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ALGORITHM FOR DETERMINING THE ANGULAR POSITION OF THE PILOT'S HELMET TO CONTROL THE ON-BOARD WEAPON'S CONTROL SYSTEM

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Abstract

The following paper presents a method of determining the angular position of the pilot's helmet based on the measurement of magnetic field components, artificially generated on board the aircraft (similarly to the helmet-mounted cueing systems of the F-16 aircraft). We presented a mathematical model, which describes determining of the angular position of the pilot's helmet, based on the measurement of the magnetic field components in various moments of powering orthogonally fixed magnetic coils. We also defined modelling capabilities of the helmet-mounted cueing system, which uses the magnetic method to determine the angular position of the pilot's helmet. It has been shown that the direction cosine matrix can be used for determining the angular position of the pilot's helmet, specified based on the matrix formed from the magnetic field components in various moments of powering orthogonal magnetic coils. The paper ends with an outline of simulation tests, which enable to identify the errors of the system, using such a method.

Keywords: *helmet-mounted cueing systems, modelling and research methods*

1. Introduction

One of the most modern and currently developed on-board systems [4, 9] of contemporary aircraft and military aircraft are helmet-mounted cueing systems HAMS and helmet-mounted display systems HMDS [3].

An example of the state-of-the-art helmet-mounted cueing systems is HEMS system (Fig. 1), fixed in F-35 aircraft (with virtual display HUD and optical-magnetic method of determining the angular position of the helmet [5], with the accuracy estimated at the level of 0.1 deg.

In Poland, the helmet-mounted cueing systems are exploited in MiG-29 aircraft (SzCz-3UW version, which uses the electro-optical method with 1-2 deg. accuracy) and in F-16 aircraft (JHMCS version), (Fig. 2), using the magnetic method [6], with 0.3-0.5 deg. of accuracy.

Fig. 1. View of Helmet-Mounted Cueing Systems elements for the F-35 aircraft [5]

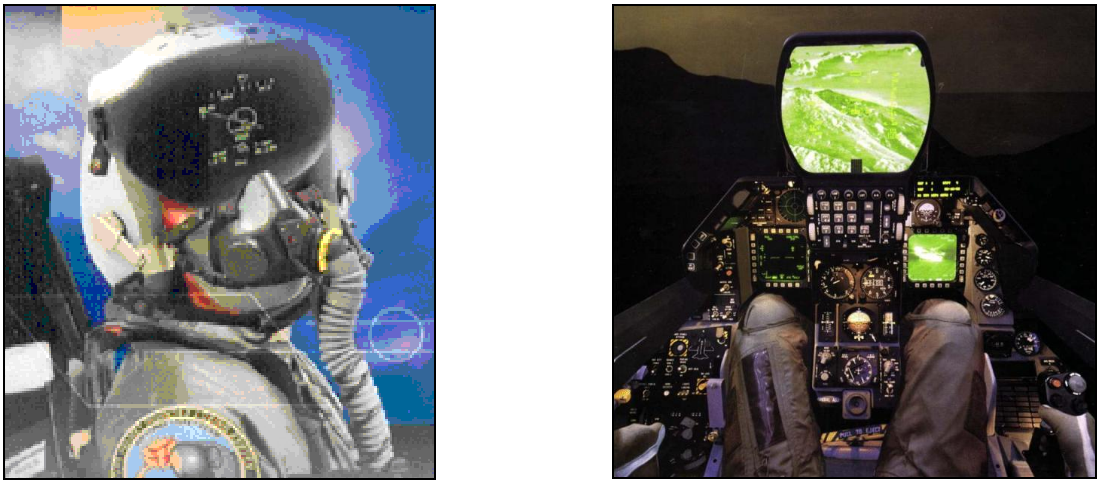

Fig. 2. View of Helmet-Mounted Cueing Systems elements for the F-16 aircraft [6]

The helmet-mounted cueing systems employ helmet-mounted display elements and modules to determine the angular position of the pilot's helmet in the reference system related to the aircraft. The source of data for imagery in helmet-mounted systems might also be derived from observational-cueing heads [5, 6]. Thus, it is possible to display the imagery, right in front of the pilot, in the day mode and the night vision mode, as well as automatic tracking down the target, indicated by the pilot.

