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Modulation Transfer Function of the Thermal Imaging Monocular

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The modulation transfer function (MTF) of thermal imaging monocular (TIM) was investigated in this article. TIM consists of a lens, a microbolometric matrix (MBM), an electronic system of video signal amplification and processing, a micro display and an eyepiece. The monocular is considered as a linear invariant incoherent system. It's MTF is equal to the product of the modulation transfer functions of the components. For the convenience of practical application, it is proposed that all MTFs are considered as a function of the angular spatial frequency in the space of objects. An example of TIM MTF calculation with given characteristics was considered. The study of the MTF showed that the spatial impact of the MBM, which is determined by matrix structure, has the greatest influence on the deterioration of this function.

Key words: thermal imaging monocular; modulation transfer function; angular spatial frequency

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Introduction

Thermal imaging systems are widely used in various fields of human activity, including security systems, medical thermal diagnostics, aeronautical and space systems, remote sensing of the Earth's surface, military affairs, etc. [1–5]. In many cases, such systems are small-dimensional thermal imaging monoculars (TIM) in which the heat-contrast image of an object is observed by the operator on the display screen with the help of an eyepiece. The main characteristics of TIM are the spatial and temperature resolution, the maximum detection and recognition distances. They depend on the modulation transfer function (MTF) of the monocular [6–8]. Significant amount of scientific papers [9–15] are devoted to investigation of the thermal imagers MTF, the main components of which are the lens and the radiation detector. At the same time, there is a lack scientific and technical information about the development of methods for determining the MTF of a TIM, which consists of objective lens, microbolometric matrix (MBM), electronic system, display and eyepiece. Therefore, the development of such methods for determining the generalized MTF of thermal imaging monocular is an important task.

1 Problem formulation

The purpose of the article is to develop a method for determining the modulation transfer function of a thermal imaging monocular, which includes lens, microbolometer matrix, electronic system, display and an eyepiece that will optimize the characteristics of the monocular to solve a particular observation problem.

2 Physic-mathematical model of thermal imaging monocular

The functional scheme of the TIM is shown in Fig. 1. Infrared (IR) radiation from the object of observation is absorbed in the atmosphere and enters the entrance pupil of the lens. IR lens forms an image of the object and background on MBM sensitive surface. The electric video signal from the MBM is processed by the electronic system and enters the micro display, which forms the image of the object on the screen. The operator observes this image with an eyepiece.

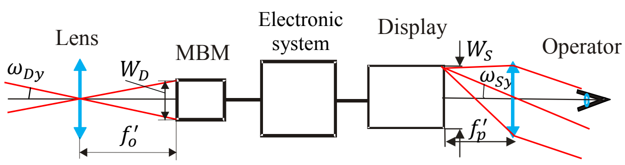

Fig. 1. Functional scheme of TIM

The mathematical model of TIM will be considered in the frequency domain (spatial and temporal) considering that the monocular is a linear invariant system. It is supposed that he object and background emit incoherently and each element of TIM has its own MTF.

3 Modulation transfer function of thermal imaging monocular

Modulation transfer function of TIM is determined by the product of its separate components MTFs: lens, MBM, electronic unit, display and eyepiece. For a one-dimensional case we have

$$M_s(\nu_x) = M_o(\nu_x) M_{Ds}(\nu_x) M_{Dt}(t) \cdot M_{El}(t) M_d(\nu_x) M_{ep}(\nu_x), \quad (1)$$

where $M_o(\nu_x)$, $M_{Ds}(\nu_x)$, $M_{Dt}(t)$, $M_{El}(t)$, $M_d(\nu_x)$ and $M_{ep}(\nu_x)$ are the MTFs of the lens, MBM, electronic unit, display and eyepiece respectively.

High-quality lenses without central screening and with the entrance pupil diameter D_{po} canbe considered as diffraction limited. Their MTF is determined by the function [7]

$$M_o(\nu_x) = \begin{cases} \frac{2}{\pi}\arccos x - x\sqrt{1-x^2}, & if\ 0 \le x \le 1; \\ 0, & if\ x > 1, \end{cases} \quad (2)$$

where $x = \lambda \frac{f_o'}{D_{po}} \nu_x$.

