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Mathematical simulation of the dependence of aircraft radiation power on the observation angle

The software model environment developed allows us to estimate the power characteristics of aircraft radiation at different observation angles. The method of implementation of this environment makes it possible to get results with an accuracy sufficient to determine the characteristics of the indicatrices of the aircraft under study. The high level of versatility of the model environment enables us to make calculations for any aircraft with different flight conditions in several spectral ranges.

Keywords: radiation simulation, aircraft radiation, computational research, radiation indicatrix.

Introduction

When simulating the movement of an aircraft, its spatial orientation determines the radiation power of the aircraft. Equally important is the possibility of determining the most advantageous position of the optoelectronic system relative to the aircraft for its detection. The existing methods of modelling power distribution are based either on certain approximations [1], or on using only the thermal radiant exitance of the aircraft [2]. While a description of methods and techniques for a comprehensive computation of the spatial energy distribution [3] exists, there is no corresponding software implementation. When performing calculations for actual power plants, the Monte Carlo method is used, which implies a random direction of emanating rays, without taking into account the presence of aircraft plume [4]. Other existing distributions of radiation power in space for some aircraft types do not cover the entire range of angles and spectral ranges or are made in larger increments. The above indicates the need for a universal tool for performing such calculations.

Calculation method

The calculations are based on the principle of collecting the spectral power of the aircraft radiation in one fixed-size receiving cell at the required sight angle. To perform the calculations, the spectral characteristics of the aircraft were used in wave number units, since in most of the databases used, the spectral characteristics are presented in these units of measurement [5]. This simulation environment allows to select a spectral range, the distance to the aircraft, size and instrument function of the receiving cell, as well as a range and increment of indicatrix formation.

The aircraft model used in the calculations is uploaded into the software environment as a 3D model. The model is manually divided into several elementary units, depending on the properties and materials of the original aircraft (Fig. 1). All elementary units, in turn, are divided into the simplest surfaces, with each of them having its own properties, depending on the location of this element on the aircraft. After that, exposed surfaces are determined, spectral density of the radiation power flux is calculated and the contribution of this area unit to the total power upon integration is identified. The radiating surfaces of the aircraft can be divided into several categories: opaque
parts of the body, transparent parts of the body, and engine plumes. Materials and properties of individual subobjects are set prior to the calculation process. Particularities of generation and accounting of each category are discussed below.

In Figure 1, the end of the nose and wingtips are accentuated due to a significant difference in the properties of these parts of the aircraft from the adjacent ones due to aerodynamic heating. The cockpit canopy is a transparent part of the body with the other parts being opaque.

The aircraft body parts temperature is different from the ambient temperature due to aerodynamic heating [6]. To determine the spectral characteristics of the radiation of heated parts of the aircraft, an approximation of black body radiation was used with the grayness coefficient \( \alpha_g \), depending on the type of surface selected. The radiation power was calculated using the Planck formula for wave numbers

\[
L_{bb} = \frac{2\hbar c^2\omega^3}{e^{\frac{hc\omega}{kT}} - 1}, \quad \text{W/(cm}^2 \cdot \text{sr} \cdot \text{cm}^{-1}), \quad (1)
\]

where \( \omega \) is a wave number, cm\(^{-1}\).

In case of opaque materials of the aircraft body, the grayness coefficient \( \alpha_g \) is used, multiplied by the spectral density of the radiation power flux obtained using formula (1).

Since the aircraft planes are located at different angles relative to the sighting direction, it is necessary to take into account the associated change in power. For materials with the indicatrix of luminescence \( X(\alpha) \), the coefficient given in it is taken into account; if for some materials it is not present, the radiation is considered isotropic.

In the first case, the radiation from the platform, calculated in W/sr in the direction of the normal to the platform, is multiplied by this coefficient:

\[
L(\alpha) = SX(\alpha)L_{bb}\alpha_g. \quad (2.1)
\]

In the second case, the concept of effective area is introduced — it is equal to the product of the platform area and the cosine of the angle between the normal and the sight angle — which is multiplied by the baseline radiation:

\[
L(\alpha) = S\cos\alpha L_{bb}\alpha_g. \quad (2.2)
\]

In addition to their own thermal radiation with a grayness coefficient, transparent parts of the aircraft body are also characterized by additive radiation that passes through them with a given transmission factor.

The radiation of aircraft engine plumes was modelled using the gas-dynamic calculation method described in [7]. After obtaining the required indicators of temperatures, pressures and concentrations of the exhaust components, the spectral power of the luminescence of the gaseous components of the plume is calculated according to the Beer – Lambert – Bouguer law:

\[
I = L_{bb}e^{-k(\omega)l}, \quad (3)
\]

where \( l \) is the thickness of the gas layer.

The required absorption coefficients \( k(\omega) \) are calculated on the basis of the HITRAN database [5]. Since the radiation (absorption) for gas components depends on the thickness of the radiating (absorbing) layer, the simulation environment calculates the depth of the radiating (absorbing) layer for each elementary area observed at a given sight angle. In the case of a multilayer structure of the engine plume, the radiation of each layer \( i \) is calculated with its absorption by the subsequent layers \( j \) and summation of the total radiation:

\[
I_{sum} = \sum_{i=1}^{N} I_i \prod_{j=i+1}^{N} e^{-k(\omega)l_j}. \quad (4)
\]

This method of calculating multilayer radiating and absorbing structures is described in article [8].

