IRSTI 37.21.02 https://doi.org/10.26577/JGEM.2023.v68.i1.07

A.B. Togay*, G.T. Suleimenova, A.S. Nyssanbayeva

Al-Farabi Kazakh National University, Kazakhstan, Almaty
*e-mail: togay.anara@bk.ru

REPEATABILITY OF AIRCRAFT VIBRATION AT THE INTERNATIONAL AIRPORT OF ALMATY

The movement of air particles is a very mobile medium, which is usually chaotic or turbulent in nature. Turbulence (translated from latin "turbo" means vortex) is a state of the atmosphere in which a vortex and wind can form horizontal and vertical cracks. The influence of atmospheric turbulence on the flight of the aircraft is manifested in sudden and unexpected changes in the horizontal flight configuration. A sharp and sudden change in flight mode due to the effect of turbulence is usually called a "vibration" or bump. Vibration depends on the physical state of the atmosphere, time of year, time of day, altitude of the terrain, its orographic features and meteorological conditions. In the article, work was carried out to identify the features of vibration propagation and its relationship with meteorological parameters at the airport of Almaty in the period from 2015 to 2019. As a result, it was showed that the maximum frequency of vibration at the considered standard levels of 960-110 hPa corresponds to the cold period of the year and occurs at the height of takeoff and landing. As for the connection between air temperature and vibration, it has found that vibration is most common in the temperature range from -4 ° C to 0 ° C. It was also revealed that the frequency of vibration most often coincides in cloudless conditions, i.e. the total number of cases is 439 (00 hours) and 609 (12 hours), respectively, the frequency is 61 and 84%. During the study of the relationship between vibration and clouds, it was recorded that vibration exists only with 3 different clouds, i.e. Ci, Ac and Sc. The results of the study can be widely used in the fields of civil aviation, military aviation.

Key words: atmospheric turbulence, vibration, vibration repeatability, aerological diagram, altitude, air temperature, cloud cover, vibration intensity.

А.Б. Тоғай *, Ғ.Т. Сулейменова, А.С. Нысанбаева

Әл-Фараби атындағы Қазақ ұлттық университеті, Қазақстан, Алматы қ.
*e-mail: togay.anara@bk.ru

Халықаралық Алматы әуежайы бойынша әуе кеме дірілінің қайталанушылығы

Ауа – бөлшектердің қозғалысы әдетте ретсіз немесе турбулентті сипатта болатын өте жылжымалы орта. Турбуленттілік (латынша «турбо» сөзінен аударғанда құйындалу, иірім дегенді білдіреді) – бұл атмосфераның түрлі өлшемінде құйын мен желдің көлденең және тік жарықтары пайда бола алатын жай-күйі. Атмосфералық турбуленттіліктің ұшақтың ұшуына әсері көлденең ұшу режимінің күрт және кенеттен өзгерістерінде көрінеді. Турбуленттіліктің әсері салдарынан ұшу режимінің күрт және кенеттен өзгеруін әдетте «діріл» немесе рема деп атайды. Діріл атмосфераның физикалық жағдайына, жыл уақытына, тәулік уақытына, жергілікті жердің биіктігіне, оның орографиялық ерекшеліктеріне және метеорологиялық жағдайларға байланысты. Мақалада 2015-2019 жылдар аралығындағы дірілдің Алматы қаласы әуежайы бойынша таралу ерекшеліктері мен оның метеорологиялық параметрлермен байланысын анықтау жұмыстары жүргізілді. Нәтижесінде, қарастырылған стандартты 960-110 гПа деңгейлердегі дірілдің қайталанушылығының максимумы жылдың суық кезеңіне сай және ең көп ұшу-қону биіктігінде кездесетіні көрсетілді. Ауа температурасы мен дірілдің байланысына келетін болсақ, діріл көбінесе -4°C пен 0°C температура аралығында болатындығы анықталды. Сондай-ақ, дірілдің қайтанушылығы көбінесе бұлтсыз жағдайларда сәйкес келетіні анықталды, яғни жалпы жағдай саны 439-ға (00 сағат) және 609 (12 сағат) тең, сәйкесінше қайталанушылығы 61 және 84%-ды құрайды. Діріл мен бұлттылықтың байланысын зерттеу барысында діріл тек 3 түрлі бұлттылық кезінде, яғни Ci, Ac және Sc болатындығы тіркелді. Зерттеу нәтижелерін азаматтық авиация, әскери авиация салаларында кеңінен қолдануға болады.

Түйін сөздер: атмосфералық турбуленттілік, діріл, дірілдің қайталанушылығы, аэрологиялық диаграмма, биіктік, ауа температурасы, бұлттылық, дірілдің қарқындылығы.

