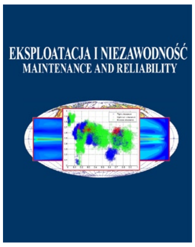

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Innovative application of quality methods in the homogeneity assessment of the F-16 aircraft group in terms of generated noise

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Highlights

- Measurements of F-16 aircrafts noise during takeoff.
- The stability of production assessment method applied in noise significance estimation.
- Contribution to the state of knowledge on the homogeneity of the F-16 noise results.
- Basis for the decision regarding the sample selection data in further noise analyses.

Abstract

Given the high-power concentration of combustion engines used in military aviation, it is reasonable to measure the instantaneous surges in the sound pressure level. Therefore, a research question was raised regarding the differences in this level for various aircraft engines of the same type (F100-PW-229) to assess their size and statistical significance. The aim of the paper is to discuss the attempt to check the significant difference between the parameters of the acoustic level generated by the aircraft engines. The measurements were carried out for 32 engines of the F-16 Block 52+ multirole aircraft during takeoff process. The parameters of noise in the point system and in the octave distribution were subject to analysis. Statistical methods dedicated to assessing production stability, i.e. the Shewhart chart, were applied. The results of the analysis showed that the discrepancies generally do not exceed a value of $+/- 3\sigma$. Therefore, it can be concluded that the analogous results for F-16 noise are homogeneous. Thus, the Shewhart chart method proved useful for assessing the homogeneity of these measurements.

Keywords

noise measurements, F-16 aircrafts, the homogeneity assessment, quality control methods

1. Introduction

Air traffic and aircraft ground services generate noise, the main source of which are the engines operating in the air and on the tarmac [7, 12, 59]. Sometimes, increased noise is also the result of efforts to increase the performance of aircrafts [28]. So, a fundamental element of protection against noise is the practical application of scientific and technological achievements. The optimization of takeoff and landing profiles and correct generation of airport takeoff and approach trajectories should constitute an inseparable element of improvement of the airport management systems. This, however, forces continuous exploration of new possibilities of forecasting of the impact of this type of noise on the environment. The assessment of acoustic effects and noise is already a well-researched topic in the road vehicles application [1, 42]. In the aviation, both in the civil and the military ones the noise is the constantly researched problem. In [16] a statistical analysis of the relationship between pilot actions and noise emitted into the environment was undertaken. In [22, 33, 50] authors analyze the problem of environmental noise pollution at various airports. One of the still unsolved problems related to the aircraft noise measurement is the assessment of the level and structure of noise in different examples of the same aircraft. It is generally known that each of them generates different level of acoustic pressure, mainly due to different technical, operating and weather conditions [17, 48, 49]. The evaluation of different types of noise can be presented in many ways. The first one is the evaluation based on the measurements, processing and analysis of physical quantities, i.e. acoustic pressure. In the presented investigations, no other approach than the subjective assessment of the nuisance of aircraft noise has been taken into account (frequently used and based on subjective popular survey evaluation) [9, 26, 45]. Another approach is the determination and assessment of psychoacoustic indicators (or complex models) such as loudness, tonality or roughness of sound [11, 41, 52]. There are also mixed approaches which includes both processing of physical quantities and assessment of psychoacoustic indicators [43]. These have not been taken into account in the paper.

The effectiveness of using the noise assessment has been successfully proven for both the maintenance and the reliability in different branches. There are various maintenance approaches which are taking into account different signal processing methods and main noise parameters in time domain (e.g. using wavelet transform in [18] or [29]) and frequency domain (e.g. using frequency filtration or/and Fourier

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transform as in [53, 55, 58]). However, especially in the case of reliability assessment of mechanical objects it is a very important issue because different noise parameters can be very good diagnostic information carriers [5, 25, 38, 54]. Therefore one can expect that a proper noise assessment is a crucial aspect in the aviation management. In the effect, it becomes fundamental to assess in what boundaries we can acknowledge the similarity of differences of the measured sound levels (analysing an individual measurement as a parameter for an objective aircraft noise assessment) in the cyclic investigations approach, identical in terms of the applied methodology. In this paper the first stage of the investigations was the performance of several series of measurements of the noise generated by the F-16 military aircraft during takeoff. The main purpose of this paper was to present a new way of the homogeneity assessment of the noise level distribution generated by aircrafts. The group of aircrafts is called as homogeneous in terms of the generated sound when the parameters describing the sound are within a defined range, and their deviations from the expected value/level are not statistically significant.

In practical training performed in tactical aviation bases it is required to maintain high technical efficiency of the aircraft. From this, among others, the maintenance of the imposed rhythm of flight training depends. Furthermore, the effectiveness of the system for the implementation of technical services performed on individual aircraft is connected to high technical efficiency of the system operation. Technical maintenance can be performed both within own internal units and outside the organization. The manner in which the periodic and pre-flight maintenance of the F-16 aircrafts are performed determines their technical condition, which directly affects the emitted noise level. A proper decision regarding the implementation of maintenance requires considering many factors, including the assumptions of the organization's aircraft operating policy and the requirements set out in its statute. However, it should be considered that the operation policy developed by the airworthiness unit relates to the previously identified conditions. It means that this data set is not limited. Thus, additional data mining related to aircraft technical condition parameter are required based on ongoing operations and continuous updating of the aircraft damage risk indicators. One of the possible indirect sources of this kind of knowledge may be the result of noise analysis using the Shewhart control charts. This means that the measurement results of selected aircraft, which significantly differ from the established reference range, may indicate to poor technical condition and the further need to unplanned maintenance action.

2. Selected methods of measurement and analysis of the aircraft noise

The assessment of the nuisance of aircraft noise in the airport surrounding environment in Poland is carried out based on long-term mean sound level determined as an average long-term value obtained from the equivalent sound levels A. The admissible noise level in the environment, expressed with the noise indexes L_{DWN} and L_N as well as L_{AeqD} and L_{AeqN}, is specified by the regulation of the Minister of Environment dated 14 June 2007 regarding the admissible noise levels in the environment [60]. It is differentiated depending on the category of geographical area and the type of facility or activities generating the noise. The situation is similar in Europe and worldwide, as confirmed in [23].

The L_{DWN} index determines the long-term mean sound level A expressed in [dB], obtained during all trials throughout the year, differentiated into time of day/evening/night. L_N is a long term mean sound level A expressed in [dB], obtained during all nights throughout the year. Besides, in order to determine and control the conditions of environment burden in reference to a single day, equivalent sound A indexes apply, expressed in [dB] for the daytime L_{AeqD} and nighttime L_{AeqN} respectively. These indexes apply in the performance of a long-term policy of environment protection against noise. The examples of works, in which they were used have been described in [2, 3, 44, 47].

In relation to a single flight operation, such as takeoff, cruise and landing, another index of objective noise nuisance applies - a noise A exposure one: L_{AE} [37, 51]. It appears as though instantaneous oscillations of the acoustic pressure are a very good parameter in the consideration of the discussed problem as well as the qualitative structure of the generated signal, as has been confirmed in [48]. In [17] a continuous measurement of noise in the vicinity of the Ben-Gurio airport was carried out, taking into account different types of aircraft, its operating conditions (aircraft height and takeoff time) and the weather. The main parameter under analysis was the instantaneous level of acoustic pressure, particularly its maximum peaks related to the takeoff.

A combination of the equivalent and the exposure sound levels has been presented in [24]. Based on the investigations, the authors confirmed that the sound level equivalent index (e.g. related to the daytime L_{AeqD}) may be a correct parameter defining the noise nuisance for high traffic airports, similarly to the instantaneous maximum sound level. If, however, the number of aircraft takeoff/landing operations amounts to approx. five per hour, these parameters begin to vary significantly, which, in the aspect of objective aircraft noise analysis excludes the equivalent sound level as the correct decision-making parameter [24].

Therefore, a research question arises whether we can check the comparability of sound A (L_{AE}) with the available measurement and analytic methods for different types of the same aircraft and whether we can infer on the entire group of a single type of aircraft based on a low number of measurements.

Advanced research results were performed in the USA. There are reports on experimental procedures addressing some jet-noise phenomena observed during the measurements made in the geometric near field of the jet produced by an engine installed on an F-22A Raptor. Following the reports, the results of the measured jet noise values such as general sound pressure levels (OASPL), spatial diversity of the spectral content and basic time wave properties were obtained. Based on these results, frequency-dependent radiation patterns were observed, two separate spectral peaks unique for full-scale jets were identified, and a non-linear content of acoustic shock was shown. Noteworthy is the observation resulting from the comparison of the spectral shapes for the 'military' and 'afterburner' engine mode measured at z = 15.2 m (see Fig. 1).

