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EVALUATION OF CHROMATICITY COORDINATE SHIFTS FOR VISUALLY PERCEIVED IMAGE IN TERMS OF EXPOSURE TO EXTERNAL ILLUMINANCE

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ABSTRACT

The problem of the software-based correction method dealing with digital codes of color palette components used in on-board indication equipment has been considered and the appropriate research has been performed. It is shown that color palette, obtained with the use of any given source of external illuminance that is mounted in automated workstation, cannot be successfully used for all possible operating conditions when color temperature of external illuminance source is varying widely (from 2,000 to 20,000 Kelvins). In order to display an image in varying conditions of external illuminance falling on the screen the method and formulas were proposed, which allowed correcting digital codes of any given color palette. It is shown, that relations between brightness value of an image on the LCD-panel and brightness of the color, caused by diffuse reflection of the light of external illuminance source, not only determine the technique for calculation of the contrast value for any given image element, but also restrict color gamut visually perceived by the person.

Keywords: indication, avionics, chromaticity coordinates, external illuminance, correction.

INTRODUCTION

Practical operating experience of using on-board flat liquid crystal (LCD) displays of MFDU class (Many Functional Display Units) showed that reliability of perception by the flight navigation data observer depends significantly on MFDU lighting characteristics and viewing conditions (Barber S., *et al*., 2008).

MFDU lighting characteristics are determined by screen image brightness in colors preset in the software palette, as well as by diffuse and specular reflection coefficients. Viewing conditions suggest visual perception of information by the observer on the background of external illuminance source (natural or artificial), creating an increased level of illumination in the plane of the LCD-panel screen. Available external illuminance exerts noticeable influence on the visual perception of the displayed information and in a number of cases results in the reflected light inversion, which is unacceptable in the aviation instrumentation engineering.

To reduce the influence of spectral composition and external illuminance level on the image visual perception quality, various approaches are used that are based on (Kumar, Ramana, 2014; Ibraheem *et al.,* 2012):

- increase of MFDU image brightness by means of using limiting electric modes of LCD-panel lamps (line emitting diodes);
- usage of specialized light-absorbing coatings that reduce values of diffuse and specular reflection coefficients;
- following the results of theoretical studies and experimental practice on the lighting test facilities, selection of software components of color codes comprising color palette of on-board display equipment and possessing the best characteristics of visual perception for the observer.

Each of these approaches taken separately has some restrictions concerning their potential use. Thus, significant increase in image brightness on the LCD-panel screen dramatically reduces the operating life of the device. Introduction of anti-glare and anti-reflection films into the MFDU design impairs LCD-panel reflectivity by times and increases image contrast. However, the coatings that are applied on the factory-made LCD-panel using adhesive are susceptible to mold fungi, increased humidity and salt spray. In practice software color codes are defined using only one type of lighting fixtures under the assumption of the emission spectra equivalence of artificial and natural light sources in all possible operating conditions of the aircraft.

In connection with the above, the task of research and development of the method combining all three of the above approaches is vital. This method should ensure perception of flight navigation information by the observer for all possible types of natural light sources, which occur in practice, with regard to the intensity of their radiation.

ARPN Journal of Engineering and Applied Sciences

Image Observation under External Illuminance Conditions

The spectral composition of the light source that illuminates the MFDU LCD-panel largely affects the colorimetric properties of color, visually perceived by the observer. One and the same color which is displayed on the MFDU screen is perceived by the observer differently in the presence or absence of external illuminance and external illuminance sources having different color temperatures T_k, measured in Kelvins.

Shift of (x, y)-chromaticity coordinates of pixels displayed on the MFDU LCD-panel and narrowing of color gamut perceived by the observer is conditioned by the influence of the properties of the LCD-panel reflecting surface. A part of external illuminance created by the light source in the LCD-panel plane is reflected in the direction of the observer proportional to the non-zero value ρ_d of the diffuse reflection coefficient. Influence of the specular reflection coefficient of the LCD-panel can be reduced to zero due to the MFDU constructive placement in the aircraft cabin, when the external incident light is re-reflected specularly not in the direction of the observer.