Тогай А.Б.*, Сулейменова Г.Т, Нысанбаева А.С.
Казахский национальный университет имени аль-Фараби, Казахстан, г. Алматы
*e-mail: togay.anara@bk.ru

Повторяемость болтанки воздушного судна в международном аэропорту Алматы

Движение частиц воздуха представляет собой очень подвижную среду, которая обычно носит хаотичный или турбулентный характер. Турбулентность (в переводе с латинского «турбо» означает вихрь) – это состояние атмосферы, при котором вихрь и ветер могут образовывать горизонтальные и вертикальные трещины. Влияние атмосферной турбулентности на полет самолета проявляется в резких и внезапных изменениях горизонтального режима полета. Резкое и внезапное изменение режима полета из-за эффекта турбулентности обычно называют «болтанкой» или ремой. Болтанка зависит от физического состояния атмосферы, времени года, времени суток, высоты местности, ее орографических особенностей и метеорологических условий. В статье проведена работа по выявлению особенностей распространения болтанки и ее связи с метеорологическими параметрами по аэропорту города Алматы в период с 2015 по 2019 годы. В результате было показано, что максимум повторяемости болтанки на рассматриваемых стандартных уровнях 960-110 гПа соответствует холодному периоду года и встречается на высоте взлета и посадки. Что касается связи температуры воздуха и болтанки, то установлено, что болтанка чаще всего находится в интервале температур от -4°С до 0°С. Также выявлено, что повторяемость болтанки чаще всего совпадает в безоблачных условиях, т. е. общее число случаев равно 439 (00 часов) и 609 (12 часов), соответственно повторяемость составляет 61 и 84%. В ходе исследования связи болтанки и облачности было зафиксировано, что болтанка существует только при 3-х различных облачностях, т. е. Ci, Ac и Sc. Результаты исследования могут быть широко использованы в сферах гражданской авиации, военной авиации.

Ключевые слова: атмосферная турбулентность, болтанка, повторяемость болтанки, аэрологическая диаграмма, высота, температура воздуха, облачность, интенсивность болтанки.

Introduction

Atmospheric turbulence is a dangerous meteorological phenomenon that severely affects the aviation communication. An aircraft entering a zone of severe turbulence faces hefty consequences such as vibration and change in altitude, which might even lead to critical accidents and crashes (Babikov, M.A., 1951:199 p), (Nerushev A.Ph., 2019: 206 p).

According to a study by the National Transportation Safety Council (USA), from 1983 to 1997, turbulence caused 609 deaths and 823 injuries (Uhlenbrock, 2007:664p), (Kauffman P., 2002: 99p), (Kravchenko V.I., 2021: 322 p). From 1980 to 2008, 234 turbulence-related accidents were recorded in the United States alone, and caused 298 serious injuries and 3 deaths (Storer, 2019:2081p), (aerocorner.com/blog/planes-turbulence-crash). Due to high frequency of atmospheric turbulence, the aviation industry suffers financial losses up to $750 million per year. Additionally, compensation for passengers annually exceeds $10 million (John R. Mecikalski et al., 2007:1589p), (Williams, 2014), (Atmosphere…, 1991).

Accordingly, forecasters and researchers of AMSC deal with complex and responsible tasks analyzing and predicting atmospheric turbulence.

Currently, the presence of turbulence in the atmosphere and the vibration of aircrafts on the territory of Kazakhstan can be only analyzed by the reports of pilots. The disadvantage of such data collection is that turbulence is recorded only in the air, which can be limited to temporary intervals (according to the flight schedule) and spatial isolation (routes, airfield areas).

The purpose of this article is to study and analyze the features of the distribution of atmospheric turbulence and aircraft vibration at the airport of Almaty.

To conduct the analysis, it is necessary to perform the following task: calculate the repeatability of aircraft vibration according to the following meteorological parameters (altitude, temperature and cloud cover), taking into account the intensity of vibration affecting the aircraft.

Materials and Methods

As the initial data, the vibration of aircraft caused by atmospheric turbulence was taken. The calculations were carried out for the period 2015-2019 from 960 HPA to 110 hPa. By analyzing the results of vibrations, it is possible to determine the course of atmospheric turbulence.

Using a five-year collection of data from the aerological diagram of Almaty Airport for 2015-2019, it is possible to analyze the number of vibration cases and collect data about the height, temperature, cloud cover, wind speed and direction at which vibrations were observed. Data collection has been received by placing an order on the website flymeteo.org (https://flymeteo.org/arhiv/arhiv.php#forma).

The aerological diagram is intended for visual computational and graphical analysis and forecast of aerometeorological flight conditions based on the data of complex radiosonding of the atmosphere.

The meteorological service uses forms of aerological diagrams with rectangular coordinate systems (aerological diagram №1 (ADP-1) and aerological diagram №2 (ADP-2). The ATP-1 blank has a pressure scale from 1050 to 100 kpa, and the ATP-2 blank from 1050 to 10 gPa. In this work ADP-1 is used.

