016
		65	1414	434	68	X: 4.036 Y: 3.103 Z: 3.432
		60	1458	438	69	X: 3.381 Y: 2.925 Z: 3.165
		55	1516	438	70	X: 3.194 Y: 2.597 Z: 2.867
		50	1460	423	69	X: 3.688 Y: 2.908 Z: 3.180
		45	1436	399	68	X: 3.482 Y: 2.512 Z: 2.756
2350	78,33	55	1349	405	55	X: 3.745 Y: 2.477 Z: 3.268
		50	1432	410	57	X: 3.484 Y: 2.450 Z: 3.111
		45	1487	410	57	X: 3.244 Y: 2.311 Z: 3.023
		40	1429	398	56	X: 3.358 Y: 2.398 Z: 3.062
		35	1468	382	56.5	X: 2.487 Y: 1.392 Z: 2.032

This characteristic and previously mentioned temperature deviation of exhaust gases on theoretical curve are closely connected and indicating quality of combustion process.

In Figure 12 it is shown waterfall diagram for leaning regime on 2350 RPM in Y axis direction. In the main diagram it can be seen decreasing of vibrations on a double value of main frequency and increase in vibrations on frequency three time greater than the main one, and it presents combustion frequency. Dispersion of energy at frequencies a few times greater than the main frequency, apart from showing on disorder in quality of combustion process it can present the existance of some other engine malfunction [8]. With accurate examination of the engine, it was proven that the engine is in a good technical condition.

RMS accelerations are dominant in two out of three measured axis and occur on blade pass frequency BPF. In this resarch an emphasis is concentrated on the analysis of RMS accelerations measured on frequencies of BPF.

Blade pass frequency BPF can be calculates as:

$$BPF = N \cdot f \qquad (1)$$

where are:

f - fundamental frequency of engine shaft revolutions

N - number of propeller blades.

In Table 2 are shown the values of RMS acceleration measured on the engine on blade pass frequency BPF, in longitudinal X, cross Y and vertical Z axis.

In the same table are shown characteristic parameters of a working engine.

In Figures 11 and 13 are shown engine power HP [%], temperature on cylinder head CHT [°F], fuel flow qg [l/h] and RMS acceleration Arms [m/s2] in directions of X, Y and Z axses in a function of relative temperature of exhaust gases EGT [°F]. The drawn curves are based on data from Table 1 for engine working regimes at 2450 and 2350 RPM.

Maximum value of engine power HP and temperature at cylinder head CHT, in both engine working regimes, are connected to maximum temperature of exhaust gases EGT. Changing trend of these changes fits theoretical fundamentals of leaning processes and thier values decrease with lowering of EGT.

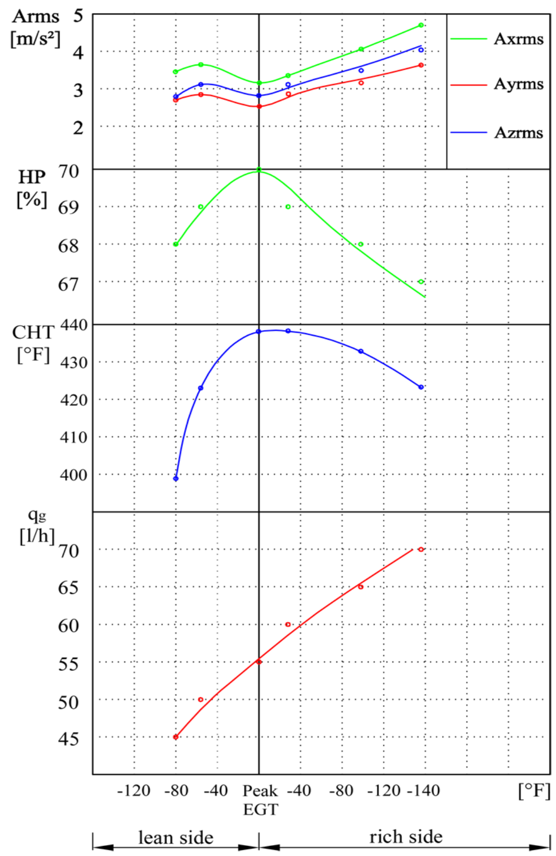

Figure 11. RMS accelerations of engine vibrations, engine power, CHT, and fuel flow as in function of relative temperature from exhaust gases for 2450 RPM and BPF=81.67 Hz

Values of RMS acceleration in the direction of all three axes decrease to the minimum with increase of EGT to the maxumum values. Decreasing of vibration level is more expressed at 2450 RPM than at 2350 RPM. The explanation of the fact that RMS accelerations are the smallest at maximum values of EGT, is found in the fact that this combustion is the closest to stoichiometric one.