The light diffusely reflected from the LCD-panel in the direction of the observer creates an additional color that is added to the color image which is displayed on the LCD-panel. Thus, the observer perceives a mixture of two colors of different brightness instead of the image color at each point of the screen: that of image color and color reflected from the LCD-panel.

The coordinates of the color emitted by the LCD-panel are defined by the transformation [Schanda, 2007]:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}, \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix}^{-1} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}, \quad (1)$$

where X, Y, Z – color coordinates; X_r, X_g, X_b, Y_r, Y_g, Y_b, Z_r, Z_g, Z_b – color components determined by the International Commission on Illumination; R, G, B – codes (decimal notation) of primary colors (red, green, blue) in the *RGB* system (R – Red, G – Green, B - Blue). X_r, Y_r, Z_r components are weights of decimal codes of the red color, X_g, Y_g, Z_g and X_b, Y_b, Z_b are weights of the green and blue color codes, respectively. Color components define the color rendering model (profile) of the LCD-panel.

Color coordinates created by diffusely reflected light produced by the external illuminance source are defined from the ratios:

$$\begin{cases} X = \int\limits_{\lambda=380}^{\lambda=780} E(\lambda)\bar{x}(\lambda)\rho_d d\lambda \\ Y = \int\limits_{\lambda=380}^{\lambda=780} E(\lambda)\bar{y}(\lambda)\rho_d d\lambda \\ Z = \int\limits_{\lambda=380}^{\lambda=780} E(\lambda)\bar{z}(\lambda)\rho_d d\lambda \end{cases}, \quad (2)$$

where $E(\lambda)$ - relative spectral power distributions of light source illuminance; $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ - tabular-driven spectral tristimulus values for primary colors.

Integration (2) is performed in the visible wavelength range by summing up products of integrands:

$$\begin{cases} X = \sum\limits_{\lambda=380}^{\lambda=780} E(\lambda)\bar{x}(\lambda)\rho_d \Delta\lambda \\ Y = \sum\limits_{\lambda=380}^{\lambda=780} E(\lambda)\bar{y}(\lambda)\rho_d \Delta\lambda \\ Z = \sum\limits_{\lambda=380}^{\lambda=780} E(\lambda)\bar{z}(\lambda)\rho_d \Delta\lambda \end{cases}. \quad (3)$$

For standard fluorescent artificial daylight lamps in (3) it is assumed that $\Delta\lambda$ =10 nm. For lamps with an irregularity in the range of less than 10 nm in the emission spectra, the range $\Delta\lambda$ is selected at the level of 5 nm.

To eliminate the influence of the image brightness on the calculated data, *XYZ* tristimulus values can be normalized to the value of Y. The chromaticity coordinates (x, y) for color produced by diffuse re-reflection of external light flux, and also for the displayed colors are defined by the rules [Schanda, 2007]:

$$x = \frac{X}{X+Y+Z},\ y = \frac{Y}{X+Y+Z},\ z = \frac{Z}{X+Y+Z},$$
$$X = \frac{xY}{y},\ Z = \frac{(1-x-y)Y}{y}. \quad (4)$$

Brightness of the mixture of two colors perceived by the observer is summed up. Image brightness L_{br} is determined by brightness of the LCD-panel in the selected color. Brightness of color diffusely reflected from the LCD-panel surface is defined as:

$$L_{ext} = \frac{\rho_d E_{ext}}{\pi}, \quad (5)$$

ARPN Journal of Engineering and Applied Sciences

where E_{ext} - screen plane illumination level measured by the lux meter.

Diffuse reflection coefficient ρ_d is determined experimentally when the LCD-panel is off by the procedure providing formation of the preset level E_{ext} in the screen plane and measurement by brightness meter L_{ext} with subsequent computation of ρ_d. The coefficient reduction ρ_d is possible by means of applying specialized coatings on the screen.

Thus, the mixture brightness is: $L_{sum} = L_{ext} + L_{br}$, where L_{ext} is defined only by the reflection coefficient ρ_d of the LCD-panel screen and the external illuminance level E_{ext}. Operating level E_{ext} is determined by the automatic brightness control system located in the MFDU front face.

