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LANDING GEAR FAILURES CONNECTED WITH HIGH-PRESSURE HOSES AND ANALYSIS OF TRENDS IN AIRCRAFT TECHNICAL PROBLEMS

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Abstract. Reliability and maintenance analysis in aviation industry focused on a main objective of the accident and incident investigations what are help to better understand the causes of accidents. In the article suggested the underlying concept by scorecard of situations what lead to aviation accidents. In the present research, the aviation accident connected with a landing gear and a problem of failure to follow maintenance instructions during a maintenance on aircraft landing gear hydraulic drive was under an investigation, on an example of root cause analysis of the failure of hydraulic flexible high-pressure hoses. The approach presented in this research of experimental measurements, based on fluid pressure measuring, high-pressure hoses vibration measuring and frequency's analysis. By spectrum analyses was found that high-pressure hoses are most susceptible to deformation at frequencies to the response of the fluid within, as well as at hoses material resonance frequencies. The compact version of hoses is more deformational on the resonance points than a standard version of hose. In final according to analyses, was established that disrespect of the frequency conditions was leaded to causes irreversible degradation changes of the hose inner structure and occurrence of material defects inside layers contact what lead in final step to hose failure.

Keywords: aircraft, landing gear, hydraulic drive, high-pressure hose, failure, maintenance, risk scorecard, non-destructive diagnostics.

Introduction: failures in aviation and the scorecard of technical problem risks

The main objective of the accident and incident investigations are to help better understand the causes of accidents and to learn how to prevent it in a future. Usually, researchers used different accident models as a basis for collecting data and identifying causal factors what lead to accidents. Since, accident models play a role in identifying causal factors, they can lead to bias towards considering only certain causes, from another side the appropriately designed and applied models can help uncover causes that may was missed, according to Leveson (2004).

The aircraft and pilot, operating the aircraft, constitute object what should be investigated like one system in a segment of time when an accidents is taken a place. Several researchers analysed an aviation accidents to find and evaluated a trends and highlight the most top causes in aviation accidents (Bazargan & Guzhva, 2007; Boyd, 2017; Rao & Marais, 2018). According to the review on general aviation safety, the are taken a focusing on topics: including operations in hazardous weather conditions (Fultz & Ashley, 2016); influence of geographical region on accident causation (Grabowski et al., 2002; Masiulionis & Stankūnas, 2018); human error (Shappell et al., 2017; Arinicheva et al., 2020) and technical problem (Boyd, 2015) in accidents causation. In these researches the frequently highlight causes such as inflight loss of aircraft control and problems during a landing. Despite the best efforts of safety analysts, regulators and manufacturers, these predictable causes continue to be most frequently cited accidents in the reports.

Since, the relatively high frequency of general aviation accidents could be due to multiple reasons including an technical problem of aircrafts (Rao & Marais, 2020). According to the review of accident models (Saleh et al., 2010; Bazargan & Guzhva, 2011; Insua et al., 2019; Latorella & Prabhu, 2000; Zhang & Mahadevan, 2019) is suggested the underlying concept by scorecard of situations what lead to aviation accidents, shown in Figure 1a. According to the underlying concept, the accidents can be a result from a combination of factors (34%), such as mechanical failures (design errors) with a pilot errors and separate by pilot errors (19%) or aircraft mechanical problems (47%). Since,

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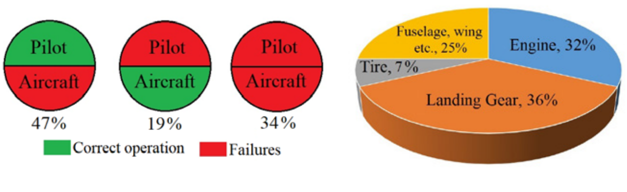

(a) (b)

Figure 1. Aviation problems risk scorecard: (a) – scorecard of situations what lead to aviation accidents; (b) – distribution of the maintenance related technical failures types for aviation incidents

the mechanical problems is common frequency pointed for an aviation accidents, the technical factors can be more detailed classified in to immediate causes (e.g., failure of the landing gear) and in to active (e.g., engine fire) or latent failures (e.g., improperly maintenance). According to the Marais and Robichaud (2012), mechanical failure (e.g., a component breaks: tire blows) or malfunction (e.g., a component does not operate correctly: jamming of the landing gears) is the primary type of technical maintenance incident. The distribution of the technical accidents types of incidents, shown in Figure 1b.