A novel Polish-made cueing system [10], which has not been yet introduced on board a military aircraft, is the NSC-1 Orion helmet-mounted cueing system (Fig. 3), dedicated for W-3PL helicopters (manufactured by the Polish scientific-industrial consortium in cooperation with the Air Force Institute of Technology), as a leader of the research project realized in the years 2009-2012.

It uses algorithms based on artificial neural network and the electro-optical method. According to the available information [10], various methods have been tested for determining the angular position of the pilot's helmet (magnetic, electro-optical and hybrid) in the phase of a technology demonstrator of the helmet-mounted system which steers moving armament in the W-3PL helicopter, in the NSC-1 Orion system.

Due to difficulties in obtaining the required precision in determining the angular position of the pilot's helmet in the NSC-1 Orion system [10], the magnetic method was subjected to a detailed analysis, where the authors used their own specially devised algorithm meant for calculating the helmet's position, which uses the direction cosine matrices.

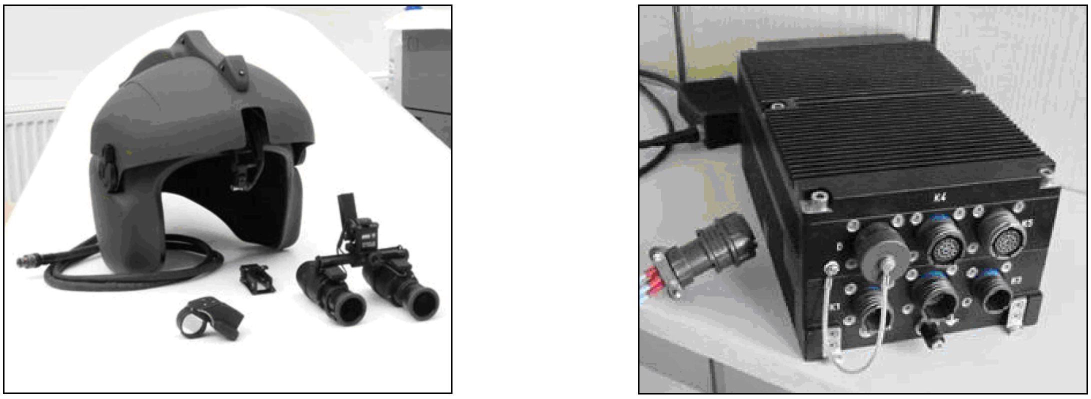

Fig. 3. View of Helmet-Mounted Cueing Systems elements for the W-3PL aircraft [10]

2. Selected methods of using the magnetic field for determining the angular position of the pilot's helmet

Among the methods used for determining the angular position of the pilot's helmet, which take into account the magnetic field in helmet-mounted cueing systems, it is possible to distinguish two groups [9]: methods based on the measurement of the Earth's magnetic field and also methods basing on the measurement of the magnetic field artificially generated on board an aircraft.

Special attention must be drawn to the method of determining the angular position of the pilot's helmet, which takes into consideration cyclic (frequent) measurements of the magnetic field components, generated on board the aircraft, similarly to the F-16 aircraft (Fig. 4).

In this method, the magnetic field is generated by three, mutually orthogonal transmission systems, the so-called transmitters, which are steered by electronic blocks [5].