To simplify mathematical transformations, we approximate the complex function (2) by linear function

$$M_o(\nu_x) = \begin{cases} 1 - 1{,}218x, & if\ 0 \le x \le 0{,}821; \\ 0, & if\ x > 0{,}821. \end{cases} \quad (3)$$

Fig. 2 illustrates the MTF of diffraction-limited lens

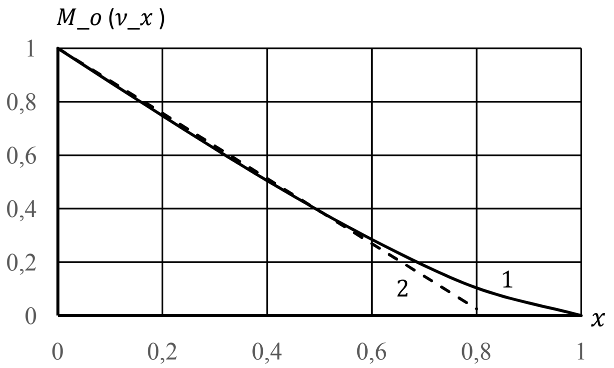

Fig. 2. The MTF of diffraction-limited lens – 1 and its linear approximation – 2

One-dimensional spatial MTF of a MBM can be approximated by function [9]

$$M_{Ds}(\nu_x) = \mathrm{sinc}(W_D \nu_x)\ \mathrm{sinc}(w_D \nu_x), \quad (4)$$

where W_D is a period of the matrix structure and w_D is a size of sensitive pixel area.

The temporal MTF of the MBM is a spatial low pass filter, which is approximated by the function [7]

$$M_{Dt} = \frac{1}{\sqrt{1 + 4\pi^2 t_D^2 f^2}}, \quad (5)$$

where t_D is a constant time of the microbolometer.

The MTF of the electronic block $M_{El}(t)$ is modeled by n-order Butterworth filters [7]. Modern electronic blocks have $M_{El}(f) \approx 1$ [6].

The MTF of the matrix display is approximated by a function similar to the MBM MTF, i.e.

$$M_d(\nu_x) = \mathrm{sinc}(W_d \nu_x)\ \mathrm{sinc}(w_d \nu_x). \quad (6)$$

The eyepiece MTF is approximated by a function similar to lens MTF, i.e.

$$M_{ep}(C) = \begin{cases} 1 - 1{,}218x, & if\ 0 \le x \le 0{,}821; \\ 0, & if\ x > 0{,}821, \end{cases} \quad (7)$$

where $x = \lambda \frac{f_{ep}'}{D_{pe}} \nu_x$, f_{ep}' and D_{pe} are the focal length and the exit pupil diameter of the eyepiece, respectively.

As Fig. 1 shows, the MTFs of the lens and the MBM are defined in the lens back focal plane. The display and the eyepiece MTFs are defined in the display screen plane. It should also be noted that in most cases the spatial frequency ν_x is determined in objects space and is measured in mrad^{-1}. The temporal MBM MTF and electronic unit MTF depend on the time frequency f.

The relationship between the spatial ν_x and temporal f frequencies is determined as [7]

$$f = \frac{\alpha_D}{t_o} \nu_{xa},\ \mathrm{Hz}, \quad (8)$$

where α_D is angular pixel matrix size and t_o is one pixel generation time.