In the absence of maintenance, most system parts deteriorate due to use or age, which results in wear and eventually failure of the part, which may compromise system safety. According to (Civil Aviation Authority, 2015; European Union Aviation Safety Agency, 2019; International Air Transport Association, 2017; Japan Transport Safety Board [JTSB], 2019; Matuszczak et al., 2021; Che et al., 2021) from all aircrafts technical parts the engines and a landing gear are the most likely to result in a component failure incident. The 43% of all maintenance component failures involved the aircraft landing gears (directly to landing gear – 36% or tires – 7%), 32% failures involved by the engines and 25% by other technical parts (fuselage, wings etc.) failures. During that, a maintenance is plays an important role in the aviation industry. Not only an absence of maintenance can compromise system safety, but also an a small mistakes during maintenance can lead to aviation accident in a future. The scientific purpose of the current study is to investigate an aviation accidents connected with a landing gears and its maintenance, since, according to technical problems risk scorecard, it is the most common aircrafts system liable to failure.

1. An aircraft pipelines failure and maintenance problems

In the present research, the aviation accident connected with a landing gears and it maintenance was under an investigation, since, according to technical problems risk scorecard, it is the most common aircrafts system liable to failure. Usually, the problem with a landing gear is lead to aircraft accident during a landing and damages of aircraft fuselage, since it sliding on a runway road until stopping, shown in Figure 2a by JTSB (2020). Generally, an aircraft landing gear (Figure 2b) hydraulic system consists of a fluid tank, pressure pump, antisurge booster, distribution valves, filters, accumulator's and actuators (cylinders) what connected to one system by a pipelines (Green, 1985). Depends from the aircrafts types their hydraulic drive

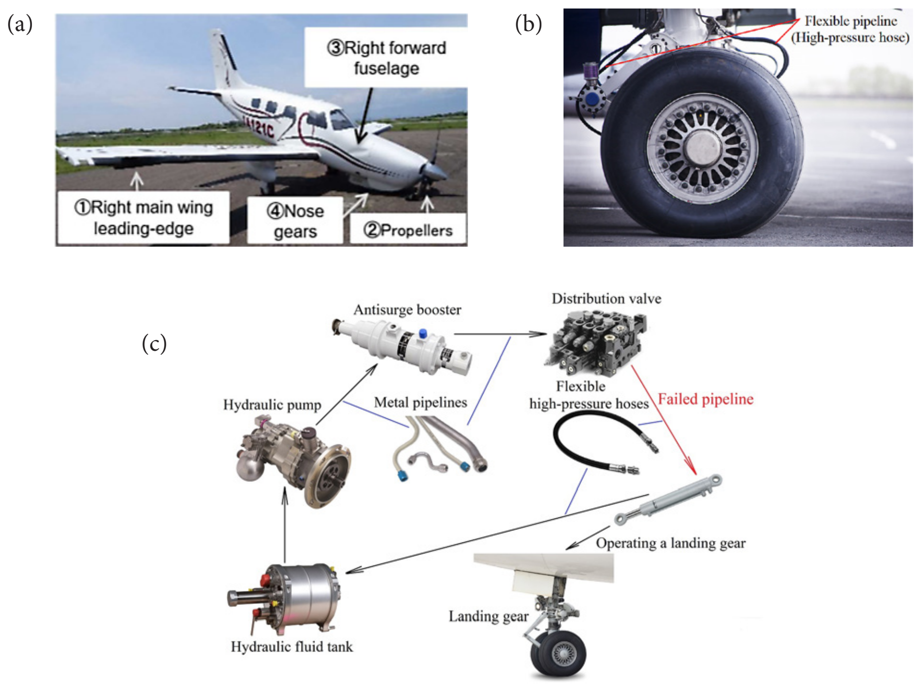

Figure 2. An aircraft pipelines failure: (a) – the accident during non-extended aeroplane landing gear (JTSB, 2020); (b) – an aircraft landing gear with a flexible pipelines; (c) – a schematic of the aircraft landing gear hydraulic system what under a study with a main components (by red colour pointed a failed pipeline)