The analysis of technical documentation concerning the LCD-panel shows that, depending on the LCD-panel purpose, the white screen light intensity varies in the range: $300\frac{cd}{m^2} \le L_{br} \le 300\frac{cd}{m^2}$, and diffuse reflection coefficient value is within the range of: $0{,}1\,\% \le \rho_d \le 1{,}5\%$. Thus, with the external illuminance level below 100 kLx, white color brightness of the LCD-panel $L_{br} = 300\frac{cd}{m^2}$, $\rho_d = 1\%$ and such LCD-panel installed in the MFDU, ratio of intrinsic brightness (in the white color) and diffusely reflected color brightness will be: $L_{br} : L_{ext} \approx 1:1$. At the same time, for $L_{br} = 1000\frac{cd}{m^2}, \rho_d = 0{,}1\%$; $L_{br} : L_{ext} \approx 1:30$. Brightness ratio in other colors is defined by the LCD-panel brightness in these colors with retained brightness (5) for the preset level of external illuminance E_{ext}.

Evaluation of Chromaticity Coordinate Shift of the Image Visually Perceived By the Observer

To study the observer's color gamut in the conditions of the image visual perception at the enhanced external illuminance level, a series of experiments was carried out and specialized software was written in the MathCad 15.0 environment.

The experiments were carried out on the lighting device using mass-produced MFDU model. Examples of test navigation frames displayed on the MFDU LCD-panel are shown in Figure-1.

Figure-1. Examples of test navigation frames displayed on the MFDU LCD-panel.

Lighting device (Seetzen *et al.*, 2007; Menesatti *et al.*, 2012; Evanicky *et al.*, 2009) is a test desk designed to measure lighting characteristics of on-board display equipment (MFDU, control and display consoles, etc.)

The lighting device used in the experiment consists of:

- digital photometer measuring external illuminance level on the MFDU screen plane;
- brightness meter measuring image brightness on the MFDU screen;
- colorimeters measuring colorimetric properties of image on the MFDU screen;
- two lighting lamps producing illumination in the screen plane from the source of artificial light compositionally similar in the emission spectrum to the natural light source;
- linear autotransformer (LATR) carrying out voltage regulation of lighting lamp power supply to create the preset level of external illuminance in the MFDU screen plane;

ARPN Journal of Engineering and Applied Sciences

- structural elements providing equipment fastening.

The lighting device enables to create external illuminance level adjustable via LATR in the MFDU screen plane from 0 to 75 kLx and measure the brightness level, color coordinates and chromaticity coordinates of each pixel displayed on the MFDU screen, as well as the background color brightness.

The method of brightness meter and calorimeter fastening allows moving the measuring devices up and down, left and right to provide possibilities for the measurement of the image characteristics anywhere on the MFDU screen. Lighting lamps are arranged at an angle of 45 degrees relative to the normal to the plane of the MFDU LCD-panel. Brightness and color coordinates (chromaticity) are measured along the normal to the MFDU screen.

Distance from lighting lamps to MFDU (about 700 millimeters) eliminates the possibility of the thermal effect influence due to the lamp heating on the MFDU LCD-panel and provides light scattering in the MFDU screen plane. A parabolic reflector forms the basis of the structural elements of the lighting stand.

The computer software designed specifically for this study in the MathCad 15.0 environment provides:

- computation by formulas (1), (4) of chromaticity coordinates of red, green and blue colors, defining the position of the color gamut triangle of the LCD-panel on the *XY* plane and the color gamut triangle boundary display;

- computation by formulas (2) - (4) of color chromaticity coordinates formed by the external light diffusely reflected from the surface of the LCD-panel;

The software specifies successively (in the cycle) each color that is included in the set of colors displayed on the LCD-panel *R*=0…255, *G*=0…255, *B*=0…255) as the displayed color (x_1, y_1, Y_1). White color of the external illuminance source specified by the correlated color temperature T_k is used as a reflected color.