The relationship between the angular spatial frequencies in the observation space ν_{xa}'' and the space of objects ν_{xa} can be established with use of fig. 3. Let the Foucault test (four-bar target) with a linear period V_{tp} be located in the plane of objects at a distance R. Then the angular period and spatial frequency are determined as

$$\alpha_{tp} = \frac{V_{tp}}{R} \quad i \quad \nu_{xa} = \frac{1}{\alpha_{tp}} = \frac{R}{V_{tp}}. \quad (9)$$

The lens forms an image of Foucault test with linear period V_{tp}' and angular spatial frequency

$$\nu_{xa}' = \frac{f_o'}{V_{tp}'} = \frac{R}{V_{tp}} = \nu_{xa}. \quad (10)$$

The MBM forms on the screen Foucault's test image with the period V_{tp}''. It is observed by the operator through an eyepiece with a focal length f_{ep}'. The angular period of this image and the angular spatial frequency are determined as

$$\alpha_{tp}'' = \frac{V_{tp}''}{f_{ep}'}, \qquad \nu_{xa}'' = \frac{1}{\alpha_{tp}''} = \frac{f_{ep}'}{V_{tp}''}. \quad (11)$$

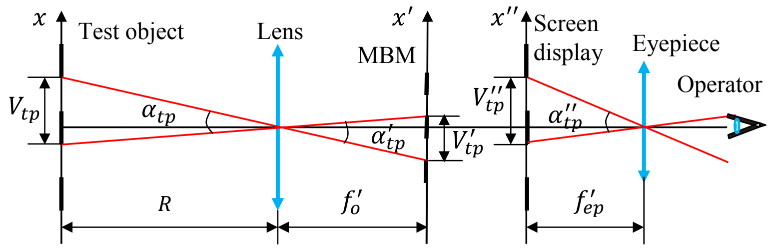

Fig. 3. The relationship between the angular spatial frequencies in the observation space ν''_{xa} and the space of objects ν_{xa}

Taking into account (10) and (11), we get the relationship

$$\nu''_{xa} = \frac{f'_{ep}}{V''_{tp}} = \frac{f'_{ep}}{V'_{tp}\beta_{el}} = \frac{f'_{ep}}{f'_o\beta_{el}}\nu_{xa}, \qquad (12)$$

where $\beta_{el} = V''_{tp}/V'_{tp}$ is an electronic magnification of TIM.

The angular magnification of the "TIM-operator" system is defined as (Fig. 3)

$$\Gamma_s = \frac{\tan\alpha''_{tp}}{\alpha_{tp}} = \frac{V''_{tp}}{f'_{ep}}\frac{R}{V_{tp}} = \frac{V''_{tp}}{f'_{ep}}\frac{f'_o}{V'_{tp}} = \frac{f'_o\beta_{el}}{f'_{ep}}. \qquad (13)$$

Therefore, (12) can be presented in the form

$$\nu''_x = \frac{\nu_x}{\Gamma_s}. \qquad (14)$$

Let put the MTFs of individual TIM components as functions that depend on the angular spatial frequency in the object space (Fig. 3).

The lens MTF is determined by (3), where $x = \lambda\frac{\nu_{xa}}{D_po}$. Then

$$M_o(\nu_{xa}) = \\ = \begin{cases} (1 - 1.218\lambda\frac{\nu_{xa}}{D_{po}}, & if\ 0 \le \nu_{xa} \le 0.821\frac{D_{po}}{\lambda}; \\ 0, & if\ \nu_{xa} > 0.821\frac{D_{po}}{\lambda}. \end{cases} \qquad (15)$$

The spatial MTF of MBM is defined from (4), which we represent in the form

$$M_{Ds}(\nu_{xa}) = \operatorname{sinc}\left(\frac{V_D}{f'_o}\nu_{xa}\right)\operatorname{sinc}\left(\frac{v_D}{f'_o}\nu_{xa}\right). \qquad (16)$$

The temporal MTF of MBM is determined from (5) taking into account (8). So, we have

$$M_{Dt}(\nu_{xa}) = \left[1 + 4\pi^2\left(\frac{t_D}{t_o}\right)^2\left(\frac{V_D}{f'_o}\right)^2\nu_{xa}^2\right]^{-0{,}5}. \qquad (17)$$

The MTF of the display is determined by (6) taking into account (12)

$$M_d(\nu_{xa}) = \operatorname{sinc}\left(\frac{V_d}{f'_o\beta_{el}}\nu_{xa}\right)\operatorname{sinc}\left(\frac{v_d}{f'_o\beta_{el}}\nu_{xa}\right). \qquad (18)$$

