Information model for determining the significance of factors influencing the level of digital noise in photographic images

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Abstract

Accuracy of reproduction of visual information is a priority task of modern media technologies. Digital photographic images, in addition to useful information, mainly contain also a harmful signal - digital noise, the presence of which is considered a significant drawback, which negatively affects the quality.

In the article, the authors systematized the factors influencing the size of noise generation of digital photoimages, and also developed an information model that allows to highlight the most significant of them. On the basis of developed model, it was established that certain steel factors (the diagonal of the photosensitive matrix, the type of photosensitive receivers) have the greatest influence on the size of noise production. Among the variable factors, photosensitivity has the maximum effect on the level of noise production, which has been proven in the experimental studies outlined in this work. Long exposures have been found to cause lower digital noise than higher ISO levels, which should be taken into account by DSLR users. It has been proven that digitizing a photo into raw format increases the level of both components of digital noise.

The described results make it possible to select technical shooting parameters for obtaining photographic images with high quality indicators, in particular, structural characteristics.

Keywords

Digital noise, CMOS, CCD, photocamera, ISO, shutter speed, photosensitive matrix, digitized, physical sizes of photosensitive matrix, photoimage, informative model, raw-format, lightness, jpeg, description of materials.

1. Introduction

The human brain is designed in such a way that we perceive visual information much faster than verbal information. Therefore, the content of modern media is saturated with illustrative material, among which the photographic image occupies a dominant role. The documentary nature of photography forms in the recipient of visual information a sense of direct presence in the events, in turn, provides a long-term fixation of his attention on the illustrated material. Of course, in order to achieve the desired effect, editors of media content (both electronic and printed) are interested in saturating the content of publications with high quality photographic images, primarily with satisfactory technical and reprographic characteristics.

Digital photographic images are characterized by the following quality indicators: reproduction of brightness and gradation, reproduction of color content, in particular memorable colors, balance of neutral shades, reproduction of fine details and image sharpness, as well as structural characteristics, which include the presence of artifacts in the image, in particular digital noise.

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The last two criteria have a particularly significant impact on the perception of information by human vision, since the observer perceives the environment as sharp, and therefore expects to see illustrative content as clear and with good reproduction of small details. These qualitative characteristics of the photographic image are ensured by the technical parameters of the optical system of a digital camera and the matrix of photosensitive elements with which the camera is equipped. In particular, the resolution of the matrix ensures the separate reproduction of small details, and the level of noise generation in each elementary cell of the photosensitive matrix determines the overall noise level in the photo image as a whole. It is digital noise that remains one of the limiting factors for building up the technical potential of modern digital photographic equipment. Moreover, these technical parameters of the matrix (resolution and noise level) are directly dependent on each other. Thus, increasing the matrix resolution leads to a decrease in the size of its elementary cells, in turn, leads to a decrease in their threshold photosensitivity, and this affects the integral photosensitivity of the matrix as a whole. Reducing the light sensitivity of the matrix requires the use of a long exposure when shooting, which is mainly controlled by the exposure time - shutter speed, since the value of the relative aperture of the lens aperture is mainly used to solve compositional problems of photography. Long exposure, in turn, again leads to increased noise production due to the technical features of the operation of the elementary photosensitive cells of the matrix. The choice of high values of photosensitivity within the range available for a particular photosensitive matrix also inevitably leads to an increase in the level of digital noise.

Thus, in case of insufficient illumination of the scene, structural flaws in the photographic image inevitably arise – the digital noise.

2. Related works

As discussed above, obtaining a digital photographic image with high technical characteristics is one of the main tasks of creating high-quality content. And it is the structural characteristics of a photographic image that is the most critical indicator for the perception of information by an ordinary observer.

At the stage of obtaining an image by a camera, its structural characteristics are determined by the size of noise in the signal from the photosensitive matrix. The level of digital noise, in turn, depends on a number of factors, and the first of them is the type of light-sensitive receivers (elementary cells). According to current practical experience and theoretical information, CMOS-matrixes form an image with higher digital noise values than the second type of photosensitive receivers – CCD- matrixes [11, 8]. The reason for this phenomenon lies in the structure of the photosensitive matrices themselves and the technical features and devices for processing an analog signal into a digital one. In a photosensitive matrix with CMOS elements, signal conversion occurs in each cell in particular, for which they are equipped with special microcircuits and an analog-to-digital converter. This, as you know, greatly simplifies the process of digitizing the data array, and a digital signal is obtained at the output from the photosensitive matrix. But this structure also affects the level of noise production.