components can be connected by metal pipes (Marais & Robichaud, 2012) or by flexible high-pressure hoses (Bogdevičius et al., 2021). The schematic of aircraft landing gear hydraulic system is shown in Figure 2c, indicating main accessories interconnected by flexible pipelines.

Failure of hydraulic pipelines is a critical problem in aviation industry. Factors what is associated with pipelines failure can be divided on a groups by: material characteristics problem (Tawancy & Al-Hadhrami, 2009; Lubecki et al., 2021); pipelines geometry problem (Firoozabad et al., 2016); during an environmental conditions (Fedorko et al., 2015; Karpenko et al., 2022); by internal or external loadings (Edjeou et al., 2018; Luczko & Czerwinski, 2014); residual stresses for a metal and plastic pipelines (Mankari & Acharyya, 2018; Urbanowicz et al., 2021) and in final by manufacturing flaws (Drumond et al., 2016). The interaction of these factors is very complex to analyse. But, the main contributing factors what lead to failure can be segregated on the basis during different operation conditions (Rezaei et al., 2015; Kubrak et al., 2021). By an example (Ułanowicz et al., 2020), in an aircraft hydraulic system, pressure pulsations and flow transients cause cyclic stresses leading to fatigue failure of pipelines. Due to the same reason, a limiting factor in the operational life of a hydraulic system is the fatigue life of hydraulic pipes (Gates Corporation, 2009). Under the influences of base excitation of engine and fluid pressure pulsation from the hydraulic pump, the pipelines may be subjected to the large amplitude bending resonance, which will lead the pipelines fretting fatigue, according to Gao et al. (2016). Therefore, it is very important to study fretting fatigue and pipelines failure mechanism for improving the reliability of hydraulic pipelines system of aircrafts landing gears.

According to the Marais and Robichaud (2012), aircraft hydraulic drive pressure lines should be detailed revised after 1200 flying hours and based on the physical appearance (e.g. chaffing, dents, nick marks) should be replaced. In the current study, the failure cases of the non-extending landing gear of the aircraft were selected for the analysis. According to the research of Zimmermann and Mendoca (2021) and National Transportation Safety Board (2006) accident summary report, the are a problem of failure to follow maintenance instructions during a maintenance on aircraft landing gear hydraulic drive. For example, a flexible high-pressure hose was replaced to the similar type but in compact version of hose. It is pertinent to mention that mid-air fracture of the replaced hydraulic hose caused loss of hydraulic fluid and pressure in the system, what lead to a problem of non-extending landing gear during an aircraft landing and endangered aircraft. Therefore, root cause analysis of the failure of hydraulic flexible high-pressure hoses, replaced by compact version during a maintenance, is deemed to essential.

2. Research objects

In current research, for comparing analysis and investigation a root cause analysis of the failure of hydraulic flexible high-pressure hoses, replaced by compact version during a maintenance a two layers braided high-pressure hose under investigation. The two layers braided high-pressure hose with inner diameters 1/2” is one of the most frequently used type of high-pressure hose in the hydraulic drives, according to Karpenko and Bogdevičius (2020). The standard two metal braid reinforced hydraulic hose (2SN) is accepted for investigation according to iTeh standards (2015a). The compact version (2SC) of two metal braid reinforced hydraulic hose according to iTeh standards (2015b) is accepted for investigation. The 3D models of high-pressure hose with two braid layers (2SN/2SC) are presented in Figure 3 (Karpenko, 2021). The high-pressure hoses consists of three main elements: the inner rubber layer, reinforcing layers and the outer rubber layer (protective cover).

Parameters of used high-pressure hoses in the research is presented in Table 1 and the material of high-pressure hoses layers presented in Table 2.