The analysis of the aerological diagram provides for the allocation of layers and levels in the atmosphere characteristic of the distribution of temperature, humidity and wind, the calculation of convection parameters, the determination of cloud layers of non-convective origin, icing zones, aircraft turbulence and condensation traces, as well as the calculation of a number of thermal and hygrometric characteristics of the air used in various methods of analysis and prediction of meteorological quantities and weather phenomena(https://flymeteo.org/stat/diagram.php).

For the period from 2015 to 2019, a 5-year series was built with the registration of data on the aerological chart for each day. Taking into account the intensity of the aircraft vibration, the altitude, temperature, cloud cover, wind speed and direction were determined at the level at which it was recorded.

The width of the series of variations of fixed meteorological parameters was made using the Stergy formula.

$$\lambda = \frac{x_{max} - x_{min}}{1 + 3.32 \log n} \quad or \quad \lambda = \frac{x_{max} - x_{min}}{k} \qquad (1)$$

where,

$k = 1 + 3.32 \log n$ when n=30

$k = 5 * \log n$ when n>100

$$x_{low} = x_{min} - \frac{\lambda}{2} \qquad (2)$$

where,

x_{low} – lower limit of the 1st class interval

After this, the class ranks were built. Using these results, various graphs were constructed in Microsoft Excel.

The analysis of this new method, which is used for the first time, has not been compared with the works of other authors for this reason.

Results and Discussion

Atmospheric movements are disordered. At the same time, the zones associated with turbulence are located not only on the layer of precipitation, but also on the layers in a calm state. The thickness of the layers does not exceed 300-600 m, and their length is 60-80 km. However, sometimes turbulence takes over even higher layers with a thickness of 2-3 km to 1000 km. The stronger the intensity of turbulence, the less is the thickness and duration of the turbulence layer in the atmosphere (Baranov A.A., 1975), (Shakina N.P.,2016)

The duration of the turbulent zone lasts a few hours only, and in some cases it might reach up to a day. Turbulence is often observed in the lower layers of the atmosphere (up to an altitude of 2-3 km) (Brovkin V.V., 2016), (helpiks.org/4-22100.html). In higher layers, it is spotted less often, and usually closer to the tropopause layers. In the stratosphere, at altitudes up to 15-16 km, the repeatability of turbulence is reduced back to its usual state. The turbulence that causes aircraft shaking is associated with the horizontal currents described above, specifically with vertical movements of air (in particular, with the friction layer, during the intense solar heat of the Earth, the current flow at an altitude of 8-14 km, tropopause, mountainous areas, ascending and descending currents, etc.) (Cherednichenko A.V. and Cherednichenko V.S., 2017a:124p), (*meteoinfo.ru / glossary/4806-atm-vert-structure*).

Some aircraft are more sensitive to the effects of turbulence than others. The light aircraft is prone to shocks and has a significant impact even in weak turbulence. Some reports of turbulence come from operational military jet aircraft with a high degree of stability (WMO Geneva: 2007. – 53 p), (Leshenko, G.P., 2010:11p).

For example, supersonic aircraft – from a few tens of meters to several hundred meters, and supersonic aircraft – from several hundred to several thousand meters.

A very large vortex pulls the plane towards its current. At the same time, the aircraft does not vibrate, but, on the contrary, together with the flow, causes a uniform change in flight altitude. The plane is also not affected by very small turbulent vortices, as they are different signs and mutually compensating. In addition, the modern aircraft also has an impressive volume, so it is not able to act on small vortices by inertia (Bogatkin O. G., 2005:45p), (Bogatkin O.G., 2009: 84 p), (Saphanova T.B., 2014:119p). In general, modern aircraft are able to respond to the range of such vortices within 20-800 m (Vorontsov P. A., 1966:296p.).

Almaty Air Station was chosen as the research area of this work.

Almaty airfield operates in two categories with a minimum (the meteorological minimum of the second category is from 60 to 30 m with a decision-making height of 800 to 400 m with a visibility distance on the runway), but the nature of local synoptic processes and orographic features of the airfield create conditions for the flight and landing of all types of aircraft to have very thick fog, and the landing of all types of aircraft is completely excluded (Pchelko I. G., 1962a:94p.).

The total number of vibration cases at Almaty Airport between 2015 and 2019 amounts 1,446, of which 718 cases were registered in 00 hours, and 728 cases in 12 hours, as shown in the table below (Tables 1, 2).