Chromaticity coordinates (x_2, y_2, Y_2) of the external illuminance source white color are defined in the simulation program from the ratios:

$$x_2(T_k)=\begin{cases}\dfrac{-4,6070\cdot10^9}{T_k^3}+\dfrac{2,9678\cdot10^6}{T_k^2}+\dfrac{0,09911\cdot10^3}{T_k}+0,244063, 2000K\le T_k\le 7000K\\ \dfrac{-2,0064\cdot10^9}{T_k^3}+\dfrac{1,9018\cdot10^6}{T_k^2}+\dfrac{0,24748\cdot10^3}{T_k}+0,237040, 7000K< T_k\le 25000K\end{cases},$$

$$y_2(T_k)=-3x_2^2(T_k)+2,87x_2(T_k)-0,275 \; .$$

Evaluation graphs of chromaticity coordinate shift obtained by simulation are shown in Figure 2. The dotted line on the graphs indicates the true value of the chromaticity coordinate for the displayed color with regard to the specified color profile of the color rendering model of the LCD-panel.

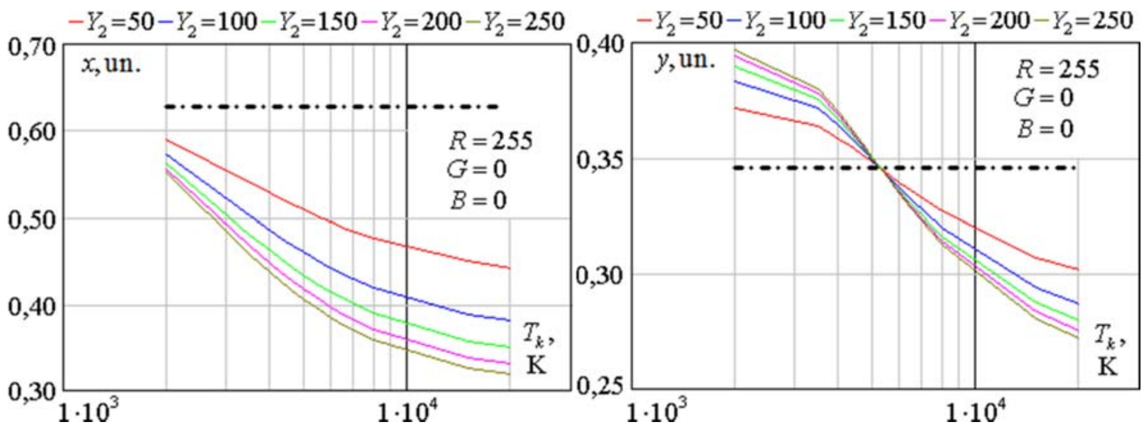
The enhanced external illuminance sources with “warm” white color are characterized by significant shift of colors visually perceived by the observer from the area of saturated blue and green colors towards the point of white color determined by the light source. Thus, in the conditions of enhanced illumination from the source of “warm” white light the observer’s visual perception of green and blue colors and their shades, which are formed by minor addition of red color in the *RGB* code of the component, deteriorates. Red color shades are distinguished by the observer in full with the sufficient level of the image brightness contrast.

For enhanced external illuminance sources with “uniform” white color, and also with white color, T_k point coordinates of which coincide on the *XY*-plane with the white color point coordinates of the gamut triangle inherent in the MFDU LCD-panel, primary colors (red, green, blue) and yellow, cyan, magenta are equally susceptible to shift of colors visually perceived by the observer. In this respect it is undesirable to use “pure” colors in the software *RGB* code of MFDU color palette.