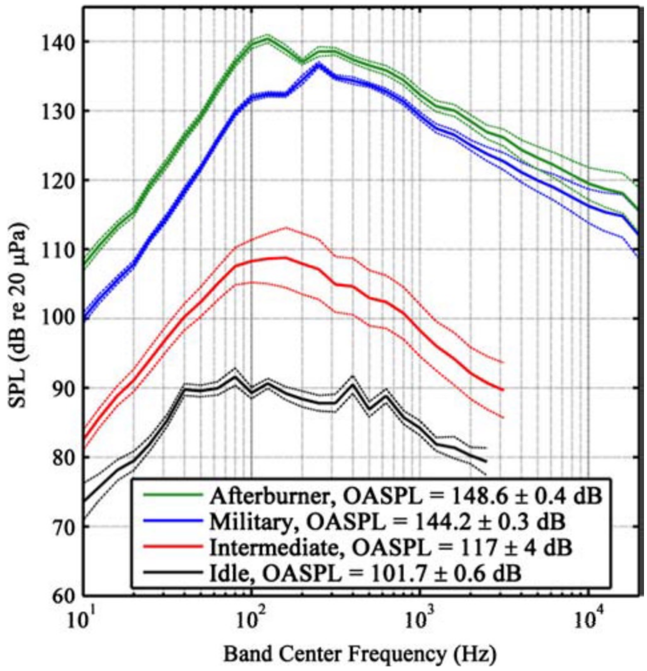

Fig. 1. 1/3 octave spectra measured along the reference array at z=15.2 m. Solid lines represent the SPL values averaged over all scans [56]

With the increase in power from ‘military’ to ‘afterburner’, high frequencies are boosted by approx. 3 dB, while low frequencies are boosted by approx. 8 dB. This is accompanied by a double-peak near the dominant frequencies [56]. Evidence of a double peak also appears in the flyover measurements of the F-15 ACTIVE Aircraft 30 and in the flyover measurements of a military jet. Information on the structure of the impact in the propagation wave was disclosed. Above the peak frequency of approx. 200 Hz, it reached an average of 3 dB / octave, up to the frequency of approx. 1.25 kHz [35].

Other research regarding the correlation analyses of ground-based acoustic-pressure measurements of noise from a tethered F-22A provided insights into the sound-field characteristics. To the side of the nozzle exit, the temporal-correlation envelope decays rapidly, whereas the envelope decays more slowly in the maximum radiation region and further downstream [19].

The Alabama research centre has developed an innovative measurement method. The purpose of the tool is to measure the far-field noise radiated by the engine plume. In addition, the tool is equipped with a prediction package based on a semi-empirical far-field acoustic radiation model and an existing CFD database of the engine plume. The tool is able to display both the predicted and the measured results in real time [14].

Military aviation noise tests are also carried out in Europe. Based on the United Kingdom restrictions to limit noise from low-flying military jet aircraft, special research was conducted. The limits are based on a scientific assessment of the actual noise characteristics of different aircraft types and, for operational reasons, they are in the form of speed and height restrictions. The project was based on both laboratory and field studies of the reactions of humans to such noise. Each noise characteristic (using examples of noise signatures obtained during field trials and controlled flyovers) and comments on its application and validity were considered[27].

The above-mentioned research results do not answer the research question regarding the possibility of assessing the homogeneity of the noise level distribution generated by aircraft. Therefore, the authors decided to validate the new application of the method of control of statistical parameters, particularly the control $\overline{X}$ chart –R, usually used in the industry for the assessment of the stability of the production processes [36].

3. Statistical parameter control method (control chart)

The Shewhart control chart is used to control the quality of production [30, 34] or control the widely understood analysis of multidimensional statistical data [8, 15]. In [13] the authors used this method (along with its different variances) for a statistical analysis and control of the water consumption in flush toilets in a public building. There are also some articles which are in opposition to the Shewhart control method. In [10] the main aim was to show the advantages of the Wiebe function utilization for statistical processing of data characterizing the nonhomogeneity of the combustion engine process between individual cycles. The results shown that statistical processing of data can be done by different ways, e.g. using Wiebe function. What is more important, it is significant due to reliability assessment of various technical object, especially complex machines [21]. However, the main issue is to collect an appropriate amount of homogeneous data. The above-mentioned examples indicate the topicality of this method in different scientific areas. Therefore, the authors decided to use it in the assessment of the homogeneity of the distribution of the noise level generated by F-16 aircraft.

The essence of the $\overline{X}$ –R chart is the control of statistical stability of a process performed through observation of the average value tracing $\overline{X}$ and the tracing of the range R from the samples of count n each (Fig. 2). The condition for the application of the chart is the assumption that an investigated characteristic has a normal distribution or similar to a normal distribution [32, 57]. The control chart is made of three parts [40]; the calculation form, the investigated statistical parameters variability graph (control chart tracings) and the descriptive part.

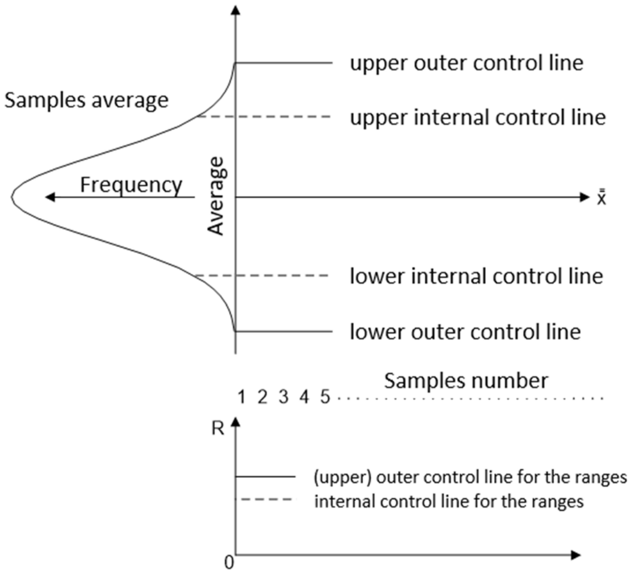

Fig. 2. Variability of the statistical parameters (chart $\overline{X}$ - R), proprietary data based on [20, 32]

The calculation form includes: subsequent numbers of samples, time intervals (frequency) between the subsequent samples and the sample count (ascertained individually for each kind of control chart due to different statistical parameters). Upon inserting the results for each element of the investigated sample into the control chart, an arithmetic average $\overline{X}$ of the results in the sample must be calculated (the sum of the results divided by the sample count/number of samples). The next step is the calculation of the range (the difference between the highest and the lowest value in the sample) [21].

The tracing of the variability of the investigated statistical parameters (control chart tracings). This part of the chart has two coordinate systems. On the horizontal axes of both systems we have the same scale denoting the subsequent number of the sample. In the vertical axis of the upper system we have a scale of numerical values (units, in which the measurement of the average values in the samples is performed). The scale range is limited to the interval of variability of the probable averages during the observation. The system pertaining to the ranges has the same scale but it is adapted to the scope of its variability (start of the scale at zero). The components of the tracing are: the central line determined as $\overline{\overline{X}}$), the external control lines (upper control limit - UCL and lower control limit - LCL) for $\overline{\overline{X}}$ and the external upper control line for the range. In the coordinate systems we can additionally introduce internal control lines that are to indicate changes in the process prior to the occurrence of the distortions [40]. Upon overlaying the results of the average value and the range on the appropriate tracing (corresponding to the value of the samples and its location on the vertical numerical axis) the tracing must be analysed. The occurrence of a point outside of the area designated by the limits denotes: the occurrence of a signal and an interference in the course of the signal, which is recorded in the chart [31]. The method of calculation of the control lines is presented as follows [39, 40]:

$$UCL = \overline{\overline{X}} + \frac{1,96}{\sqrt{n}}\sigma \quad (1)$$

$$LCL = \overline{\overline{X}} - \frac{1,96}{\sqrt{n}}\sigma \quad (2)$$

where: n - sample count, $\bar{\bar{X}}$ - arithmetic average of the obtained results, σ - standard deviation of the investigated characteristic.