Table 1 – Almaty Airport for 2015-2019 prevalence of recorded vibration cases in 00 hours between

Years	Winter			Spring			Summer			Autumn			Total
	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	
2015	24	18	15	15	20	7	5	3	8	8	14	12	149
2016	14	18	19	7	15	9	4	2	8	7	17	14	134
2017	27	16	14	9	16	9	6	9	7	12	16	15	156
2018	21	20	17	12	15	7	2	3	4	19	15	18	153
2019	22	16	16	9	13	4	4	4	3	8	10	17	87
Total	108	88	81	52	79	36	21	21	30	54	72	76	718

As shown in Table 1, according to the obtained annual values, it is shown that there is an uneven distribution of cases with recorded vibration at 00 hours. The maximum number of vibration cases correspond to the winter season (277), and the minimum number of cases correspond to the summer season (72). The maximum number of vibration cases were spotted in December 2017 (27), the minimum cases were spotted in July 2016 (2) and June 2018 (2).

Table 2 – Almaty Airport for 2015-2019 prevalence of recorded vibration cases in 12 hours between

Years	Winter			Spring			Summer			Autumn			Total
	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	
2015	16	17	12	17	15	11	6	0	3	15	17	19	148
2016	16	25	15	6	11	10	4	7	1	3	15	13	126
2017	20	25	18	15	16	11	9	7	9	7	11	19	167
2018	17	24	10	8	11	17	5	2	13	16	15	12	150
2019	18	13	12	14	14	8	3	9	12	10	10	14	137
Total	87	104	67	60	67	57	27	25	38	51	68	77	728

As shown in Table 2, according to the obtained annual values, it is shown that the conditions of the recorded vibrations that occurred at 12 hours are uneven and have a slight distribution difference from the vibration state at 00 hours. The maximum number of vibration cases correspond to the winter season(258), and the minimum number of cases correspond to the summer season(90). The maximum number vibration cases were seen in December 2016 and 2017 (25), the minimum in July 2015, were not seen the whole year.

The aircraft vibration's repeatability was calculated to clearly show the specificity of the vibration propagation in the above-mentioned time period of 00 hours and 12 hours for 5 years (Figure 1).

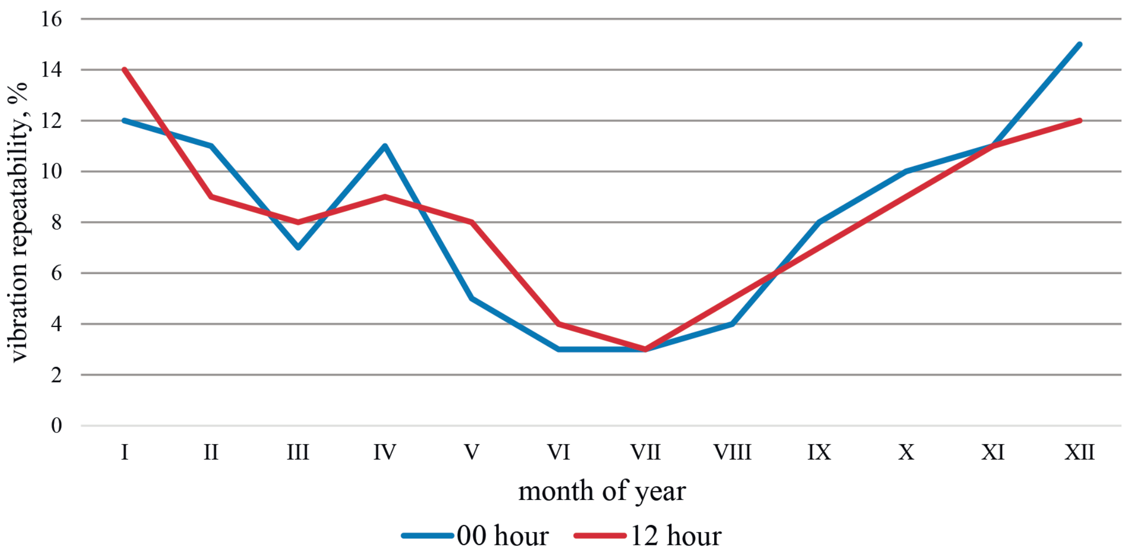

Figure 1 – Almaty Airport for 2015-2019 repeatability of recorded vibrations during the day and evening periods, %

As shown in Figure 1, the greatest frequency of vibration corresponds to the coldest half of the year, which makes up 66% of 00 hours and 63% of 12 hours in all cases. And in the warm period of the year, the vibration resistance is relatively low, respectively 34% and 37%.

The work of I. G. Pchelka explains the reason of the phenomenon mentioned above (Pchelko I. G., 1962b:97p), (Shakina N.P., 2013:27p), (Shusharina L.M., 2019:12p). According to his study, it was noted that in the cold period of the year, the repeatability of vibrations in the upper troposphere were much higher than in the warm period of the year. Rain clouds are the main reason that cause precipitation recorded during the cold season. Hence, the vibrations within a radius of 35 km are necessarily observed. While calculating the repeatability of vibrations, it is mandatory to take into account the length of the control area. The longer the area, the bigger is the number of vibrations that could be reflected on other layers.