In contrast, the CCD matrix does not provide for the possibility of data digitization and it serves only for recording optical information, while at the output from the matrix an analog-to-digital converter transforms the analog signal (current) into digital data. However, this class of photosensitive matrices is difficult to manufacture, therefore their cost is significantly higher than in CMOS matrices. Manufacturers find ways to reduce the cost of the matrix in reducing the size of the matrices themselves. However, this again leads to an increase in the size of digital noise, since with smaller physical dimensions of the matrix and high resolution, as required by a modern consumer, the size of a unit cell becomes critically small. The small size of the photosensitive element again leads to an increase in digital noise.

Since it is impossible to completely get rid of the problem of noise, therefore, manufacturers of photographic equipment predominantly choose compromise technical solutions. Small and medium-sized CCDs are used in the hobbyist category, while full-frame or APS-C CMOS sensors are used in professional cameras. The latter, due to their large size of the matrix as a whole and of each elementary cell in particular, form a low level of noise generation in the photographic image. Small in size, but with lower noise production, CCDs will provide satisfactory structural performance for photographic images in the amateur photography sector. At the same time, such a standard size of photosensitive matrices does not entail a significant increase in the price of the camera [4, 5].

In this way it is possible to only partially reduce digital noise when photographing with certain models of cameras, but it is impossible to completely get rid of this negative phenomenon. All technical classes of light-sensitive matrices, under certain conditions for obtaining a photoimage, form a certain size of noise, in some cases critical for the consumer of visual information.

In addition to considered factor, a number of others also have an effect on the level of noise generation of a digital photo image. Separately, the structural characteristics are significantly influenced by such technical parameters of photography as photosensitivity and shutter speed (frame exposure). These means regulate the tone of the photographic image depending on the exposure conditions (the brightness of objects and the power of the scene illumination) and the specific artistic concept. But both long exposures and high levels of photosensitivity, as evidenced by many information sources, cause an increase in the size of noise reduction [1, 3]. Long exposures lead to excessive overheating of the sensors, provoking an increase in the harmful signal, since technically the receivers of light-sensitive sensors are not designed for long-term registration of a light signal.

At the stage of digitizing data from the matrix, there is also a possible deterioration in structural characteristics, in particular, when recording in the JPEG format. Some information sources report that digitizing data in RAW format (without data compression) provides a low noise level [8, 10].

As can be seen from the above, the size of digital noise is influenced by a wide range of variable factors that need to be systematized and their significance determined. This will make it possible to more reasonably approach the choice of technical parameters for obtaining photographic images with high quality indicators.

3. Compilation of an information model to determine the importance of means that affect the amount of noise

The issue of noise in digital photographic images is still relevant in the future. Pixels of different brightness and color, randomly located in the photo image, are clearly visible to the consumer of visual information, especially on image elements with a uniform tone, for example, human skin, sky, areas of shadows.

Digital noise is of two types: fixed and random. Fixed noise results from different sensitivities of individual sensors to luminous flux, which is a constant characteristic of a particular matrix. Random noise is caused by a different reaction of the matrix photosensors to the same brightness value, which is variable in time and manifests itself in the form of randomly located multi-colored dots on the photo image. Random digital noise is generated by two components: chromatic and luminance. Luminance noise is identified in the picture as small dark dots, similar to the grain of photographic materials. Chromatic digital noise is small spots of different colors that differ significantly in color from the rest of the background and are easily identified by the observer.

Causes of digital noise in the photoimages:

1. The diagonal of the photosensitive matrix is a parameter that describes the physical dimensions of the array of photosensitive elements.
2. The sensitivity of individual elements of the matrix and the photosensor as a whole (ISO). In general, the ability of the elementary cells of the matrix to respond to the luminous flux is constant, and the magnitude of the response is changed by amplifying the signal to varying degrees. In this case, both the useful signal from the matrix and the harmful (noise) are amplified by the same degree. Thus, the higher the ISO value, the greater the noise level.
3. Technical features of the matrix (purity of the substance from which the individual receivers are made, inoperative pixels, etc.).
4. The number of photosensitive cells per unit area of the sensor - a parameter that connects the physical dimensions of the matrix and its resolution. The higher the resolution with constant physical dimensions of the matrix, the smaller its elementary center. It is considered optimal if the size of a single pixel is in the range of 6-11 microns. If the pixel size is half as much, as, for example, in compact cameras - it is already 3-5 microns, then the level of noise becomes critically high.