It is assumed that 95% of the sample averages will fall in the range $-\frac{1,96}{\sqrt{n}}\sigma$ to $+\frac{1,96}{\sqrt{n}}\sigma$. In practice, 1.96 is substituted with 3 assuming that approx. 99% of the averages occur within the limits of the control lines and the upper and lower control lines are defined as (±) 3σ :

$$UCL = \bar{\bar{X}} + 3\sigma \tag{3}$$

$$LCL = \bar{\bar{X}} - 3\sigma \tag{4}$$

In order to improve the analysis, alert lines are placed in the graph shown as (±) 2σ .

Research in Polish scientific centre is worthy of attention in this context. The comprehensive and diverse research based on measurement data included a four-year period and sixty-nine measurement stations: noise of different origins was recorded: traffic noise, railway noise, industrial noise and aircraft noise. The data set was analysed in terms of determining the forms of probability distributions. Only for 3% of the analysed one-day noise indicators, were the distribution functions confirmed to be normal. In this case, using the classical method (the law of uncertainty propagation) for determining type A measurement uncertainty may lead to the erroneous determination of the uncertainty interval. Following analysis of the data set, the possibility of modelling the distributions of one-day noise indicators with a mixture of two normal distributions was verified. Such an approach would significantly simplify uncertainty determination using the non-classical method based on probability distribution propagation. It was indicated that 94% of the analysed samples are characterised by a distribution that is a mixture of two normal distributions [46].

Such assumption gives rise to the search for new solutions in the field of aircraft noise assessment. Two decades ago, French researchers suggested the detection of environmental changes using Shewhart's control chart detection algorithm that searches for the changes in the means of Gaussian sequence. This technique is general since no assumption is made on the nature, level and occurring time of noise and gives significant improvement compared to classical compensation algorithms [6].

The possibility of using control charts in noise investigation is also highlighted by Danish research. The objectives of their study were to explore what impact of variation (noise) in the data had on the performance of different statistical monitoring methods (such as univariate process control algorithms-Shewhart Control Chart, Tabular Cumulative Sums, and the V-mask-and monitoring of the trend component-based on 99% confidence intervals and the trend sign). Results revealed that the Shewhart Control Chart was better at detecting increases over decreases in sero-prevalence, whereas the opposite was observed for the Tabular Cumulative Sums. The trend-based methods detected the first event well, but performance was poorer when adapting to several consecutive events [4].

Considering the above scientific achievements and the assumption that noise generated by aircraft during individual aircraft operations can be treated as a source under constant conditions, the Shewhart chart quality method can be used in this case. Possible minor deviations due to corrections for noise distribution similar to normal have a marginal impact and are acceptable. The spread chart was not applicable here due to single measurements for each object [57].

4. Empirical research method

The location of the empirical research validating the new application of the $\bar{X}$ chart in the assessment of the homogeneity of the noise level distribution generated by aircraft was the immediate surroundings of the airfield complex of the 31 Tactical Airbase located in the south-eastern part of Poznań. The area occupied by the military unit is 928.88 ha, including the airstrip of the area of 874.5ha. The length of the runway (DS-1) is 2500m and its width - 80 m. After the modernization of the airfield (2001/2002), the runway was extended by 300 m and now has a total area of 19800 m^2.

The measurements of the exposure sound level A were carried out in relation to takeoffs of individual multirole F-16 Block 52+ aircraft. The measurement point was located at the extension of the RWY30 takeoff edge at a distance of 200m. The selection of the times of measurements was tightly dependent on:

- monthly flight schedule for the Poznań – Krzesiny Airfield,
- daily flight schedules determining the air operations and their objectives,
- direction of the takeoffs specified by the control tower for each individual air operation,
- procedurally adopted independent causes of flight cancellations (bad weather conditions, human factor, equipment factor).

Example results of the recorded signals have been shown in Fig. 3. Furthermore, all sound measurements were not exposed on other disturbances (e.g. background noise), thus it can be concluded that each measurement was carried out under the same conditions.

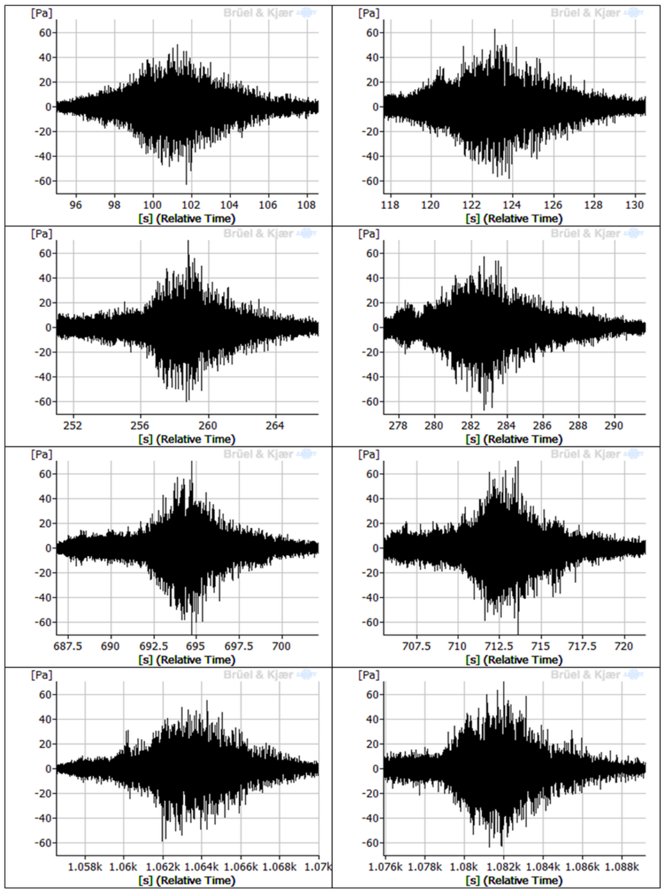

Fig. 3. Selected time tracings of the acoustic pressure signals

Based on the analysis of the signals presented in Fig. 3, one cannot confirm whether they are statistically homogeneous. In order o assess the homogeneity, a parameterization of the signals was performed and then statistical analyses were carried out.

Due to the specificity of the performance of military tasks, the noise investigations were performed in two stages. The measurements aimed at the obtainment of the exposure noise level – L_{AEq}. A time constant of 100 ms was adopted. During the investigations, the authors recorded sound signals of 32 F-16 aircraft. Based on the results of the measurements, point measures L_{AEq} were determined along with the octave and 1/3 octave spectra. In reference to the point values, calculations were performed with a view to carrying out a further analysis. To this end, the average and the standard deviation were obtained using Statistica 13.1 and then, on this basis, the authors obtained the boundary values - the upper control limit (UCL) and the lower control limit (LCL). The results of the calculations have been shown in Table 1.

Table 1. Results of the analysis of the LAE point values

Parameter		Calculation results	
Highest value [dB]		103,93	
Lowest value [dB]		96,88	
Average value [dB]		100,29	
Standard deviation (Sigma)		1.45	
Upper control limit UCL [dB]		104.65	
Lower control limit LCL [dB]		95,94	
Number and percentage of outliers	> UCL	0	0%
	< LCL	0	0%

The graphical interpretation of the $\overline{X}$ chart made with Statistica 13.1 has been shown in Fig. 4.

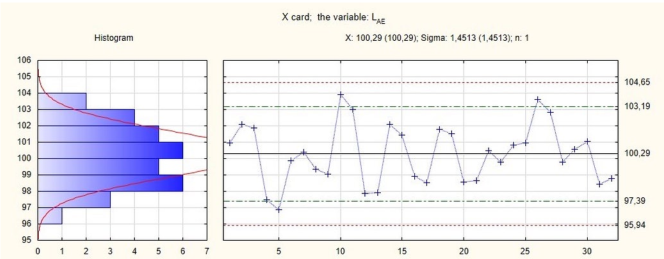

Fig. 4. Chart $\overline{X}$ for the L_{AE} point results

The analysis of the $\overline{X}$ chart allowed determining the trend in the differences between the L_{AE} sound levels of individual aircraft. All the results of the measurements fell in the range between the upper control limit (UCL) and the lower control limit (LCL), i.e. none of the results exceeded the upper and lower limits. Taking this dependence into account, one can assume that the results of the point measurements are homogeneous.