Furthermore, let's look at the vertical structure of atmospheric turbulence. The repeatability of vibrations is calculated in relation to cases of completed information about the controlled altitude level. Below is a histogram showing the repeatability of the vibration distribution by height in the lower and upper floors.

The visual representation of the annual rate of vibration repeatability at different altitudes in the morning and evening for the period, from January 2015 to December 2019, is shown in a histogram down below (Figure 2).

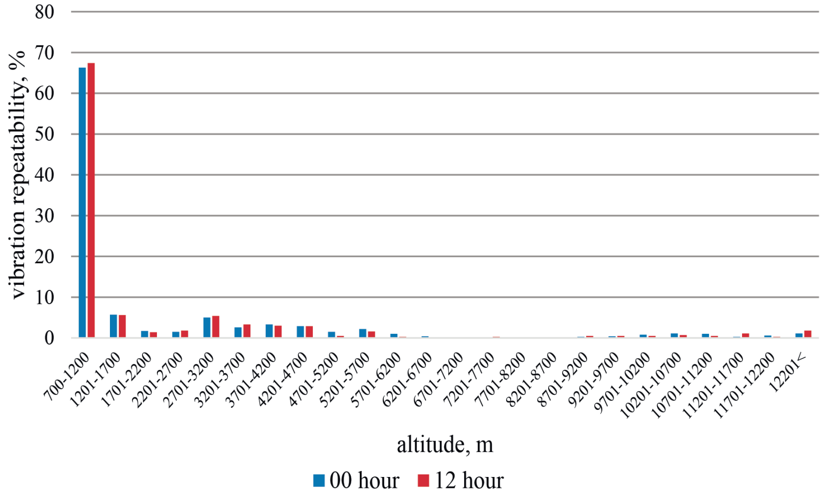

Figure 2 – Almaty Airport for 2015-2019 repeatability of vibrations in the morning and evening periods between, %

Figure 2 shows the frequency of vibrations that occur in the troposphere and the levels of altitudes. The analysis of recorded data provides the following concepts:

1) the aircraft is exposed to the greatest vibration during takeoff and landing in the lower four thousand layers of the troposphere, especially in the layer up to 0.7-1.2 km, the record shows 476 (00 hours) and 491 vibration conditions (12 hours) (repeatability of 66.3% and 67.4%, respectively);

2) after 4.7 km, the repeatability of vibrations is significantly reduced;

3) the relative minimum repeatability was spotted on the 6.2-10.2 km floor.

At an altitude of 6.2 -10.2 km, as shown in Figure 8, the vibration repeatability is low, and the repeatability of vibrations vary from 0 to 0.8%.

This zone is called the "turbulence zone with minimal repeatability" on the territory of Kazakhstan (Cherednichenko A.V. and Cherednichenko V.S., 2017b:128p).

In the study of atmospheric turbulence, not only the vertical distribution, but also the atmospheric temperature is of great importance. Because of an uneven temperature distribution, thermal turbulence occurs and increases the possibility of vibration. The following is the repeatability of temperature vibrations at the airport of Almaty for a period of 5 years.

The values of temperatures obtained during the day (00 hours) and night (12 hours) for a period of 5 years with gradations of every 5 °C are recorded, and it is shown how many vibration conditions were observed between these values (Figure 3).

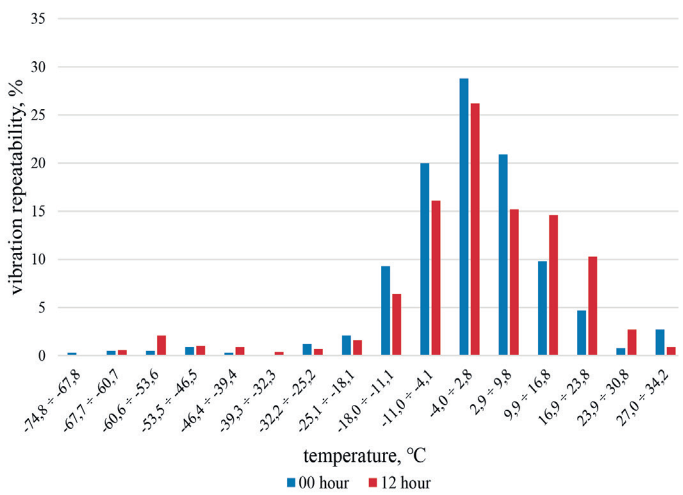

Figure 3 – 2015 – 2019 recorded vibration repeatability at temperatures between 00 hours, %

As shown in Figure 3, the maximum vibration repeatability is between minus 4,0 and 2,8 °C both in the morning and in the evening, and the minimum repeatability is between minus 74,8 and minus 18,1 °C.