In X and Y axes directions vibrations levels in both engine working regimes are nearly the same, while in Z axis direction RMS acceleration is changing on 2350 RPM.

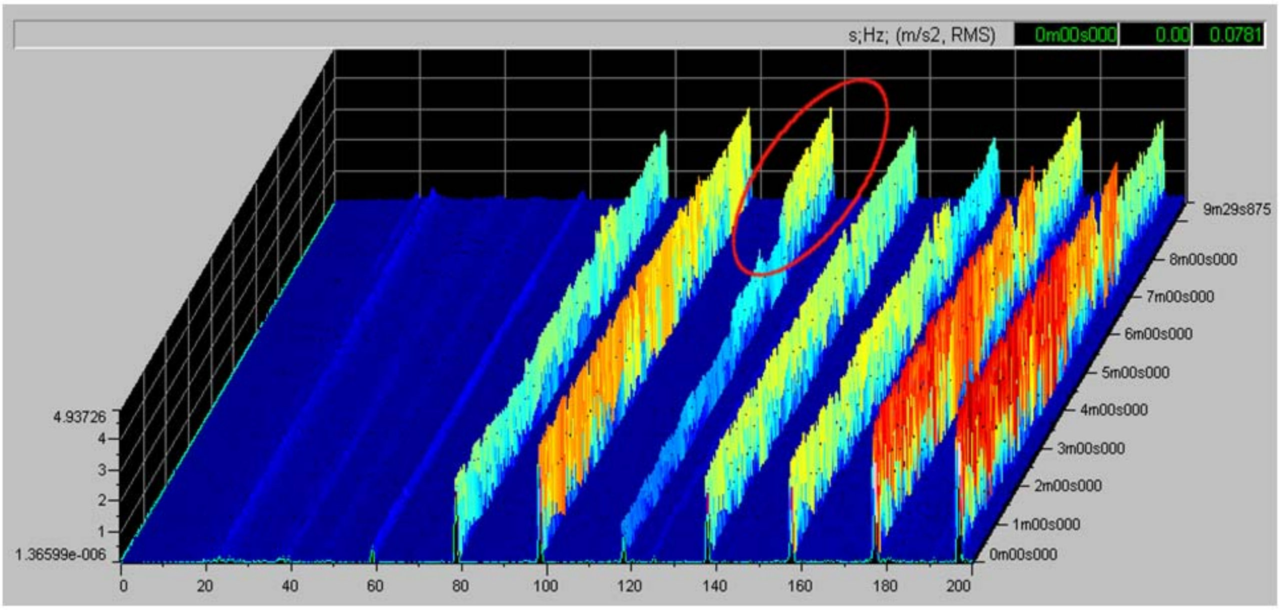

Figure 12. Waterfall diagram for engine leaning regime on 2350 RPM in y axis direction

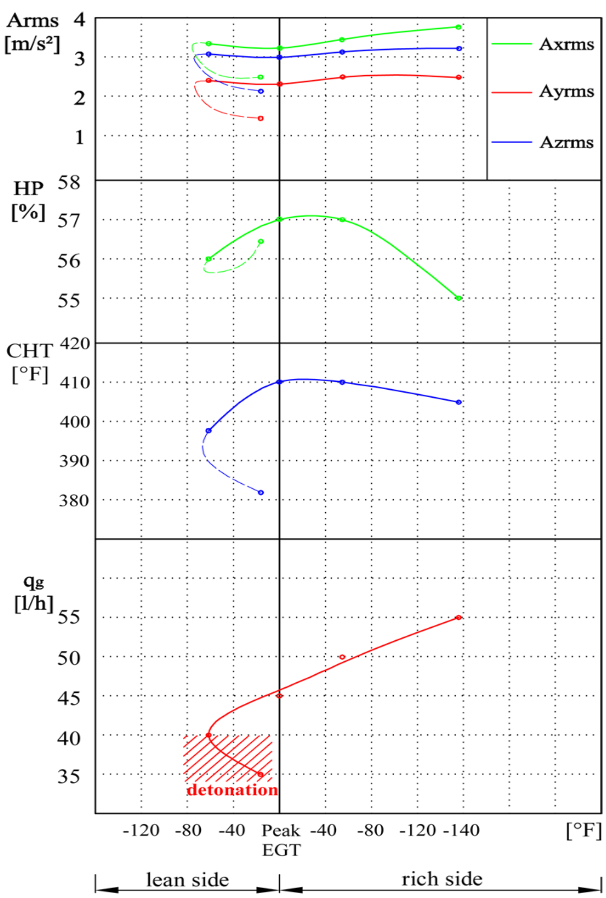

Figure 13-RMS accelerations of engine vibrations, engine power, CHT, and fuel flow as in function of relative temperature from exhaust gases for 2350 RPM and BPF=78.33 Hz