5. The shutter speed or exposure time of the frame is used as a means of adjusting the tone-visualization and as a compositional technique. But the duration of exposure of the photosensor to light energy determines the degree of its heating.
6. Type of photosensitive receivers - as noted above, due to the design and technical features of signal processing.
7. Exposure conditions (brightness of objects and level of illumination of the scene) - affect the noise level not directly, but indirectly, since the choice of specific levels of light sensitivity and exposure, that is, technical parameters of shooting, depends on this.

The factors described above that influence the level of digital noise can be conveyed by a variety of linguistic variables that are similar to the factors of influence on the technological process.

The process of forming digital noise of a photographic image is represented by a function, the elements of which will be the selected factors:

$$PR = F\left(d_1, d_2, d_3, d_4, d_5, d_6, d_7\right), \quad (1)$$

where d_1 – photosensitive matrix diagonal (PMD); d_2 – photosensitivity of the photosensor (PHP); d_3 – shutter speed or frame exposure time (SET); d_4 – number of photosensitive cells per sensor area (NPS); d_5 – exposure conditions (EXC); d_6 – technical features of the matrix (TFM); d_7 – type of photosensitive receivers (TPR).

To determine the importance of the influence of factors and their order of influence on the process, a directed graph is presented in Fig. 1, the result of which will be a model of the priority influence of influencing factors on the level of digital noise. For the synthesis of a linguistic model, we will apply the method of calculating the corresponding weighting factors [12].

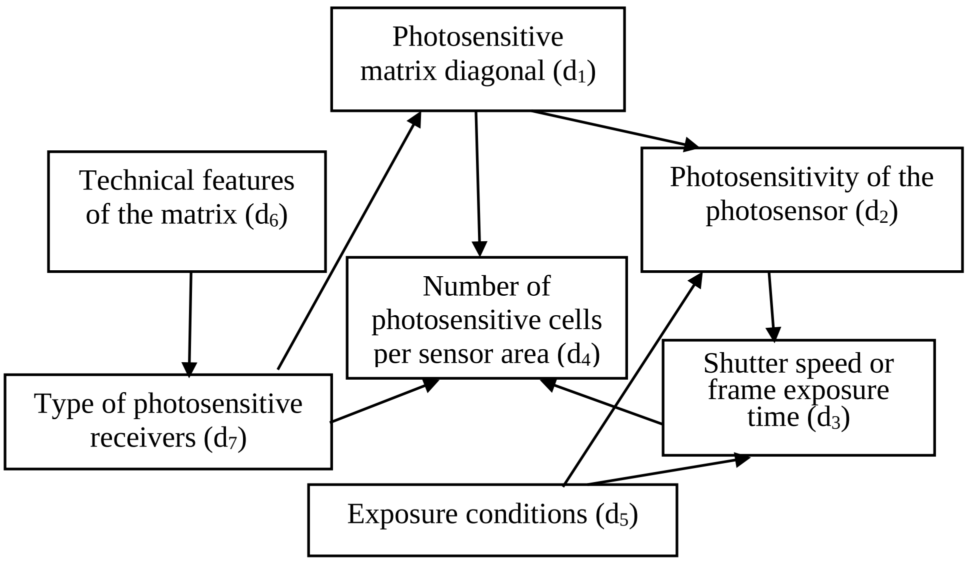

Figure 1: Directed graph of paired exposure (connections) between factors that determine the level of noise production

Calculation of the total weight values of the direct and indirect influence of factors and their integral dependence on other factors will determine their importance in order. We use the following notation.

We denote k_{ij} number of impacts $(i=1$ – direct, $i=2$ – mediated) or dependencies ($i=3$– direct, $i=4$ – mediated) for the th factor $(j=1,...,n)$; w_i – weight of the -th type. Let's represent the following conditional values for weighting factors in conventional units: $w_1 = 10$, $w_2 = 5$, $w_3 = -10$, $w_4 = -5$. The total weight quantities are denoted by S_{ij}.