By studying the relationship between temperature and vibration, we can conclude that the maximum and minimum frequency of vibration was observed in the morning and evening periods between 2015 and 2019 in the following temperature range. In the morning, the maximum number of cases is 365 (50.8%) cases in the area of temperatures below 0°C, and in the evening, 394 cases (58.9%) were recorded at positive temperatures.

According to the data for 2015-2019, the vibration intensity was divided into 3 groups: weak, medium, and strong. And they are shown on the aerological diagram, respectively, as follows (figure 4):

Figure 4 – Determination of vibration intensity on the aerological diagram: 1-weak; 2-medium; 3-strong

In general, low intensity cases are the most dominant vibration conditions at the airport of Almaty. As shown in the gitogram below (fig.5)

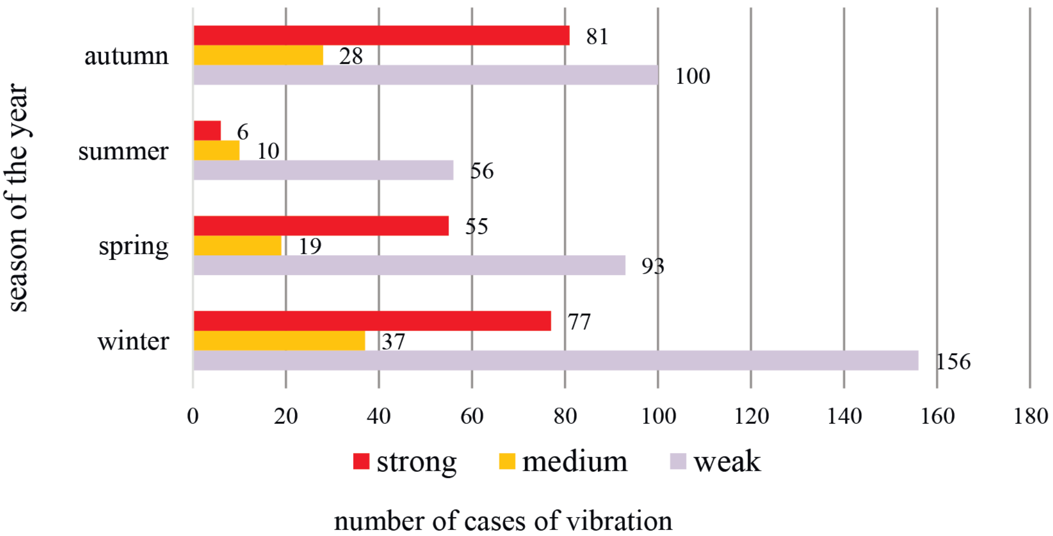

Figure 5 – 2015-2019 in the period from June to early morning, the frequency of vibrations of varying intensity is recorded, %

As shown in Figure 5, in the morning, the highest number of repetitions are vibrations with a weak intensity, the number of vibration cases with a weak intensity is 405, i.e. 56.4%. The 2nd most noticeable intensity is the strongest intensity. According to the 5-year data, the number of cases of strong-intensity vibrations is 219, which is 30.5% repeatability. And the least common type of intensity is medium-intensity vibration. In the period from 2015 to 2019, the state of their stay is only 94, i.e. 13.1%.

According to the pilots, most often the vibration is observed when flying inside the clouds, and then, according to forecasters, it is most often observed in cloudless regions. This difference can be explained by the fact that forecasters record all cases as having vibrations, while pilots record only cases when vibrations were felt. Moderate and strong vibrations are often observed in cloudy weather months.

Let's look at how the intensity of vibration in the evening spreads by season (Figure 6).

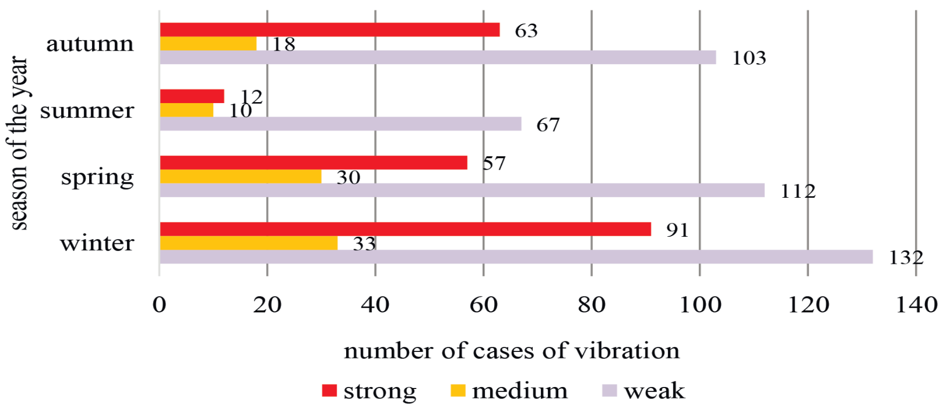

Figure 6 – 2015-2019 repeatability of vibrations of varying intensity, recorded in the evening during the season, %