The confirmation had to be additionally found in the spectral analysis of the acoustic signals. To this end, the authors performed calculations, the effect of which were octave and 1/3 octave spectra of the recorded signals. The example octave spectra have been shown in Fig. 5.

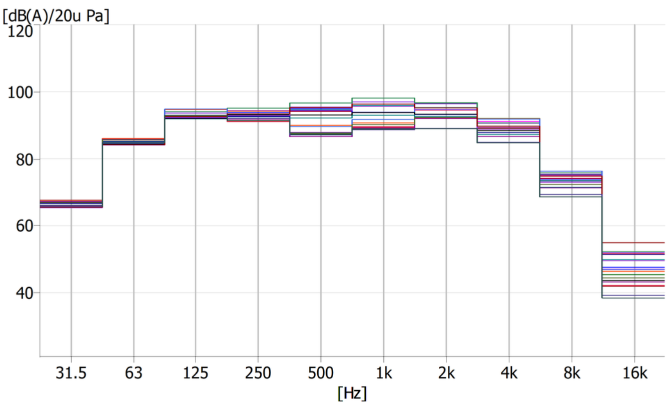

Fig. 5. Octave spectra of the acoustic signals

Based on the analysis of Fig. 5, the authors observed differences in the sound levels in the octave bands for different sound signals recorded during the aircraft takeoffs. A question arose whether these differences were statistically significant.

Results of the statistical calculations in relation to the values obtained for the octave spectral bands have been shown in table 2.

The data in Table 2 present the spectral shapes for the military engines. They indicate an increase in the acoustic level along with the increase in the frequency to approx. 200 Hz and then its drop from the average of 102.73 dB for 250 Hz to the average of 50.81 dB for 16 kHz. This spurred the authors to more thoroughly scrutinize the 63 Hz, 125 Hz and 250 Hz spectra that have the greatest impact on the total noise level. During the analysis, the authors also had to allow for the spread of the results that influenced the value of the standard deviation and, indirectly, the control limits. The graphical interpretation of the $\overline{X}$ charts made with Statistica 13.1 has been shown in Figs. 6-15.

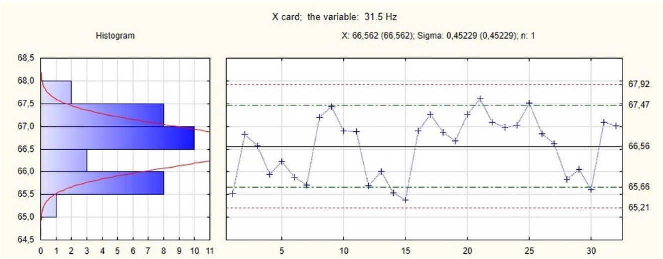

Fig. 6. $\overline{X}$ card for the 31,5 Hz octave spectrum

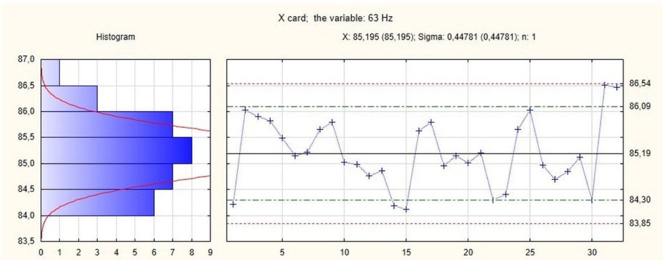

Fig. 7. $\overline{X}$ card for the 63 Hz octave spectrum

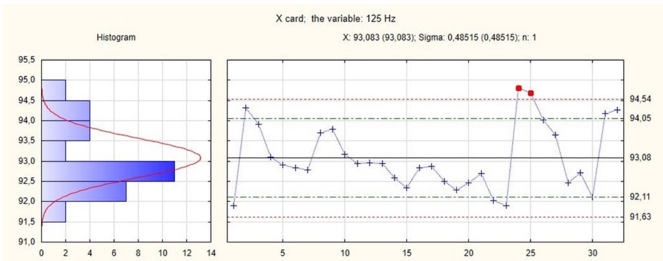

Fig. 8. $\overline{X}$ card for the 125 Hz octave spectrum

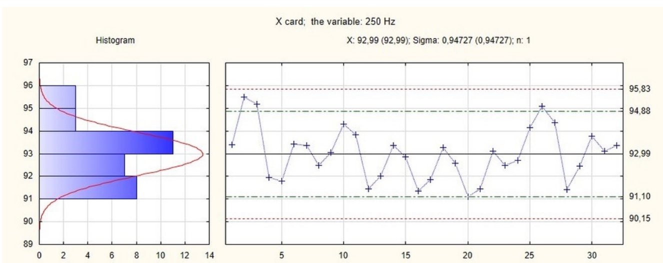

Fig. 9. $\overline{X}$ card for the 250 Hz octave spectrum

Table 2. Results of analyses of the octave spectra

Parameter \ Frequency		31,5Hz	63Hz	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	8kHz	16kHz
Highest value [dB]		67,60	86,50	94,81	95,51	96,62	99,25	97,79	92,01	78,11	59,96
Lowest value [dB]		65,38	84,11	91,90	91,11	85,20	85,89	84,63	77,80	62,41	36,02
Average value [dB]		66,56	85,19	93,08	92,99	91,06	92,47	92,67	87,23	71,97	46,44
Standard deviation (Sigma)		0,45	0,45	0,49	0,95	3,35	1,10	1,96	1,92	2,04	4,54
Upper control limit UCL [dB]		67,92	86,54	94,54	95,83	101,11	101,77	98,55	93,00	78,09	60,06
Lower control limit LCL [dB]		65,21	83,85	91,63	90,15	81,00	83,16	86,78	81,46	65,85	32,82
Number of outliers	> UCL	0	0	2	0	0	0	0	0	1	0
	< LCL	0	0	0	0	0	0	2	4	3	0