Calculation formulas will eventually be presented:

$$S_{ij} = k_{ij} w_i \ \ (i = 1, 2, 3, 4; \ \ j = 1, ..., n), \qquad (2)$$

where n - factor number.

For the selected initial graph in Fig. 1 taking into account (2) we get:

$$S_{ij} = \sum_{i=1}^{4} \sum_{j=1}^{8} k_{ij} w_i \qquad (3)$$

To establish the ranks of factors, the table will receive the form.

Table 1

Calculation of the ranking of factors in the formation of noise

Room factor j	k_{1j}	k_{2j}	k_{3j}	k_{4j}	S_{1j}	S_{2j}	S_{3j}	S_{4j}	S_{Fj}	Rank factor r_j	Level prioritization
1	2	1	1	0	20	5	-10	0	60	7	1
2	1	0	2	0	10	0	-20	0	35	5	3
3	1	0	2	1	10	0	-20	-5	30	4	4
4	0	0	3	3	0	0	-30	-15	0	1	7
5	2	1	0	0	20	5	0	0	25	3	5
6	1	1	0	0	10	5	0	0	15	2	6
7	2	1	1	0	20	5	-10	0	45	6	2

From table. 1 it is seen that $\max|S_{3j}| = 30$; $\max|S_{4j}| = 15$. The presented values are summed up in each of the rows of the presented weight values in the columns S_{1j}, S_{2j} S_{3j}, and S_{4j}. To establish the rank of a factor r_j, serves as the basis for the resulting weight S_{Fj}, which will prioritize its effect on the noise generation process.

The last column "Priority level" represents the order of importance of the influence of factors on the process, from which we will construct a multi-level priority model of influence on the quality of noise formation in photographic images (Fig. 2).

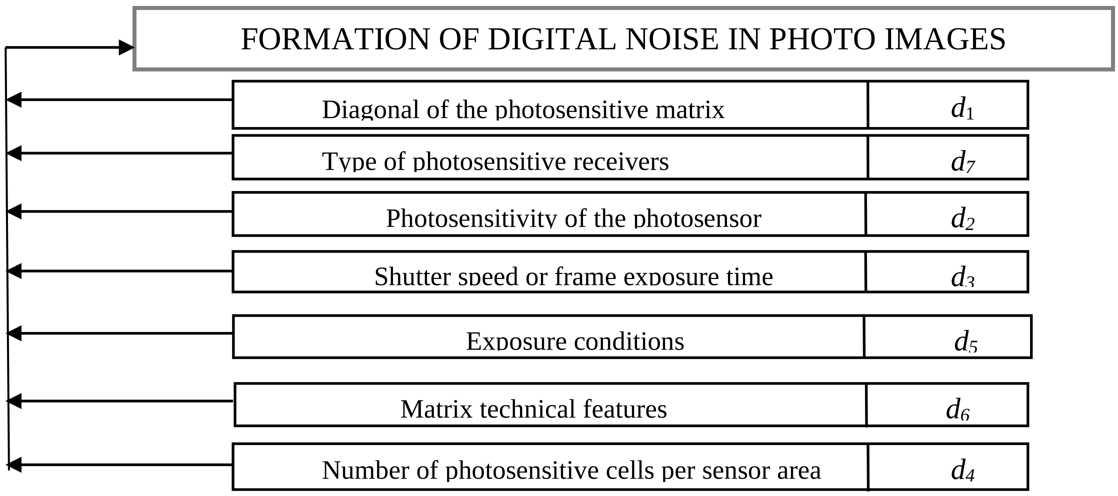

Figure 2: Model of the priority influence of factors on digital noise

Thus, as a result of applying the developed method, the ranks of the factors were calculated and a multilevel model of their priority influence on the process of influencing digital noise was built, which can be used to further optimize the weight values of the factors and calculate alternative options for the selected process.

The presented information model shows that the physical size of the photosensitive matrix, expressed by the size of the matrix diagonal, has the maximum effect on the level of noise generation, the next in ranking is the type of photosensitive receivers of the matrix, shooting modes, namely photosensitivity and exposure, exposure conditions, technical parameters of the photosensitive matrix and the number of photosensitive ones. cells per unit area of the sensor.