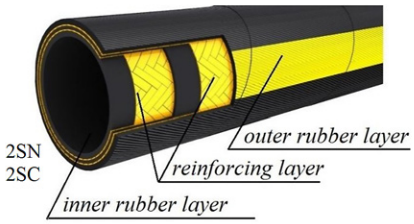

Figure 3. 3D view model of two metal braid high-pressure hose

Table 1. Physical and geometrical parameters of the high-pressure hoses

Type	Inner diameter, mm	Outer diameter, mm	Max working pressure, bar	Min brake pressure, bar	Weight, kg/m
2SN	1/2” or 12.7	23.2	275	1100	0.63
2SC	1/2” or 12.7	20.4	275	1100	0.54

Table 2. High-pressure hoses layers material

Type	Internal layer	Reinforcement	Layer between reinforcement	External covering
2SN	Synthetic rubber (NBR), extruded whole without joints	Steel wire (braid)	Synthetic rubber, uniform thickness	Anti-abrasive synthetic rubber NBR/PVC
2SC	Synthetic rubber (NBR), extruded whole without joints	Steel wire (braid)	Synthetic rubber, uniform thickness	Anti-abrasive synthetic rubber NBR/PVC

Presented high-pressure hoses standards are International Certificated and are used in the most hydraulic drives. The length of both high-pressure hoses, used in the current research is equal to 1 meter. According to the Table 1 and Table 2, the only one and a main different between a hoses – the compact versions has a less rubber material on 2.8 mm comparing to a standard version. The analysis is based between a standard and compact versions of high-pressure hoses deformations and frequency responses of hoses depend from the fluid flow and performed during an experimental measuring's.

3. Experiment test bench

The present experimental research was conducted towards establishing the reasons that led root cause of the failure of hydraulic flexible high-pressure hoses, replaced by compact version during a maintenance. The experimental tests is performed via Two Sample Measurement Design and based on One-Sample Statistical Method with Estimating Uncertainty in Repeated Measurements of data processing (Karpenko, 2021).

Test bench for the experimental research shown in Figure 4 and include: hydraulic drive station with a fluid pressure measuring equipment's, research objects (high-pressure hoses) and laser scanning system for measuring a vibration of hoses during fluid flow inside.

The experiment tests include a three measuring's of fluid pressure inside high-pressure hoses, and outer surface deformation velocity of hoses. For decrease during measurements was accepted and presented averages results of several measuring's. The percentage error value between measurements is displayed in the graphs of obtained results. The additional result obtained from experimental tests is frequency response of hoses based on spectrum analyses using Doppler Effect for better establishing the reasons that led root cause of the failure of flexible high-pressure hoses.

4. Analysis of obtained results and discussion

From the obtained experimental measurement's the fluid pressure inside high-pressure hoses shown in Figure 5 and outer surface displacement velocity of hoses, measured by laser scanning during the tests, shown in Figure 6.

The nominal fluid pressure inside the high-pressure hoses is approximatively $2.5 \cdot 10^6$ Pa with a fluid pressure amplitude $0.096 \cdot 10^6$ Pa. From the comparing of measuring by PSV sensor head on surface of high-pressure hoses, was found that maximum displacement was 0.0263 m/s on 2SN (amplitude of displacement velocity 0.0526 m/s) and maximum displacement on 2SC was 0.0297 m/s (amplitude is 0.0594 m/s), what confirm that a high-pressure hoses is deformation during a fluid pulsation inside. By the graphs from the Figure 6, can be point the