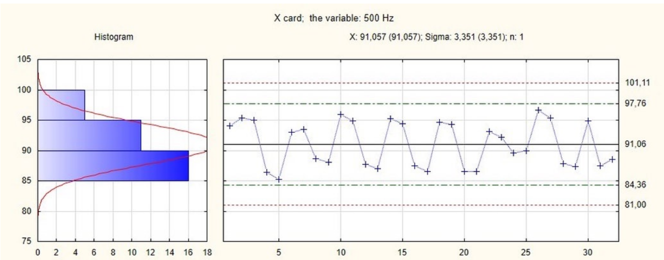

Fig. 10. $\overline{X}$ card for the 500 Hz octave spectrum

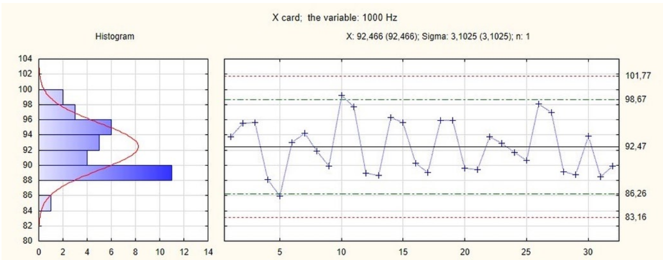

Fig. 11. $\overline{X}$ card for the 1000 Hz octave spectrum

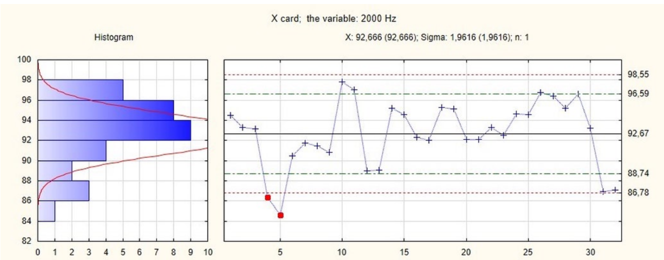

Fig. 12. $\overline{X}$ card for the 2000 Hz octave spectrum

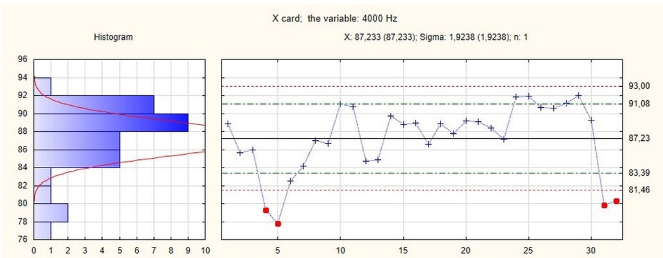

Fig. 13. $\overline{X}$ card for the 4000 Hz octave spectrum

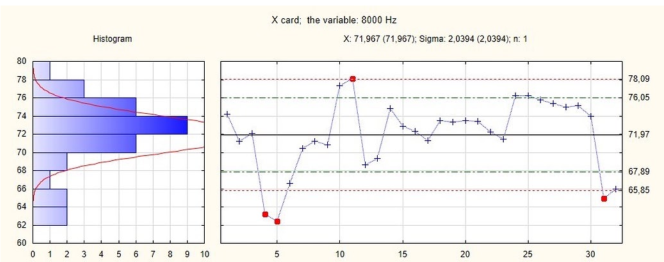

Fig. 14. $\overline{X}$ card for the 8000 Hz octave spectrum

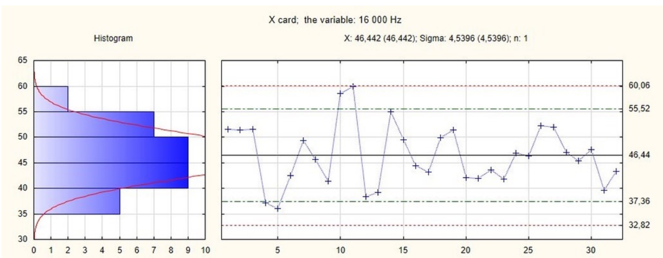

Fig. 15. $\overline{X}$ card for the 16000 Hz octave spectrum

The analysis of the distribution of individual measurements within the control limits in Figs. 6-15 was performed and the following observations were made:

1) the shape of the histogram indicated similar characteristics to a normal distribution, (based on the central limit theorem this noise assumption can be sufficient [20])
2) the results of measurements exceeded the upper control limit (UCL) or the results of measurements were lower than the lower control limit (UCL) or all the measurements fell in the admissible limits.

The first group, for which the results exceeded the upper control limit UCL was the most important due to the higher risk of noise compared to the interval resulting from the overall measurements. Such a deviation occurred for two frequencies. At 125 Hz, the exceed pertained to 2 aircraft (6.25%) numbered 24 and 25 and the highest UCL exceed value was 0.27 dB. A single exceed of the UCL line (3.12%) occurred at 8 kHz (no. 11, deviation 0.26 dB).

Another group are the outliers below the lower control limit LCL. In three spectral distributions, i.e. 2 kHz, 4 kHz and 8 kHz there were outliers below LCL, which is not a risk but a lower, safer sound level compared to the boundary interval.

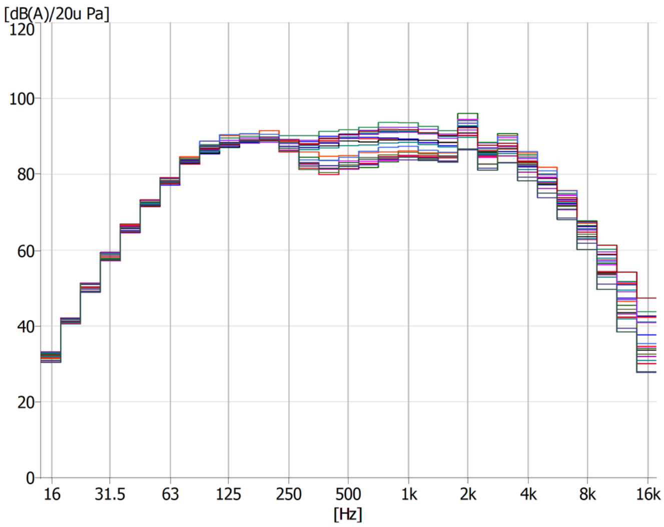

Fig. 16. 1/3 octave spectra of the acoustic signals

All the measurement results fell in the admissible limits in six distributions. This pertained to the following spectra: 31.5 Hz, 63 Hz, 250 Hz, 500 Hz, 1 kHz and 16 kHz.

When evaluating the negative impact of the upper outliers one should first of all consider their percentage share in the total number of measurements. In such an approach, one may state that approx. 9% of the aircraft exhibits discrepancies that eliminate them from the homogeneous group generating a similar level of noise.

In the further analysis the 500 Hz and 1000 Hz spectra turned out to be significant. They did not exhibit similar characteristics to a normal distribution and a relatively great spread compared to other frequencies was observed. These frequencies lacked median values and the results were close to both limits. Such an observation may indicate the necessity of analysis of this interval using a different method. The results related to all higher frequencies (in excess of 500 Hz) are also striking, for which at the increasingly reduced average value, the standard deviation remains relatively high.

An in-depth analysis was performed by making calculations in relation to the values obtained for the 1/3 octave bands, the example characteristic of which have been shown in Fig. 16 and table 3.

The data in table 3 present the spectral shapes for a military engine. The graphical interpretation of the $\overline{X}$ charts made with Statistica 13.1 have been shown in Figs. 17-44.

The analysis of the distribution of individual measurements within the control limits in Figs. 17-44 was performed and the following observations were made:

1) the shape of the histogram indicated similar characteristics to a normal distribution, (based on the central limit theorem this noise assumption can be sufficient [20])
2) the results of the measurements exceeded the upper control limit (UCL) or the results of measurements were lower than