The MTF of the eyepiece can be expressed by (7) which, similarly to the lens MTF (15) and taking into account (12) will be

$$M_{ep}(\nu_{xa}) = \\ = \begin{cases} (1 - 1.218\lambda\frac{\nu_{xa}}{D_{pe}}, & if\ 0 \le \nu_{xa} \le 0.821\frac{D_{pe}f'_o\beta_{el}}{\lambda f'_{ep}}; \\ 0, & if\ \nu_{xa} > 0.821\frac{D_{pe}f'_o\beta_{el}}{\lambda f'_{ep}}. \end{cases} \qquad (19)$$

4 Analysis of the TIM MTF

Let consider an example of TIM MTF calculation. TIM has following characteristics

- Lens: the focal length $f'_o = 70$ mm, the entrance pupildiameter $D_{op} = 70$ mm;
- MBM: the pixel size is $V_D = 17\ \mu m$, the size of the sensitive areais $w_D = 14\mu m$, the size of the matrix is $X_D = 6.8$ mm, the time constantis $t_D = 10$ ms and the frame frequency is $f_f = 50$ Hz;
- Display: the pixel size is $V_d = 17\mu m$, the size of pixel color groupis $v_D = 15\mu m$, the screen size is $X_d = 9.6$ mm;
- Eyepiece: the focal length is $f'_{ep} = 25$ mm, the entrance pupil diameter is $D_{ep} = 4$ mm.

Fig. 4 shows the MTF of the TIM separate components and its resulting MTF (1).

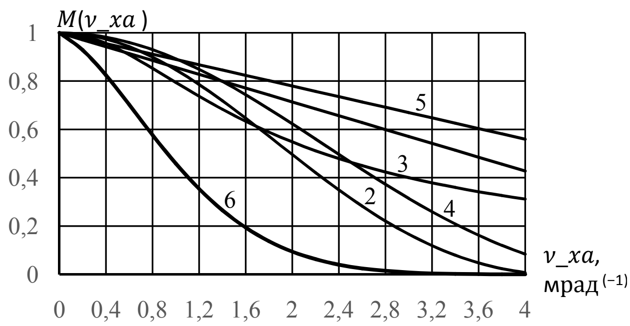

Fig. 4. The modulation transfer functions. 1 – MTF of lens, 2 – spatial MTF of MBM, 3 – temporal MTF of MBM, 4 – MTF of display, 5 – MTF of eyepiece, 6 – resulting TIM MTF

Analysis of (1), (15) – (19) and their graphs showed that

1. The MTF of TIM components as a rule are defined in different locations. The lens and the MBM MTFs are defined in the lens focal plane; display and eyepiece MTFs are defined in the display screen plane. The temporal MTF depends on the time frequency. When determining the resulting TIM MTF, it is necessary that all the components MTFs are considered in a same location. For the convenience of practical application, it is proposed that all MTF sare considered as a function of the angular spatial frequency in the space of objects.

2. The greatest impact on the deterioration of the resulting TIM MTF $M_s(\nu_x)$ has spatial MTF of the MBM $M_{Ds}(\nu_{xa})$, which is determined by the pixel size. The smallest influence on the TIM MTF have electronic system and the eyepiece.

3. At the Nyquist frequency $\nu_N = 2$ mm^{-1} the contrast decreases due to MBM to 50%, the diffraction limited lens to 71%, a display to 62%, an eyepiece to 71%. Under these conditions, the resulting MTF of TIM $M_s(\nu_N) = 0,095$.

4. The resulting MTF of TIM is well approximated by a Gaussian function [6]

$$M_{s,ap}(\nu_{xa}) = \exp(-2\pi^2 r_{sa}^2 \nu_x^2), \qquad (20)$$

where r_{sa} is an angular radius of the point source image which operator observes through the ocular on the display screen.

From the last expression it follows that the point spread function (PSF) of TIM has the form

$$h_s(\omega_x) = \\ = \int_{-\infty}^{\infty} M_(s,ap)(\nu_{xa}) \exp\left(2\pi\omega_x\nu_{xa}\right) d\nu_{xa} = \\ = \frac{1}{\sqrt{2\pi} r_{sa}} \exp\left(-\frac{\omega_x^2}{2r_{sa}^2}\right), \qquad (21)$$

where ω_x is a variable angle of field of view, mrad.