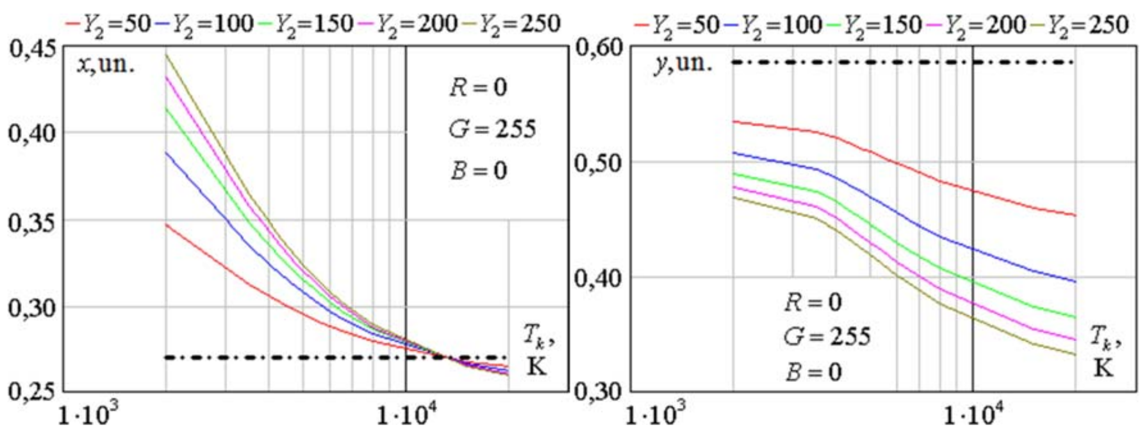
The enhanced external illuminance sources with “cold” white color are characterized by substantial shift of visually perceived colors from the area of saturated red and green towards the point of white color determined by the light source. Thus, in the conditions of enhanced illumination from the source of “cold” white light the observer’s visual perception of green and red colors and their shades, which are formed by minor addition of blue color in the *RGB* code of the component, deteriorates. Blue color shades are distinguished by the observer in full with the sufficient level of the image brightness contrast.

It is important to note that the observer’s color gamut transformation is specific to external illuminance sources with different color temperature. Therefore MFDU color palette must be developed taking into account the types of external illuminance spectra stipulated by all possible operating conditions of the aircraft.

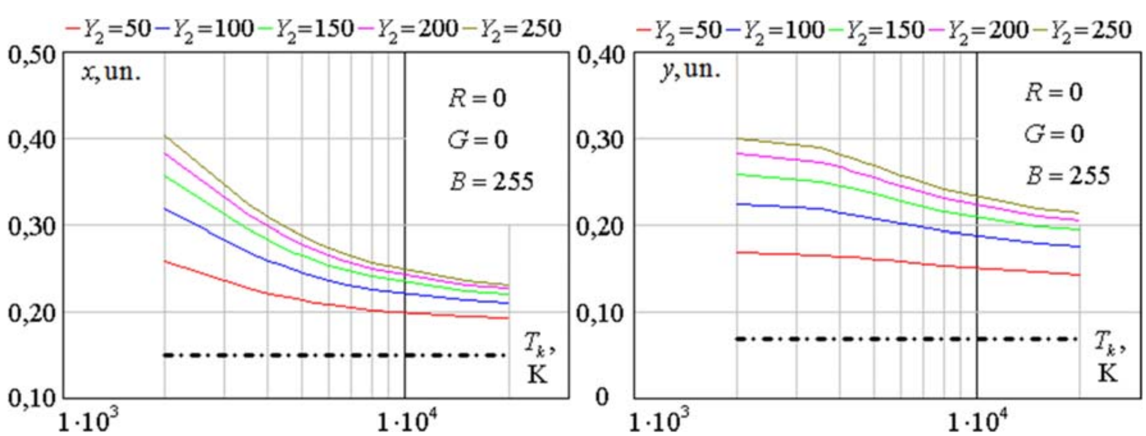
ARPN Journal of Engineering and Applied Sciences



a)