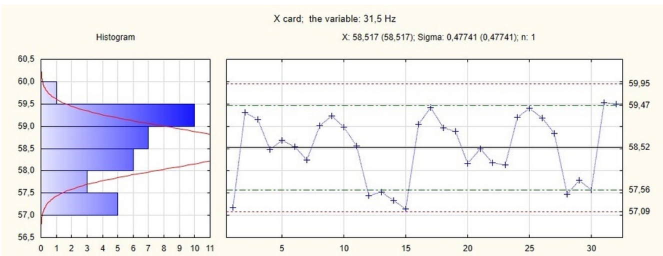

Fig. 17. $\overline{X}$ card for the 31,5 Hz 1/3 octave spectrum

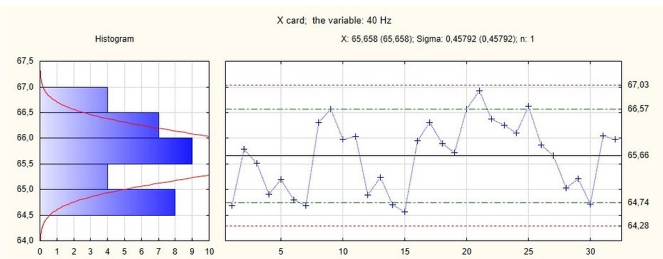

Fig. 18. $\overline{X}$ card for the 40 Hz 1/3 octave spectrum

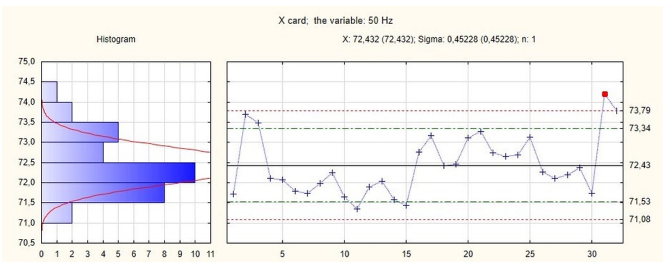

Fig. 19. $\overline{X}$ card for the 50 Hz 1/3 octave spectrum

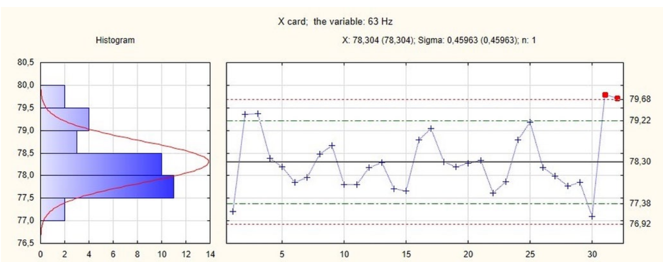

Fig. 20. $\overline{X}$ card for the 63 Hz 1/3 octave spectrum

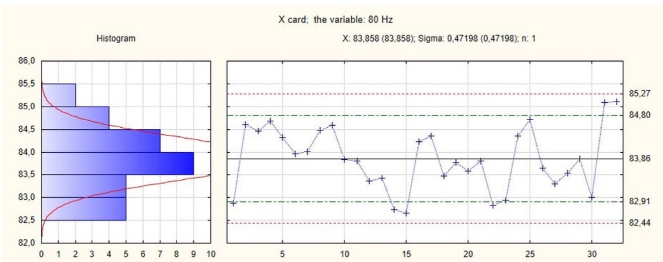

Fig. 21. $\overline{X}$ card for the 80 Hz 1/3 octave spectrum

Table 3. Results of analysis of the 1/3 octave values

Parameter \ Frequency	31,5 Hz	40 Hz	50 Hz	63 Hz	80 Hz	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	400 Hz	500 Hz	630 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz	6300 Hz	8000 Hz	10000 Hz	12500 Hz	16000 Hz
Highest value [dB]	59,53	66,93	74,20	79,79	85,11	88,76	90,42	91,08	92,05	90,17	90,17	91,33	91,74	92,41	94,11	94,83	94,52	93,68	96,03	90,66	90,70	86,02	81,87	76,66	71,93	65,91	59,19	52,33
Lowest value [dB]	57,14	64,56	71,36	77,10	82,65	85,37	87,05	88,17	88,46	85,91	81,22	79,91	79,72	79,72	80,55	81,72	81,05	80,92	79,63	78,84	76,16	71,81	66,52	61,80	53,71	44,98	35,70	26,56
Average value [dB]	58,52	65,66	72,43	78,30	83,86	87,06	88,14	89,38	89,86	87,85	85,70	85,59	86,26	86,82	87,64	87,92	87,53	86,89	89,85	84,80	85,52	81,19	76,53	71,77	64,01	55,42	46,17	36,61
Standard deviation (Sigma)	0,48	0,46	0,45	0,46	0,47	0,56	0,50	0,55	0,63	1,09	2,6	3,35	3,57	3,52	3,30	3,10	2,96	2,73	1,98	1,97	1,93	1,95	2.08	1,99	2,38	32,5	4,36	5,44
Upper control limit UCL [dB]	59,95	67,03	73,79	79,68	85,27	88,75	89,63	91,03	91,77	91,13	93,49	95,63	96,97	97,39	97,55	97,22	96,40	95,07	95,79	90,72	91,32	87,05	82,78	77,13	71,15	65,18	59,25	59,44
Lower control limit LCL [dB]	57,09	64,28	71,08	76,92	82,44	85,37	86,65	87,74	87,96	84,57	77,91	75,55	75,56	76,26	77,72	78,62	78,66	78,71	83,90	78,89	79,71	75,32	70,27	65,21	56,88	45,65	33,09	20,28
Number of outliers > UCL	0	0	1	2	0	1	2	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0
Number of outliers < LCL	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	4	1	4	4	3	4	3	1	0	0