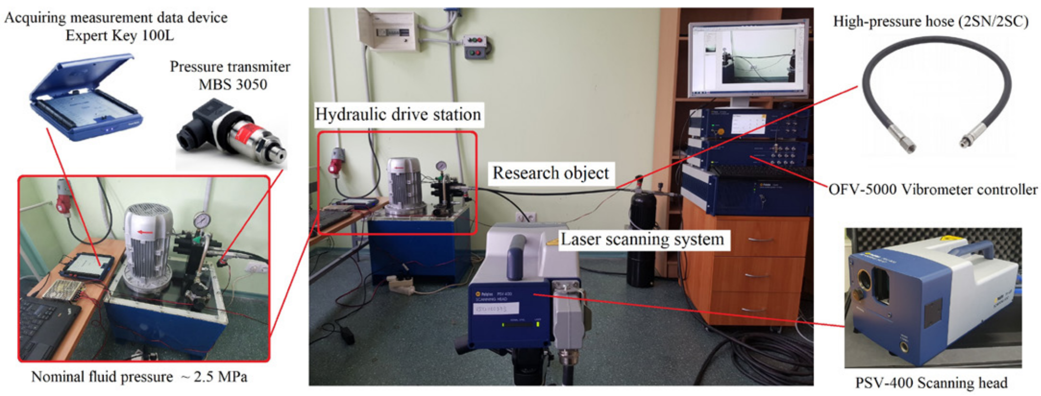

Figure 4. The test bench for experimental measuring

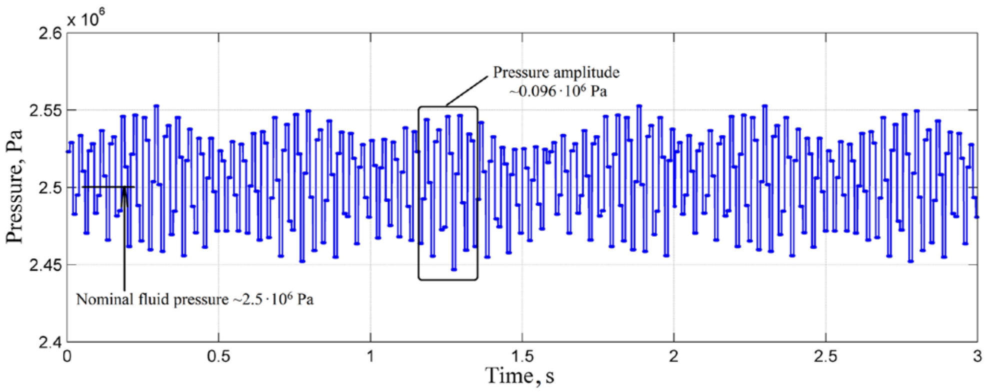

Figure 5. The fluid pressure inside high-pressure hoses

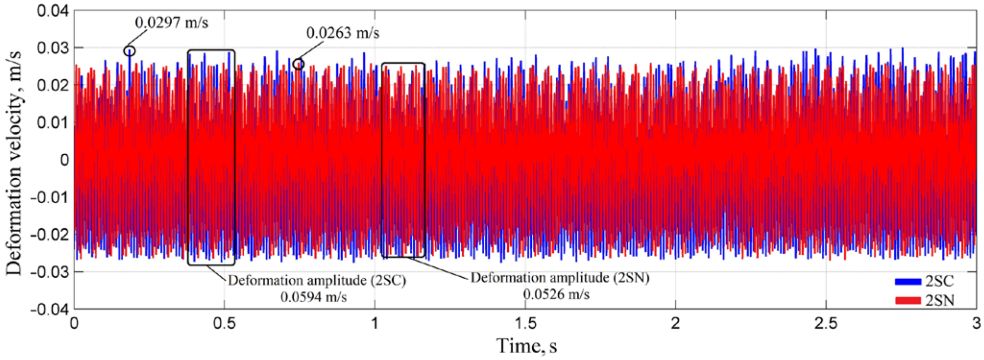

Figure 6. The outer surface displacement velocity of high-pressure hoses

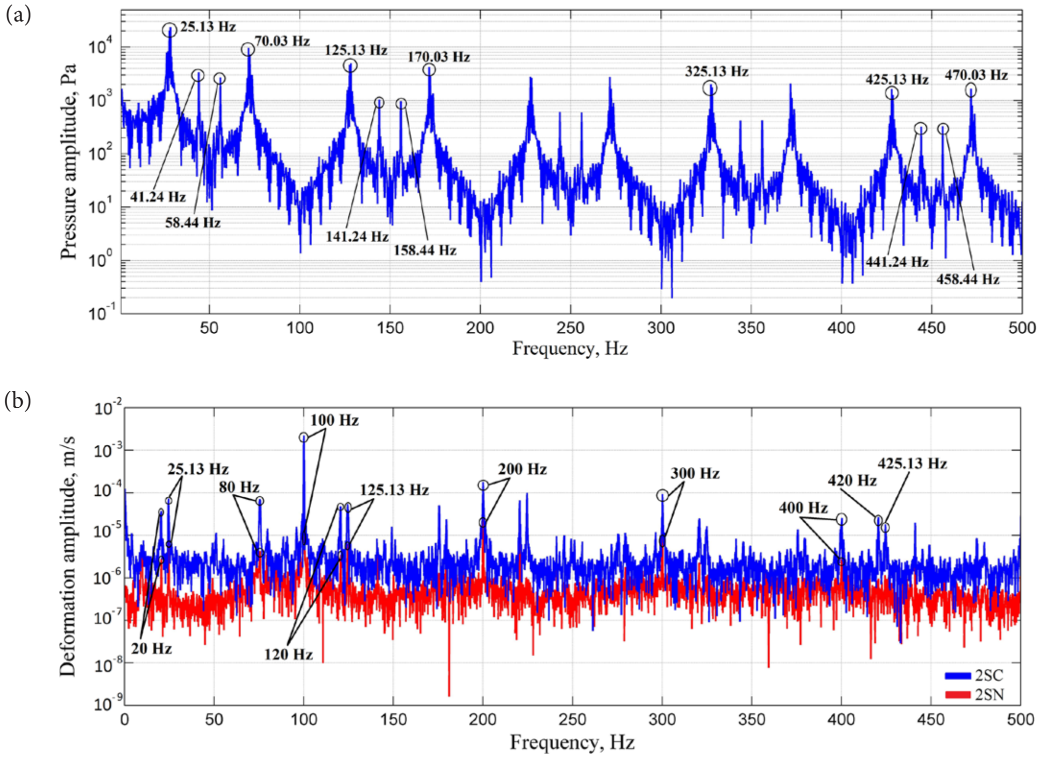

Figure 7. Graphs of spectrum analyses (in logarithm form): (a) – frequency's response of fluid pressure inside high-pressure hoses; (b) – frequency's response of high-pressure hoses surface

less displacement velocity of surface on standard version (2SN) of high-pressure hose and more displacement velocity on the surface of compact version (2SC) of high-pressure hose was obtained. That is due to the fact that in the standard version of high-pressure hose, in radial direction the rubber layers is thicker than in compact version.

The additional result obtained from experimental research is a fluid pressure frequency response inside high-pressure hoses, shown in Figure 7a, and frequency response of hoses, shown in Figure 7b, based on spectrum analyses by using Fourier transforms.

The frequency's response graph (Figure 7a) of fluid pressure inside the high-pressure hoses shows that the main fluid pressure amplitudes on frequency 25.13 Hz, 41.24 Hz, 58.44 Hz and 70.03 Hz with harmonic steps for each 100 Hz. According to the high-pressure hoses frequency analysis seems that main resonance frequency in the middle frequency range (up to 500 Hz), science in this frequency range the main resonant modes is observed. From frequency analysis it is seen that main and first resonance frequency of investigated hoses is 20 Hz with harmonic steps and maximum resonance amplitude at fifth harmonic – 100 Hz. A frequency 25.13 Hz, 125.13 Hz etc., also attended on hoses surface frequency response, that frequency is transmitted from fluid pressure pulsation and created ones from main resonance points.