Some of these factors are unchanged, inherent for a particular digital camera model, and are determined by its very technical class and manufacturer. Of particular interest are the variable factors: photosensitivity, shutter speed and exposure conditions, since their specific value is changed by the user of the camera, choosing at each exposure in particular. Therefore, in the experimental part of the study, we will determine which of the listed variable factors affects the level of noise production of a digital photo image more and which less.

4. Analysis of the degree of influence of shutter speed and light sensitivity on the absolute value of digital noise

For research, a test object was used, which consists of achromatic fields with different brightness in order to cover the entire range of possible brightness of the object. Exposures were carried out at a constant level of illumination of lamps with a color temperature of 5300K. Two camera models EOS 800D and EOS 80D from Canon were used. During the exposure, the sensitivity and shutter speed were changed each time, and each exposure result was recorded in parallel in two file formats jpeg and cr.2.

At the next stage, it is necessary to determine the criteria for assessing the value of digital noise in the photoimages. In particular it is better to choose the criterion of the standard deviation of the pixel values to assess the value of digital noise of a digital photographic image:

$$d(x,y)=\sqrt{\frac{\sum_{i=1,j=1}^{n,m}\left(x_{i,j}-y_{i,j}\right)^2}{n^2}} \qquad (4)$$

The value of noise was measured on the photographic images in a graphics editor PhotoShop (Adobe) according to the standard deviation parameter Std Dev on the "Histogram" palette, expressed in brightness levels. For an even fill in tone Std Dev = 0, for an area with an even distribution of black and white Std Dev = 127,5 $\left(\frac{255}{2}\right)$. The smaller the numerical value of Std Dev, the less noise [2, 7]. Thus, in the area of the photographic image with a uniform tone distribution, we determine the specified parameter separately in the luminance and chromaticity channels.

In fig. 3-5 the obtained practical results are demonstrated. In fig. 3. a diagram of the distribution of the values of the color and brightness components of digital noise on photographic images obtained with long exposures and digitized in jpeg and cr2 file formats is presented. The results obtained indicate that the magnitude of both components of digital noise in photographic images remains constant over a fairly wide range of exposures. But the value of the color component already at an exposure of 0.1 s exceeds the maximum allowable value, and with a further increase in exposure to 10 s, it remains approximately at the same level, exceeding the maximum allowable value by almost three times. With a further increase in the exposure by one more stop (20 s), the color noise almost doubles. Such structural characteristics of the photographic image are unsatisfactory and require correction. The studies carried out indicate another interesting result: the value of noise of a photographic image in raw format are also imperfect. Shooting at high ISO values results in a high value of both of types of digital noise in the photo image. Low shutter speed generate low-level digital noise. The constructed information model presented in this study confirms the obtained results. Thus, it is possible to recommend the priority of long shutter speeds in contrast to the high value of light sensitivity. In the next experiment to determine the dependence of the digital noise level on photosensitivity, the following results were obtained, presented by the diagrams in Fig. 4 and 5. As shown by the above dependences, the photosensitivity affects the level of digital noise to a much greater extent. Already at a light sensitivity of 100-200 ISO, the color noise exceeds the maximum permissible values, and with a further increase in light sensitivity, both components of digital noise exceed the tolerance for this indicator many times.

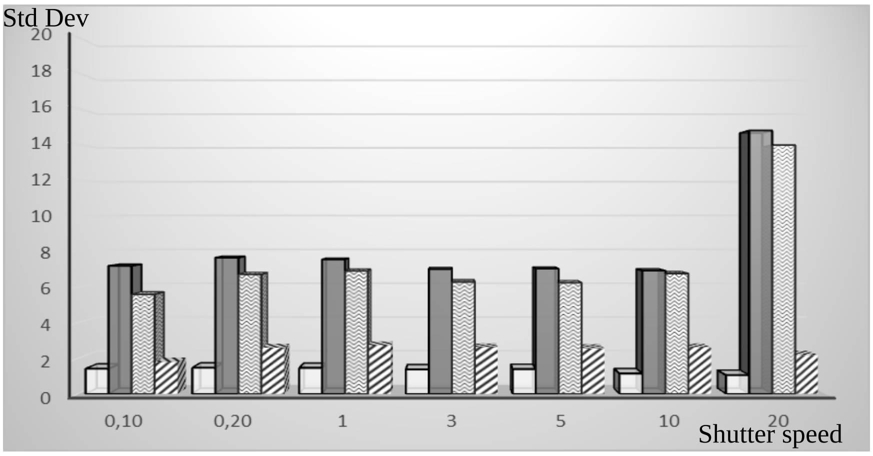

Figure 3: Shutter speed noise distribution diagram (jpeg and cr2 format, EOS-800D camera)