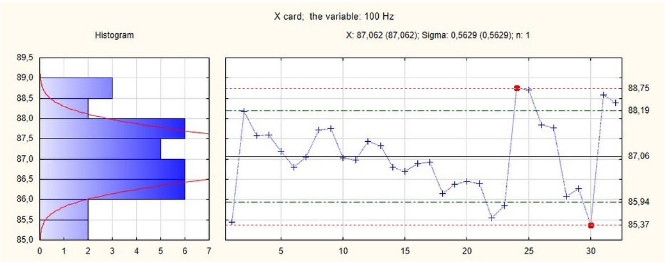

Fig. 22. $\overline{X}$ card for the 100 Hz 1/3 octave spectrum

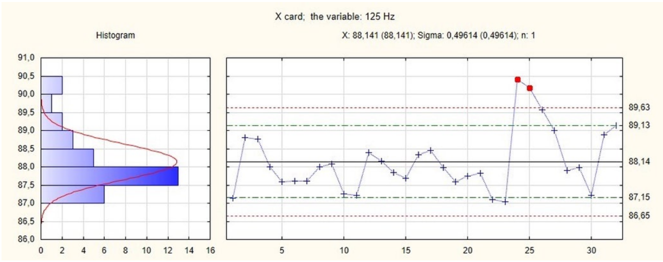

Fig. 23. $\overline{X}$ card for the 125 Hz 1/3 octave spectrum

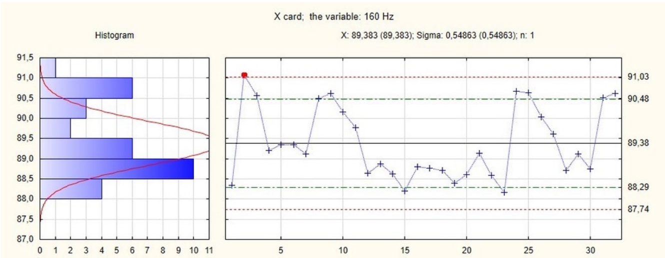

Fig 24. $\overline{X}$ card for the 160 Hz 1/3 octave spectrum

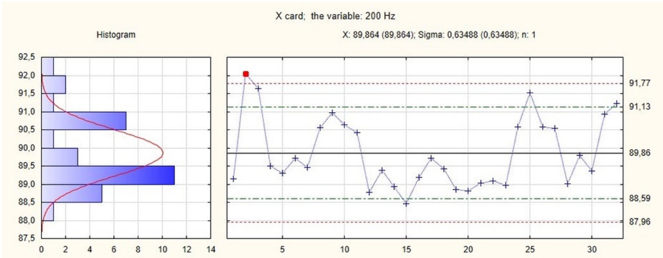

Fig 25. $\overline{X}$ card for the 200 Hz 1/3 octave spectrum

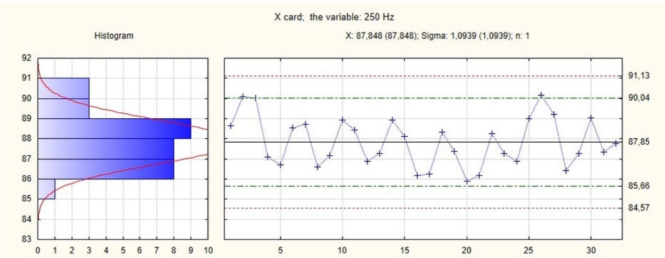

Fig 26. $\overline{X}$ card for the 250 Hz 1/3 octave spectrum

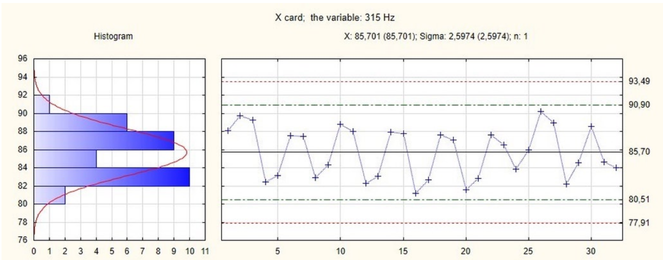

Fig 27. $\overline{X}$ card for the 315 Hz 1/3 octave spectrum

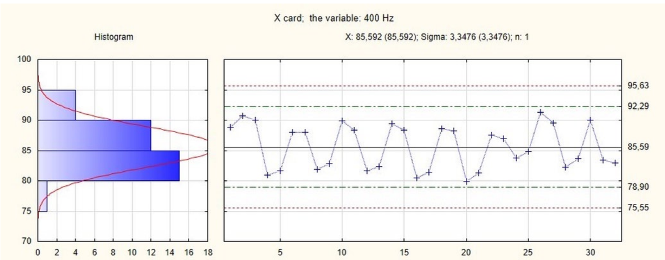

Fig 28. $\overline{X}$ card for the 400 Hz 1/3 octave spectrum

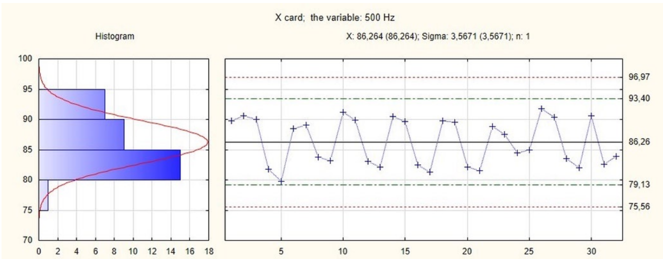

Fig 29. $\overline{X}$ card for the 500 Hz 1/3 octave spectrum

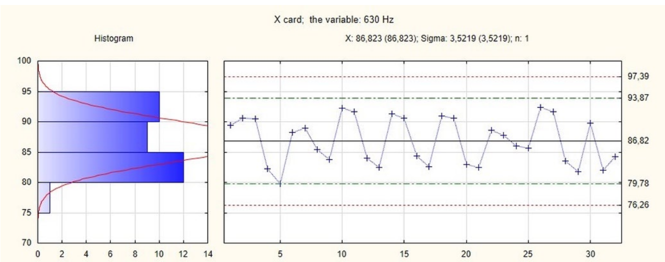

Fig 30. $\overline{X}$ card for the 630 Hz 1/3 octave spectrum

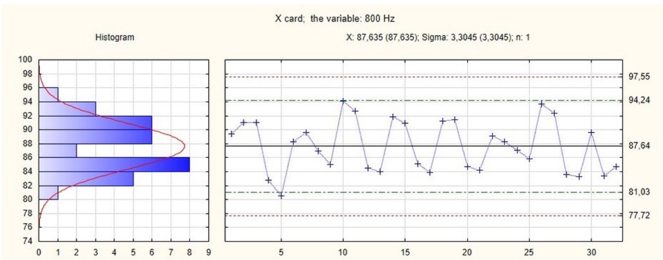

Fig 31. $\overline{X}$ card for the 800 Hz 1/3 octave spectrum

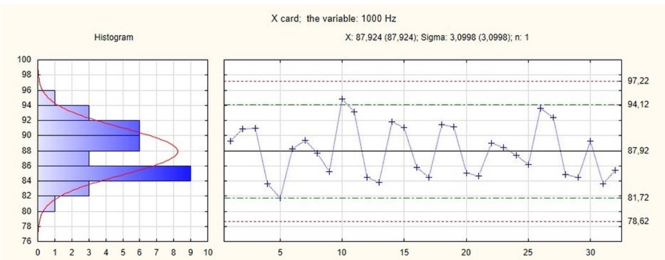

Fig 32. $\overline{X}$ card for the 1000 Hz 1/3 octave spectrum

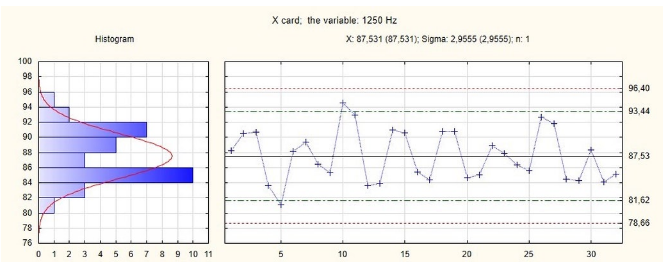

Fig 33. $\overline{X}$ card for the 1250 Hz 1/3 octave spectrum

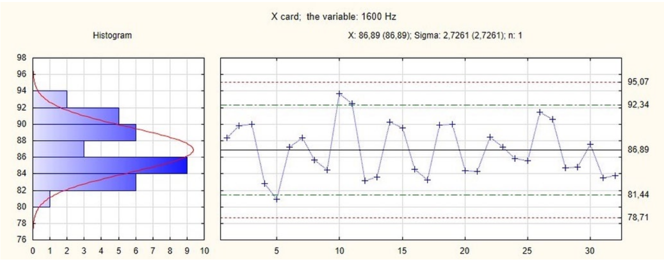

Fig 34. $\overline{X}$ card for the 1600 Hz 1/3 octave spectrum

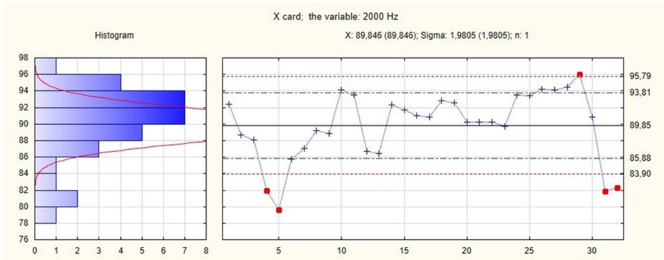

Fig 35. $\overline{X}$ card for the 2000 Hz 1/3 octave spectrum

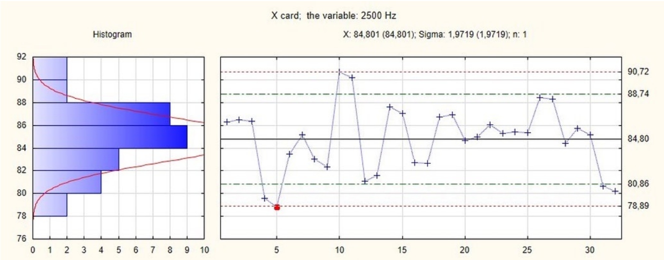

Fig 36. $\overline{X}$ card for the 2500 Hz 1/3 octave spectrum

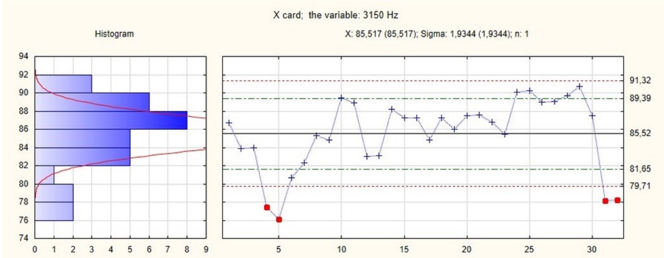

Fig 37. $\overline{X}$ card for the 3150 Hz 1/3 octave spectrum

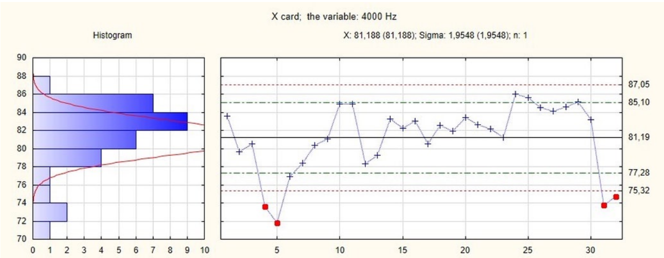

Fig 38. $\overline{X}$ card for the 4000 Hz 1/3 octave spectrum

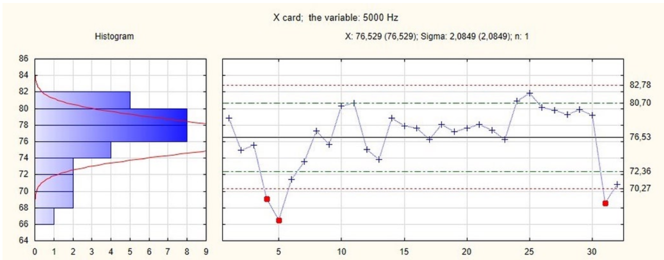

Fig 39. $\overline{X}$ card for the 5000 Hz 1/3 octave spectrum

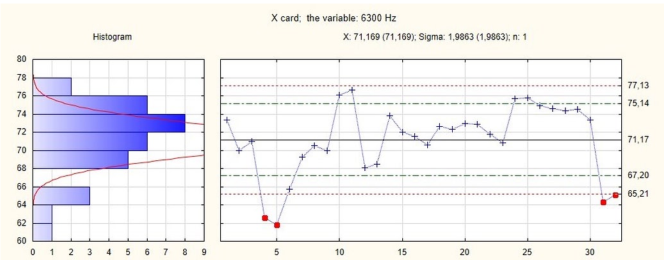

Fig 40. $\overline{X}$ card for the 6300 Hz 1/3 octave spectrum

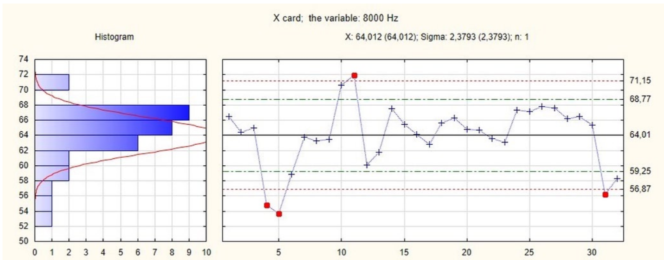

Fig 41. $\overline{X}$ card for the 8000 Hz 1/3 octave spectrum

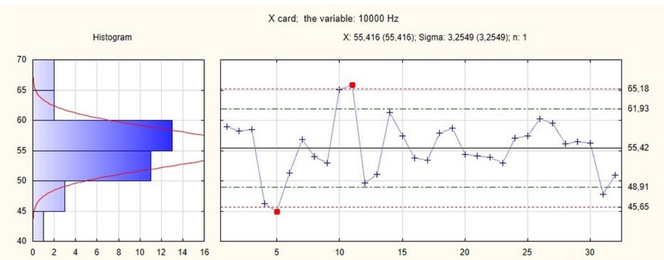

Fig 42. $\overline{X}$ card for the 10000 Hz 1/3 octave spectrum

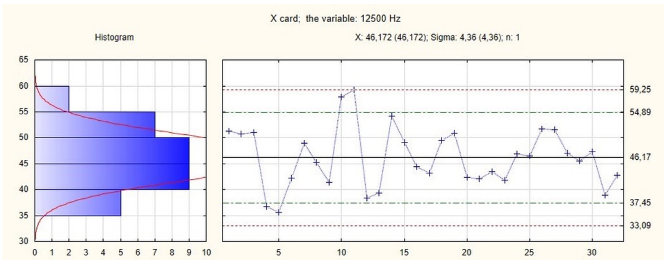

Fig 43. $\overline{X}$ card for the 12500 Hz 1/3 octave spectrum

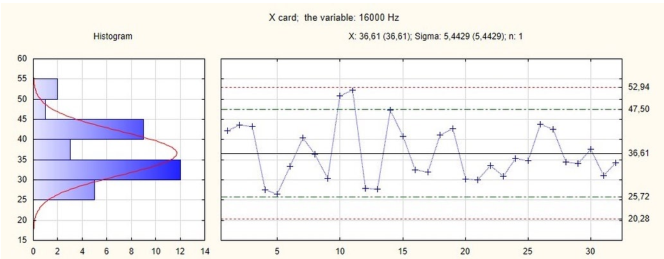

Fig 44. $\overline{X}$ card for the 16000 Hz 1/3 octave spectrum

the lower control limit (UCL) or all the measurements fell in the admissible limits.

The first group where the results in the distribution exceeded the upper control limit (UCL) pertains to 9 frequencies: 50 Hz, 63 Hz, 100 Hz, 125 Hz, 160 Hz, 200 Hz, 2000 Hz, 8000 Hz, 10000 Hz. This constitutes a consequent relation with the exceeds disclosed in the spectral distribution for the frequencies of 125 Hz and 8 kHz.

Another group are the outliers from the lower control limit (LCL). For nine frequencies, i.e. 100 Hz, 2000 Hz, 2500 Hz, 3150 Hz, 4000

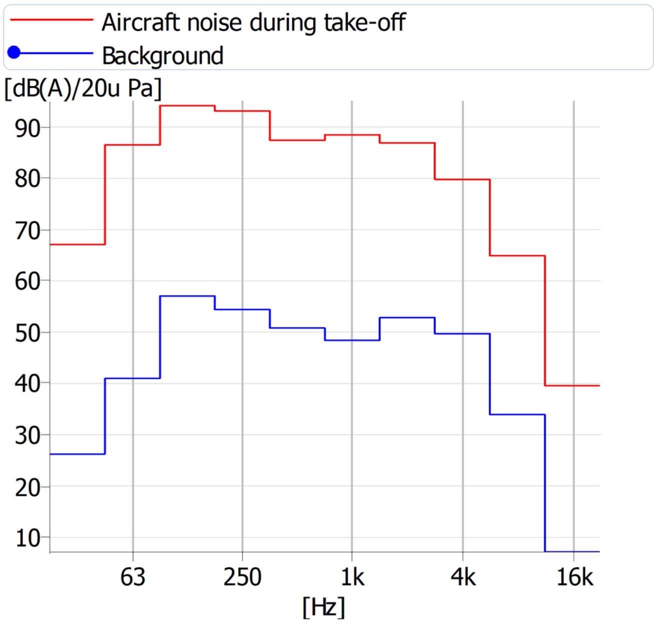

Fig. 45. Comparison of the octave sound spectrum for the noise generated by the aircraft and the acoustic background

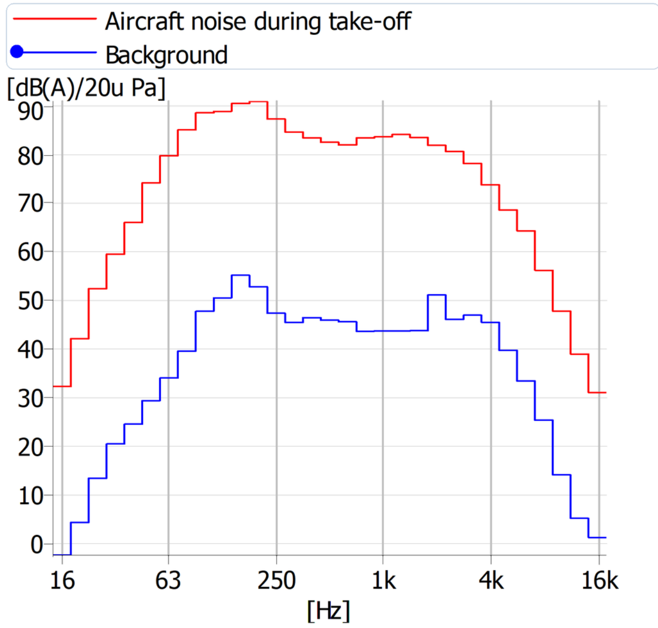

Fig. 46. Comparison of the one-third octave sound spectrum for the noise generated by the aircraft and the acoustic background

Hz, 5000 Hz, 6300 Hz, 8000 Hz and 10000 Hz, single results fell below the lower control limit LCL.