Results

In order to demonstrate the simulation results, it is possible to 3D visualize the obtained indicatrix using various methods. A 3D visualization of the simulation results for the General Dynamics F-16 aircraft in the wavelength range of 3...5 \( \mu \text{m} \) is shown in Figure 2.

The aircraft parameters correspond to movement at a speed of 900 km/h, at an altitude of 10 km in standard atmosphere. The deposition step is 1°. The first visualization method (Figure 2, a) is based on creating an array of points with each
of them corresponding to a certain sight angle and separated from the centre of the aircraft by a distance proportional to the radiation power received at this angle. In the second method (Fig. 2, b), the dependence of power on the sight angle is determined by the colour of the surface of the sphere built around the aircraft. In addition, a summary visualization method is presented (Fig. 2, c), in which both the position and colour of the point determine the received value. For a better view

![Fig. 2. Visualization of the results generated in the software environment using the example of the F-16 aircraft: a, b, c– angle of sight is the same; d – angle of sight is altered, aircraft is shown in contour](image-url)
of the indicatrix sections with low power, it is possible to display only the contours of the aircraft model (Fig. 2, d), leaving the positions and colour of the points visible. All visualization methods allow to rotate the model, changing its position, colour scheme, size of points and their average distance to the centre. Gaps between neighbouring points in some places of the indicatrix, especially noticeable in Fig. 2, c, are associated with the low polygonality of the model of the aircraft under study. As the model detail increases, the transition between different points of the indicatrix is flattened.

The simulation results are finalized into a data array, which presents the azimuth, elevation angle and power value in watts. The result

![Diagram a](image1.png)

**Fig. 3.** Dependence of the F-16 aircraft radiation power on the azimuth with the elevation angle of the receiver mounting location at 90° (a) and 45° (b), from the nose of the aircraft towards the left hemisphere

![Diagram b](image2.png)

**Fig. 4.** Dependence of the F-16 aircraft radiation power on the elevation angle with the azimuth of the receiver mounting location at 0° (a) and 30° (b), from the nose of the aircraft towards the upper hemisphere
of radiation modelling of the F-16 aircraft for a fixed azimuth (Fig. 3) or elevation angle (Fig. 4) can be built in any software environment based on the resulting file. As in the case of 3D visualization, the asymmetry of the radiation in the tail is related to the shape and polygonality of the nozzle of the aircraft engine.

The analysis of 3D visualization of the results of simulation of the dependence of power on the sight angle of the AIM-7 Sparrow missile at the speed of 3200 km/h, at an altitude of 10 km with the fixed azimuth (Fig. 5) and elevation angle (Fig. 6) also showed the asymmetry of some parts of the indicatrix. However, in this case, the asymmetry is observed in the areas corresponding not to the tail, but to the lateral part. Increasing the detail of the model will lead to greater symmetry of the indicatrix, but will significantly increase the calculation time.

**Fig. 5.** Dependence of the AIM-7 missile radiation power on the azimuth with the elevation angle of the receiver mounting location at 90° (a) and 60° (b), from the nose of the aircraft towards the left hemisphere

**Fig. 6.** Dependence of the AIM-7 missile radiation power on the elevation angle with the azimuth of the receiver mounting location at 0° (a) and 20° (b), from the nose of the aircraft towards the upper hemisphere.
When performing the calculations, the optimal ratio of model detail was chosen and, therefore, the accuracy of the recorded power, which allows to take into account all the features of this aircraft.

**Conclusion**

A simulation software environment was created for calculating the aircraft radiation power given the observation angle, with the visualization of the obtained indicatrix.

The radiation power of the F-16 aircraft and AIM-7 Sparrow missile was calculated in the specified simulation software environment.

The developed simulation software environment can be used to create databases of aircraft radiation power characteristics at different observation angles.

**Bibliography**


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Science research interests: remote optical research methods, gas-dynamic calculations of aircraft, spatial modeling of physical processes.

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Science research interests: mathematical modeling of physical processes, generation and distribution of infrared radiation.


Science research interests: mathematical modeling of physical processes, gas spectroscopy.


Science research interests: development of optoelectronic systems.
Математическое моделирование зависимости мощности излучения летательных аппаратов от угла наблюдения

Разработанная программная модельная среда позволяет оценить мощностные характеристики излучения летательных аппаратов при различных углах наблюдения. Метод реализации данной среды позволяет получать результаты с точностью, достаточной для определения особенностей индикатрис исследуемых летательных аппаратов. Высокий уровень универсальности модельной среды дает возможность проводить расчеты для любых летательных аппаратов при различных режимах полета в нескольких спектральных диапазонах.

Ключевые слова: моделирование излучения, излучение летательного аппарата, расчетное исследование, индикатриса излучения.

Область научных интересов: дистанционные оптические методы исследования, газодинамические расчеты летательных аппаратов, пространственное моделирование физических процессов.

Область научных интересов: математическое моделирование физических процессов, генерация и распространение инфракрасного излучения.

Область научных интересов: математическое моделирование физических процессов, спектроскопия газовых сред.

Область научных интересов: разработка оптико-электронных систем.