Based on measurements, it is concluded that on analyzed frequency with appearance of explosion looks of vibrations change and level of vibrations is lower.

From the above we can conclude that most dominant impact on RMS accelerations in directions of X and Y axes, on the observed frequencies, exist aerodymics convention flow of propeller. Diference in vibration size for listed engine working regimes, in the direction of Y axis, indicates the resource that contributes to size of vibrations existing on working engine.

6. CONCLUSION

For the plane with piston propeller propulsion group to achieve proposed performances it is necessary not only to monitor engine working parameters and plane flight but it is also necessary to complete measurements and analisys of engine vibration spectrum.

Vibrations are measured in frequency domain from 0 to 200 Hz. To measure not only vibrations on fundamental frequencies, it is also necessary to analyse vibrations on higher harmonics and semi-harmonics of fundamental frequencies.

Based on analysis of experimental results produced at engine leaning stage while in plane flight stage, it is concluded that RMS accelerations of engine vibrations on frequency of passing blades BPF, are inversely proportional temperature of exhaust gases EGT.

Reduction of vibration level with increasing EGT is strongly expressed at working regime of 2450 RPM than at the working regime of 2350 RPM.

The lowest measured values of RMS acceleration for vibrations in all three axes correspond to maximum values of exhaust gases temperature EGT. This conclusion is related to both analyzed engine working regimes: 2450 RPM and BPF=81.67 Hz and for 2350 RPM is BPF =78.33 Hz.

By this it is confirmed that maximum value of RMS acceleration of vibrations in the observed direction, with maximum value of EGT, is a good indicator for the existence of quality fuel/air mixture, i.e. the mixture that is with its properties the closest to stoichiometric one. This knowledge is a good basis for rational use of planes while they are in the engine leaning regime.

In the leaning regime at 2350 RPM in the direction of Y axis, there is noted dispersion of energy on frequencies few times greater than the fundamental frequency, indicating disorders in combustion quality.

By measuring vibrations on the engine, that can be easily seen the appearance detonating combustion on frequency three times greater than the fundamental one, which will obviously make it easier to exploit and maintain the engine.

The most dominant influence on RMS acceleration in the directions of X and Z axses, on analysed frequencies, has dynamic flow around propeller. Difference in size of vibrations for listed engine working regimes, in the direction of Y axis, indicates the resource which contributes to vibration size that has working engine.

Based on the size of measured RMS accelerations of engine vibrations, requirement is established to continue the research on vibrations transfer directions from the engine onto the pilot. It is estimated that vibrations measured on the engine can have impact on the pilot with a great intensity and it fully justifies investments required to continue the research.

In addition to the above direction, further researches can be developed towards vibration diagnostics method in establishing the state of the engine in different working regimes throughout the whole plane flight.

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УТИЦАЈ ПРОМЕНЕ САСТАВА СМЕШЕ ВАЗДУХОПЛОВНОГ КЛИПНОГ МОТОРА НА НИСКОФРЕКВЕНТНИ СПЕКТАР ВИБРАЦИЈА ИСПИТИВАЊЕМ АВИОНА У ЛЕТУ

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Познавање извора вибрација на авиону је битан предуслов за моделирање адекватног пригушења на уочене побудне вибрације. У раду су приказани резултати и анализа истраживања промена у нискофреквентном спектру вибрација на мотору авиона Ласта. Промене вибрација се, услед различитих режима рада и стања мотора, преносе са мотора на седиште пилота, као последица промене односа горива и ваздуха у смеши ваздухопловног клипног мотора и мере се у току лета авиона. Измерене вредности вибрација дате су у функцији промене радних параметара мотора. Приказани су испитно-мерни системи који се користе током истраживања динамичких карактеристика вибрација. Резултати истраживања показују да познавање вибрација на мотору пружа широке могућности за оцену одзива клипноелисне погонске групе на промену односа квалитета смеше горива и ваздуха у поступку линовања мотора.