Majority of the frequencies have confirmed all the measurement results within the admissible limits and these were: 31.5 Hz, 40 Hz, 80 Hz, 250 Hz, 315 Hz, 400 Hz, 500 Hz, 630 Hz, 800 Hz, 1000 Hz, 1250 Hz, 1600 Hz, 12500 Hz and 16000 Hz.

Due to the fact that not all results were within the assumed limits, it was found that it should be checked whether the analysed measurement results were not influenced by external phenomena (the acoustic background). Therefore, the parameters describing the acoustic background were determined. Three types of analyses (one-third octave, octave and broadband) were performed and the case with the lowest values was selected for the comparison. Thanks to this step, it was possible to determine minimal differences between the background noise and the sound generated by the aircraft engine during take-off. Furthermore, it is known that if the difference in sound pressure levels between the measurement of the phenomenon and the background noise is greater than 10 dB, then the background noise has no influence on the result of the sound level measurement [5].

The difference between the background noise and the noise generated by the aircraft during take-off was 37 dB in the broadband study. The noise comparison results of the one-third octave and octave spectra are shown in Figs. 45 and 46.

Based on the performed three comparison analyses, it was found that the background noise did not affect the measurement results in any case study. Differences between the measurements and the background noise in all spectrum bands were higher than 10 dB.

5. Conclusions

In the paper the authors presented a novel approach to the analysis of acoustic signal using methods of statistical quality control. The attempt to assess the homogeneity has led to a confirmation of the compliance of the point measurements based on the lack of results that exceeded the limit lines. An in-depth analysis related to the octave and 1/3 octave spectra has shown few differences, outliers and trends. The excess of the upper control limit took place for only 0.9% of the octave results, which was also confirmed by the low index of excess for the 1/3 octave results (1.2% excesses). This allows an assumption that the statistical method of quality control using chart $\overline{X}$ may turn out useful in the assessment of aircraft noise measurements.

Based on the performed analyses one can state that both the point measures as well as the octave and 1/3 octave spectra from the signals recorded during the F-16 takeoffs are mostly homogeneous. This is important as it enables a significant reduction of the recorded signals needed to identify the parameter models of sound propagation around airport runways.

The developed assessment method of the homogeneity of the acoustic signal sources group generated by takingoff aircrafts can be used as an additional diagnostic tool. It can enable the detection of sound-generating objects in the tested group of aircrafts with a spectral composition significantly different from the reference spectrum (average spectrum for a homogeneous group of F-16 aircraft). Thanks to this approach, the objects deviated from the reference tested group could be directed to an unplanned maintenance. Therefore, it would have a significant impact on increasing the level of reliability and safety indicators.

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