The radius r_{sa} is determined by the angle between the center of the PSF $h_s(\omega_x = 0)$ and its value $h_s(\omega_x = r_{sa}) = 0.606$. In some cases, (20) is used only within $0 \le \nu_{xa} \le \nu_N$ limits.

Conclusions

A method for determining the modulation transfer function of a thermal imaging monocular has been developed. The monocular consists of a lens, a microbolometric matrix, an electronic system, a display and an eyepiece. It was proposed to consider the MTF of the monocular in the space of “object – TIM”, which allows us to calculate the angular resolution of the contrast limited TIM. The obtained analytical expressions for the MTFs of individual components allow one to optimize the characteristics of the monocular for solving a specific observation problem.

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Модуляційна передавальна функція тепловізійного монокуляра

Колобродов В. Г.

В даній статті досліджується модуляційна передавальна функція (МПФ) тепловізійного монокуляра (ТПМ), до складу якого входять об'єктив, мікроболометрична матриця (МБМ), електронна система підсилення і обробки відеосигналу, мікродисплей і окуляр. МПФ визначає просторове розділення монокуляра, яке впливає на якість тепловізійного зображення і максимальну дальність виявлення і розпізнавання об'єктів спостереження. Розроблена фізико-математична модель ТПМ, в якій монокуляр розглядається як лінійна інваріантна некогерентна система, МПФ якого дорівнює добутку модуляційних передавальних функцій окремих компонентів такого ТПМ. Запропоновані аналітичні вирази для МПФ сучасних компонентів ТПМ, а саме: об'єктива, матричного приймача випромінювання, електронної системи, дисплея і окуляра. Для зручності практичного застосування МПФ запропоновано розглядати МПФ усіх компонентів в просторі "об'єкт спостереження – ТПМ", що дозволяє розрахувати кутову роздільну здатність контрастно обмеженого ТПМ. Встановлено зв'язок між просторовими частотами в просторі спостереження і просторі предметів. Отримано формулу для розрахунку кутового збільшення системи "ТПК – оператор". Розглянуто приклад розрахунку МПФ ТПМ з заданими характеристиками компонентів монокуляра. Дослідження МПФ такого монокуляра показало, що найбільший вплив на погіршення цієї функції має просторова МПФ МБМ, яка визначається її матричною структурою. Наприклад, на частоті Найквіста 2 $мм^{-1}$ відбувається зниження контрасту за рахунок МБМ до 28%, дифракційно обмеженого об'єктива до 71%, дисплея до 62%, окуляра до 71%. За цих умов МПФ ТПК дорівнює 0,094. Результуюча МПФ ТПК добре апроксимується гаусовою функцією.

Ключові слова: тепловізійний монокуляр; модуляційна передавальна функція; кутова просторова частота

Модуляционная передаточная функция тепловизионного монокуляра

Колобродов В. Г.

В данной статье исследуется модуляционная передаточная функция (МПФ) тепловизионного монокуляра (ТПМ), в состав которого входят объектив, микроболометрических матрица (МБМ), электронная система усиления и обработки видеосигнала, микродисплей и окуляр. Монокуляр рассматривается как линейная инвариантная некогерентная система, МПФ которого равна произведению модуляционных передаточных функций отдельных компонентов такого ТПМ. Для удобства практического применения МПФ предложено рассматривать МПФ всех компонентов в пространстве "объект наблюдения - ТПМ", что позволяет рассчитать угловое разрешение контрастно ограниченного ТПМ. Рассмотрен пример расчета МПФ ТПМ с заданными характеристиками. Исследование МПФ такого монокуляра показало, что наибольшее влияние на ухудшение этой функции имеет пространственная МПФ МБМ, которая определяется ее матричной структурой.

Ключевые слова: тепловизионный монокуляр; модуляционная передаточная функция; угловая пространственная частота