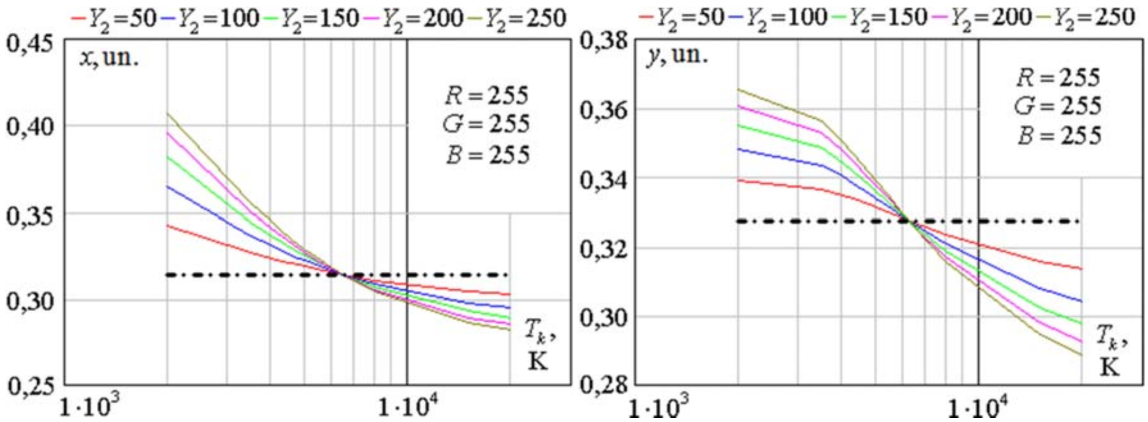


b)



c)

ARPN Journal of Engineering and Applied Sciences



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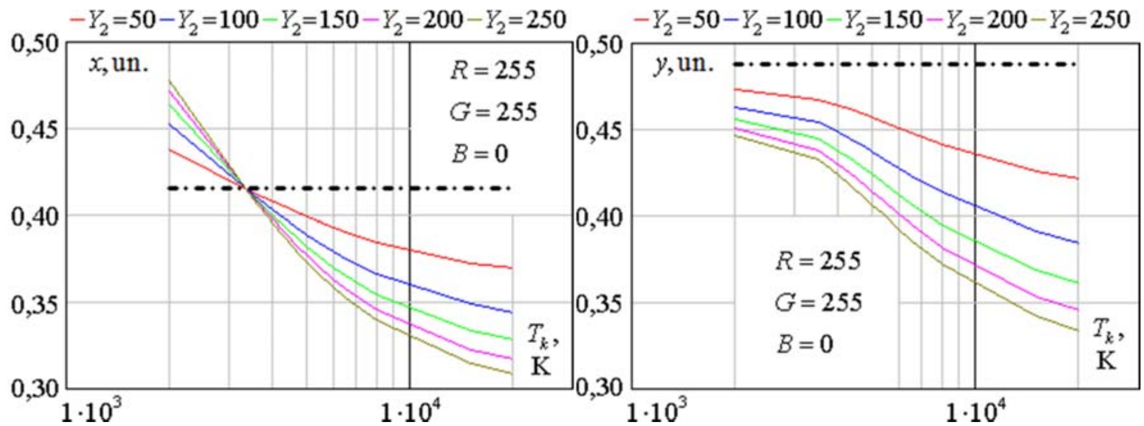
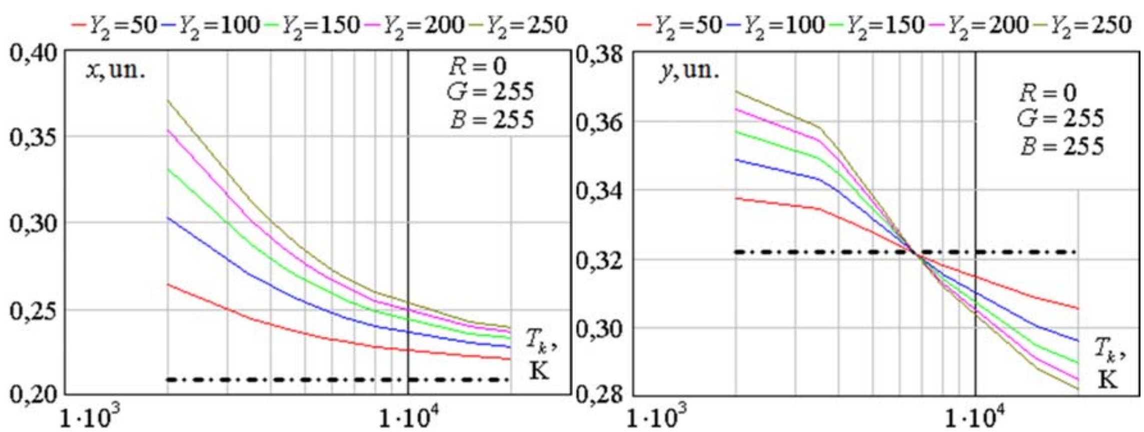


e)



f)