As shown in Figure 6, in the evening, the most frequent repetitions are vibrations with a weak intensity, the number of vibration cases with a weak intensity were 414, i.e. 56.8%. The following intensity is the strongest intensity. According to the 5-year data, the number of cases of strong-intensity vibrations were 223, which is 30.8% repeatability. And the least common type of intensity is medium-intensity vibrations. In the period from 2015 to 2019, the state of their stay was only 91, i.e. 12.6%.

Beautiful fabric clouds (cumulus) and especially rain-cloud clouds (cumulanimbus) are turbulent due to the ascending and descending currents formed inside. For the period 2015-2019, the relationship of vibration with cloudiness is shown in figure 7.

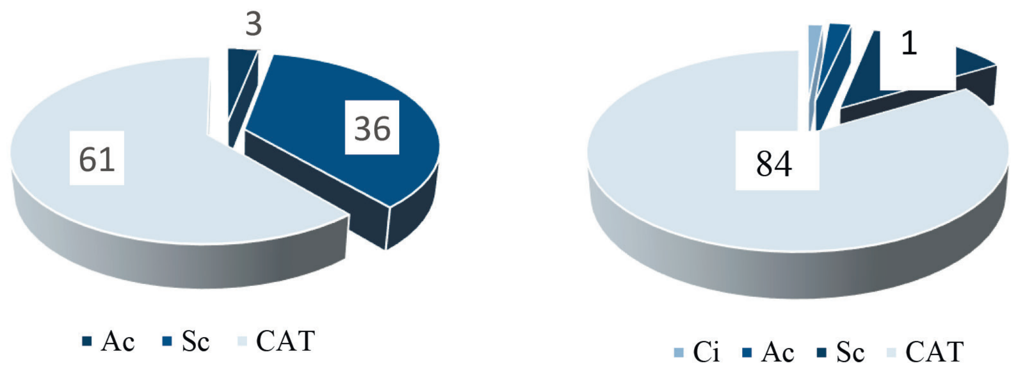

Figure 7 – Data for the period 2015-2019 repeatability of vibrations during different clouds in the morning(figure on the left) and evening(figure on the right), %

As shown in Figure 7, in the period from 2015 to 2019, vibrations were observed only in 3 different clouds. These are the CI, Ac, and Sc clouds. The maximum vibration is observed at both times in clear weather, the total number of cases is 439 (00 hours) and 609 (12 hours), with a frequency of 61 and 84%, respectively. And the minimum frequency of vibration is observed in the morning at Ac, the number of cases is 22, the frequency is 3%, and in the evening at Ci, the number of cases is 10, the frequency is 1%.

Conclusion

After conducting a statistical analysis of the 5-year course of vibration, the following conclusions were obtained:

1) in the period from 2015 to 2019, according to the aerological chart, the number of vibration cases during 1765 days was recorded at the airport of Almaty, which equals to 718 (00 hours) and 728 (12 hours). It can be seen that in the five-year course of the vibration, two maximum and two minimum cases were recorded. Accordingly, the maximum number of repetitions was observed during the winter season – December and January (13%), and the minimum in the summer period– June and July (2%). Therefore, when planning flights in December and January, it is necessary to accurately predict the vibration.

Additionally, the greatest relapse corresponds to the cold half-year, which accounts for 66% of all cases, and during the warm period of the year, it can be seen that the repeatability of vibrations was relatively low (36%).

2) considering the specifics of the meteorological parameters distribution (temperature, cloud cover) that fluctuate with vibration, referring to statistical characteristics, the following results were achieved:

2.1) it was found that the maximum frequency of vibration repeatability in the period from 00 to 12 hours, respectively, in the period from 2015 to 2019 was often from minus 4,0 and 2,8 °C which equals to 138 cases (20.8%) and 124 cases (18.5%). This means that the vibration is most likely within this temperature range, so pilots often need to increase their precautions within this temperature range.

2.2) in terms of cloud cover, in the period from 2015 to 2019, vibrations were observed during turbulence in the open sky, which gives a positive result, since there are often no convective actions during turbulence in the open sky. Also, based on 5-year statistics, vibrations of weak intensity predominate. However, even under the influence of such turbulence, there are strong vibrations, and it is very difficult to theoretically analyze their occurrence and predict it.