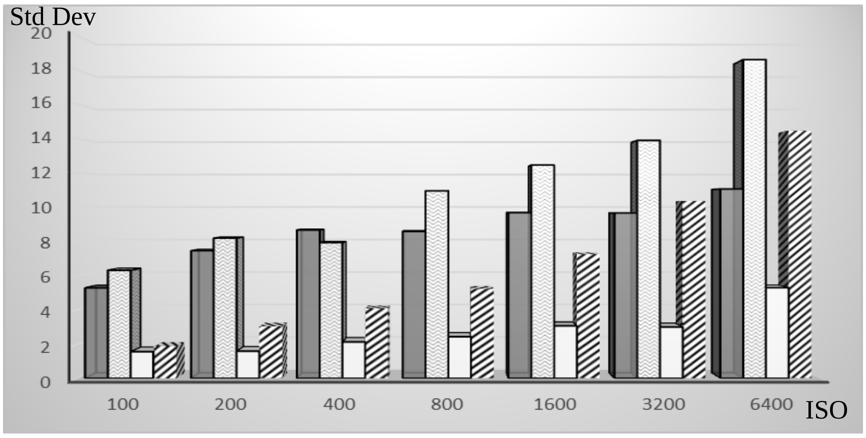

Figure 4: Photosensitivity digital noise distribution diagram (jpeg and cr2 format, EOS-800D camera)

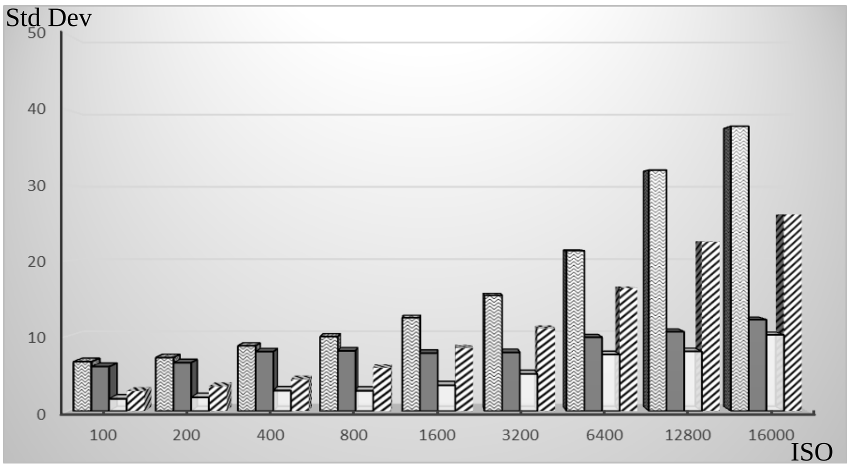

Figure 5: Photosensitivity digital noise distribution diagram (jpeg and cr2 format, EOS-80D camera)

- the luminance noise magnitude (cr2 format);
- the luminance noise magnitude (jpeg format);
- the color noise magnitude (cr2 format);
- the color noise magnitude (jpeg format)

Experiments have shown that high photosensitivity leads to significantly higher noise production than long exposure. This is confirmed by the results of mathematical modeling of the process. The model of the priority influence of influencing factors on digital noise (Fig. 2) shows that the photosensitivity factor in priority is in the hierarchy at a higher level than the exposure factor. Summarizing the results obtained, we recommend that users of SLR photographic equipment, when choosing the optimal technical parameters for shooting in conditions of low brightness of objects in the plane of the frame, choose long exposures and avoid high light sensitivity. This will ensure the proper quality of the photographic image with satisfactory structural characteristics.