By obtained spectrum analyses, it seems that high-pressure hoses are most susceptible to deformation at frequencies to the response of the fluid within, as well as at hoses material resonance frequencies. The compact version of hoses is more deformational on the resonance points than a standard version of hose. In the range of frequency from 300 Hz it can be observed that still a resonance points is existed for a compact version of high-pressure hoses, comparing to the standard version of hose. This one can be easier explained, since the compact versions has a less rubber material comparing to a standard version, in the standard version of hose the damping property is higher what lead to decrease the amplitude of hoses deformation and comparing to the compact version extinguish the resonance points after 300 Hz, according to the spectrum analyses. During that, a disrespect of the frequency conditions was leaded to causes irreversible degradation changes of the hose inner structure, creation of the cracks and occurrence of material defects inside layers contact what lead in final step to hose failure. That why is important to follow maintenance instructions, especially during a maintenance on aircraft landing gears hydraulic drive and use just a specified by manufacturing an elements for a changing. Obtained spectrum analysis of high-pressure hoses results even gives a reason to continue a research in direction of maintenance and reliability, since, in high-pressure hoses, there is a problem with damage of braided layer and the diagnosis and definitions of these damages requires a more detailed investigation. One way to diagnose and define damages in inner layers is to use non-destructive diagnostic methods and analysis results from the spectrum analysis.

Conclusions

The main objective of the accident researches is to help better understand the causes of accidents and to learn how to prevent it in a future. Since, the relatively high frequency of general aviation accidents could be due to multiple reasons including an technical problem of aircrafts, according to the review of accident models was suggested the underlying concept by scorecard of situations what lead to aviation accidents. Underlying concept include that the accidents can be a result from a combination of factors (34%), such as mechanical failures (design errors) with a pilot errors and separate by pilot errors (19%) or aircraft mechanical problems (47%). The mechanical problems is common frequency pointed for an aviation accidents and the technical factors was detailed classified. The 43% of all maintenance component failures involved the aircraft landing gear (directly to the landing gear – 36% or just a tires – 7%), 32% failures involved by the engines and 25% by other technical parts (fuselage, wings etc.) failures.

In the present research, the aviation accident connected with a landing gear and a problem of failure to follow maintenance instructions during a maintenance on aircraft landing gear hydraulic drive was under an investigation, on an example of root cause analysis of the failure (hydraulic flexible high-pressure hoses changed by a compact version during a maintenance). Proposed approach of experimental measurements is based on fluid pressure measuring, high-pressure hoses vibration measuring and frequency's analysis.

The nominal fluid pressure inside the high-pressure hoses was approximatively $2.5 \cdot 10^6$ Pa with a fluid pressure amplitude $0.096 \cdot 10^6$ Pa. From the comparing of measuring by PSV sensor head on surface of high-pressure hoses, was found that maximum displacement was 0.0263 m/s on 2SN (amplitude of displacement velocity 0.0526 m/s) and maximum displacement on 2SC was 0.0297 m/s (amplitude is 0.0594 m/s). The frequency's response of fluid pressure inside the high-pressure hoses was showed that the main fluid pressure amplitudes on frequency 25.13 Hz, 41.24 Hz, 58.44 Hz and 70.03 Hz with harmonic steps for each 100 Hz. According to the high-pressure hoses frequency analysis was found that main and first resonance frequency of investigated hoses is 20 Hz with harmonic steps and maximum resonance amplitude at fifth harmonic – 100 Hz.

By performed spectrum analyses was found that high-pressure hoses are most susceptible to deformation at frequencies to the response of the fluid within, as well as at hoses material resonance frequencies. The compact version of hoses is more deformational on the resonance points than a standard version of hose. In the range of frequency from 300 Hz it can be observed that still a resonance points is existed for a compact version of high-pressure hoses, comparing to the standard version of hose, that is due to the fact that in the standard version of high-pressure hose, in radial direction the rubber layers is thicker than in compact version of the same two metal braided high-pressure hose. Finally, according to analyses, should be pointed that disrespect of the frequency conditions was leaded to causes irreversible degradation changes of the hose inner structure and occurrence of material defects inside layers contact what lead in final step to hose failure. Performed spectrum analysis of high-pressure hoses results even gives a reason to continue a research in direction of maintenance and reliability, since, in high-pressure hoses, there is a problem with damage of braided layer and the diagnosis and definitions of these damages requires a more detailed investigation.

Disclosure statement

The Author has no conflicts of interest to declare that are relevant to the content of this article. The Author did not receive support from any organization for the submitted work.

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