References

Arhiv ajerologicheskih diagramm. – Razrazond, 2013-2022. // flymeteo.org/sounding /arhiv_one_month.php

Aviacionnye faktory riska. Programma obuchenija i podgotovki. – Zheneva: 2007. – 53 p.

Babikov. M.A. Aviacionnaja meteorologija. – L.: Izdatel'stvo Dosarm, 1951. – 199 p.

Baranov A.A., Solonin S.V. Aviacionnaja meteorologija. L.: Gidrometeoizdat, 1975. – 391 p.

Bogatkin O. G. Aviacionnaja meteorologija. – SPb.: RGGMU baspasy, 2005. – 327 p.

Bogatkin O.G. Osnovy aviacionnoj meteorologii. Uchebnik. – SPb.: Izd. RGGMU, 2009. – 339 p.

Brovkin V.V. Vozdushnye massy i atmosfernye fronty. – Samara, 2006. // meteocenter.net/meteolib/vm.htm

Cherednichenko A.V. i Cherednechenko V.S. Tropopauza i maksimal'nyj veter nad territoriej Kazahstana // Uchebnoe posobie, 2017. – 124-127 p.

Dashko N.A. Kurs lekcij po sinopticheskoj meteorologii. – Vladivostok: DVGU, 2005.

Gidrometcentr Rossii – 2022. //meteoinfo.ru/glossary/4806-atm-vert-structure

Helpiks.Org – 2014-2022. // helpiks.org/4-22100.html

John R. Mecikalski et al. Aviation Applications for Satellite-Based Observations of Cloud Properties, Convection Initiation, In-Flight Icing, Turbulence, and Volcanic Ash // Bulletin of the American Meteorological Society – 2007. – №88. 1589-1607 p.

Kauffman P., The business case for turbulence sensing systems in the US air transport sector, J. Air transport Management, 2002 Vol 8, Issue 2, pp 99-107.

Kravchenko V. I., Knjazev V. V. Molnija i letatel'nye apparaty. V treh tomah. Tom 2. Porazhajushhie vozdejstvija i destabilizirujushhie vlijanija grozovyh razrjadov. – Har'kov. Izdatel': Miroshnichenko O. A., 2021. – 322 P.

Leshhenko, G.P. Aviacionnaja meteorologija: uchebnik. / G.P. Leshhenko. – Kirovograd: GLAU, 2010. – 332 p.

Nerushev A.F., Ivangorskij R.V. Opredelenie zon turbulentnosti v verhnej troposfere na osnove sputnikovyh izmerenij. – Sovremennye problemy distancionnogo zondirovanija Zemli iz kosmosa. 2019. T. 16. №1. 206 p.

Pchelko I. G. Ajerosinopticheskie uslovija boltanki samoletov v verhnih slojah troposfery i nizhnej stratosfere. – M.: Gidrometeorologicheskoe izdatel'stvo, 1962. – 94 p.

Rukovodstvo po prakticheskim rabotam meteorologicheskih podrazdelenij aviacii vooruzhennyh sil SSSR, M. Voennoe izdatel'stvo Ministerstva oborony SSR, 1981.- p.

Safonova, T.V. Aviacionnaja meteorologija: uchebnoe posobie. / T.V. Safonova. – Ul'janovsk: UVAU GA(I), 2014. – 237 p.

Shakina N.P. Lekcii po dinamicheskoj meteorologii. – M.: TRIADA LTD, 2013. – 160 p.

Shakina N.P., Ivanova A.R., Prognozirovanie meteorologicheskikh uslovii dlya aviatsii (Forecasting meteorological conditions for aviation), Moscow: Triada Ltd, 2016, 312 p.

Shusharina L.M. Musralinova G.T. Praktikum po sinopticheskoj i aviacionnoj meteorologii. – Almaty, 2019. – 60 p.

Sostavlenie i analiz ajerologicheskoj diagrammy. – Razrazond, 2013-2022. // flymeteo.org /stat/diagram.php

Storer L.N., Williams P. D., Gill P. G. Aviation Turbulence: Dynamics, Forecasting, and Response to Climate Change // Pure and Applied Geophysics – 2019. – № 176. 2081-2095 p.

Uhlenbrock N. L., Bedka K. M., Feltz W. F., Ackerman S.A. Mountain wave signatures in MODIS 6.7-μm imagery and their relation to pilot reports of turbulence // Wea.Forecasting. – 2007. – № 22. 662–670 p .

Voroncov P. A. Turbulentnost' i vertikal'nye toki v pogranichnom sloe atmosfery. – L.: Gidrometeorologicheskoe izdatel'stvo, 1966. – 296 p.

Williams P.D., Increased light, moderate, and severe clear-air turbulence in response to climate change, Advances in Atmospheric Sciences, 2017, Vol. 34, pp 576-586.