About the value of noise of photographic images obtained at high values of light sensitivity and digitized in the raw file format, they are far from ideal. As with long exposures, this file format does not provide low digital noise. The resulting photographs are characterized by even higher noise generation (Fig. 4). Such a dependence of the structural characteristics is typical for photographic images obtained by cameras of various technical classes (Fig. 5). Note that this state of affairs is described by us for the first time; it is unambiguously interesting in the result, since this is not described in information sources. Since the issue of improving the structural characteristics is especially acute, therefore, manufacturers of SLR cameras are trying to find a solution to this at the stage of obtaining a photographic image. For example, Canon's EOS-80D software has a digital noise suppression tool. In Fig. 6 shows the results of using this tool at two sensitivity values: 6400 and 16000 ISO.

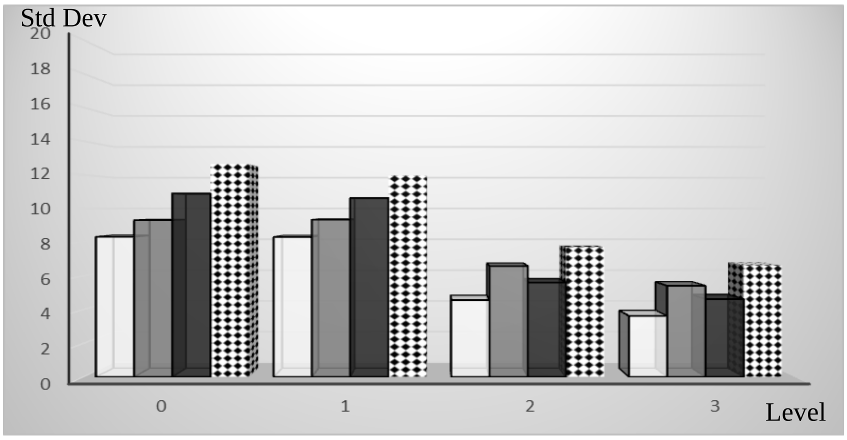

Figure 6: Diagram of the dependence of the value of digital noise on the degree of noise suppression in the camera software of the EOS-80D camera

- the luminance noise magnitude (6400 ISO);
- the color noise magnitude (6400 ISO);
- the luminance noise magnitude (16000 ISO);
- the color noise magnitude (16000 ISO)

Comparison of the results obtained allows us to conclude that the use of a noise suppression tool can reduce the absolute noise level, but it is not possible to achieve satisfactory structural characteristics even with the maximum effect of the tool (level 3). The standard deviation Std Dev is all well above the limit for both types of digital noise in photographs taken at ISO 6400 and 16000. Consequently, such a photo still needs to be refined its structural characteristics by means of graphic editors. On the positive side, we will attribute the fact that after applying the described means of noise suppression, photographic images do not lose their sharpness, although there are many algorithms in other software products that reduce the level of digital noise by somewhat reducing the sharpness in individual color channels.

5. Conclusion

Studies have shown that the use of high ISO levels and low shutter speed when shooting leads to significant noise generation. The optimal recommended light sensitivity is a value of 100-200 ISO, at which the value of noise in the photo is still within the maximum permissible limits. Long exposures (low shutter speed) are also the cause of digital noise, but its absolute value is significantly lower than with high photosensitivity. Based on the experimental results obtained, confirmed by the information model developed by the authors of the priority influence of influencing factors on digital noise, it is possible to recommend that users of SLR cameras use a low shutter speed and avoid high photosensitivity when there is insufficient illumination in the frame or low brightness of shooting objects. The camera models used in the research, although they belong to different technical classes and are equipped with different software, but the diagonal of their photosensitive matrices is the same. As a result, cameras from different segments of the photographic market and significant differences in cost produce photographic images with almost the same structural characteristics.

Using the raw format does not solve the problem of noise generation in digital photographs. On the contrary, the raw data from the matrix recorded in the raw file contains even more color and brightness noise, obviously due to the lack of noise suppression algorithms when writing data to the raw format. Noise suppression means available in the software of SLR cameras of the highest technical class does not completely solve the problems with noise generation. As a result of processing a photographic image by these means, the level of both components of digital noise is usually reduced, but its value still remains above the maximum allowable. Therefore, even with a photographic image processed by the camera software, it is necessary to improve digital noise in some else software.

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