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ARPN Journal of Engineering and Applied Sciences

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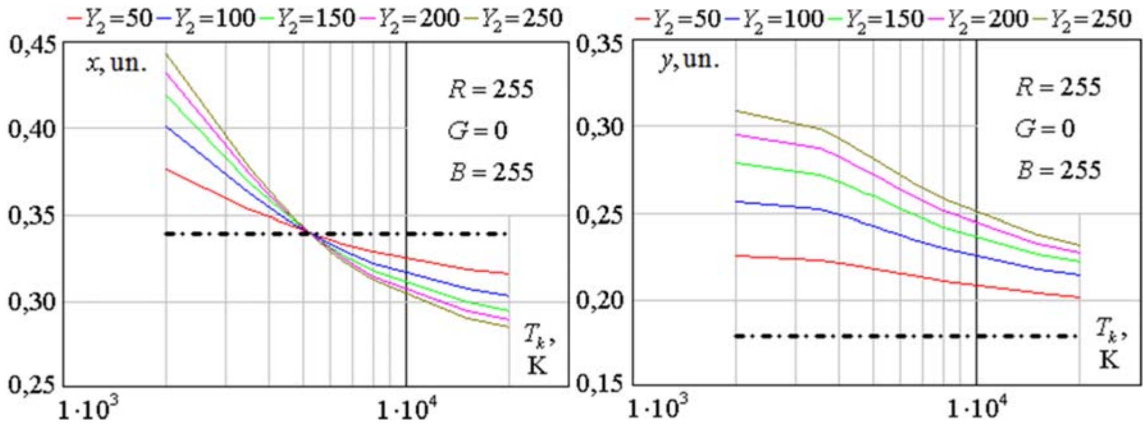

g)

Figure-2. Dependence of (x,y) chromaticity coordinates on T_k color temperature of the external illuminance Source of the LCD-panel for displayed a) red color, b) green color, c) blue color, d) white color, e) yellow color, f) cyan color, g) magenta color.

Simulation was performed on ASUS K56CB-X0391H personal computer with the following characteristics: Intel® Core™ i5-3337U processor, 4 cores, processor speed 1.8 GHz, internal memory 6 GB controlled by the operating system Windows 8.1. The LCD-panel color rendering model profile was specified during simulation by the coefficients: X_r=0,478; X_g=0,299; X_b=0,175; Y_r=0,263; Y_g=0,650; Y_b=0,081; Z_r=0,020; Z_g=0,160; Z_b=0,908.

CONCLUSIONS

Color palette of on-board display equipment should be formed based on the chart of external illuminance patterns in the supposed flying area. External illuminance is characterized by spectral composition of emission from the natural light source (the sun, the sky, the moon, re-reflection from clouds) having its specificity in the various regions of the earth surface.

Color temperature of the natural source of external illuminance varies from 2, 000 to 20, 000 Kelvins and exerts a significant impact on the visually perceived color of the image displayed on the LCD-panel (Zargaryants, 2008; Gatchin *et al*., 2015). While developing MFDU, it is necessary to provide intrinsic brightness of the device at the level of $L_{br} \geq 1000$ кд/м^2 with the diffuse reflection coefficient $\rho_d \leq 0{,}1\%$. MFDU constructive placement in the aircraft cabin should exclude the possibility of specular reflection of the light from the natural illumination source in the direction of the observer. Light specularly reflected from the LCD-panel with the specular reflection coefficient of 1% essentially eliminates possibility of image visual perception at E_{ext} =75 kLx.

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