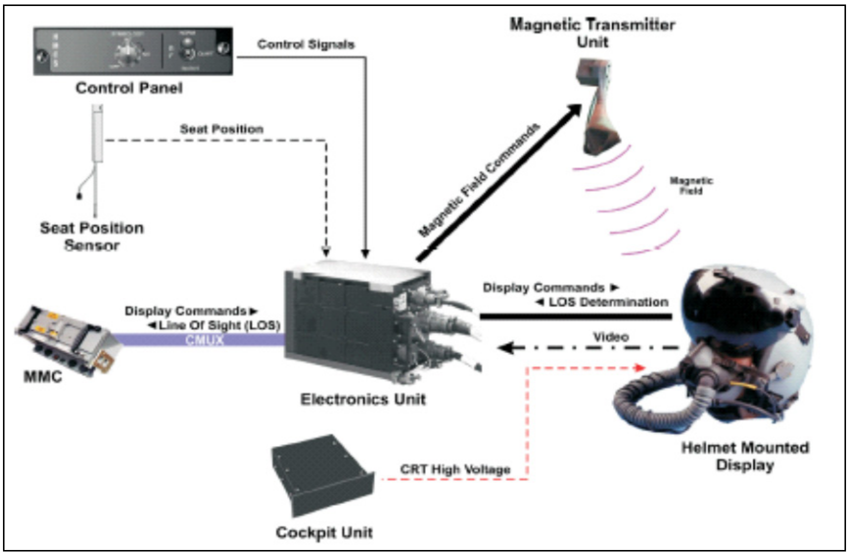

Fig. 4. View of Helmet-Mounted Cueing Systems elements for the F-16 aircraft [6]

3. Using the natural magnetic field of the Earth to determine the angular position of the pilot's helmet

In the case of determining the angular position which uses the natural magnetic field (time constant), the manner of determining the angular position of the pilot's helmet or the aircraft bases on the measurement of the components of the magnetic field, generated by the Earth, after compensating the influence of the aircraft's own magnetic field (similarly to the MIG-29 aircraft, i.e. after removing the so-called magnetic deviation).

According to the generally adopted principles, e.g. [8, 10], the magnetic course of an aircraft, can be determined from the following dependency:

$$\Psi_{SP} = \text{ATN}\left(\frac{H_{\text{SP-Z}} \sin\Phi_{\text{SP}} - H_{\text{SP-Y}} \cos\Phi_{\text{SP}}}{H_{\text{SP-X}} \cos\Theta_{\text{SP}} + H_{\text{SP-Y}} \sin\Theta_{\text{SP}} \sin\Phi_{\text{SP}} + H_{\text{SP-Z}} \sin\Theta_{\text{SP}} \cos\Phi_{\text{SP}}}\right), \quad (1)$$

where:

$H_{\text{SP-X}}$, $H_{\text{SP-Y}}$, $H_{\text{SP-Z}}$ – components of the Earth's magnetic field, present in measurement axes of the sensor for the set angular position of the aircraft against the horizontal coordinate system (connected with the Earth, beginning on the aircraft),

Θ_{SP}, Φ_{SP} – calculated aircraft's attitude and tilt in the horizontal coordinate system (connected with the Earth, beginning on the aircraft).

Likewise, it is possible to calculate the magnetic course of the pilot's helmet in the horizontal coordinate system, according to the following dependency:

$$\Psi_{PO} = \text{ATN}\left(\frac{H_{\text{PO-Z}} \sin\Phi_{\text{PO}} - H_{\text{PO-Y}} \cos\Phi_{\text{PO}}}{H_{\text{PO-X}} \cos\Theta_{\text{PO}} + H_{\text{PO-Y}} \sin\Theta_{\text{PO}} \sin\Phi_{\text{PO}} + H_{\text{PO-Z}} \sin\Theta_{\text{PO}} \cos\Phi_{\text{PO}}}\right), \quad (2)$$

where:

$H_{\text{PO-X}}$, $H_{\text{PO-Y}}$, $H_{\text{PO-Z}}$ – components of the Earth's magnetic field, present in measurement axes of the sensor for the set angular position of the aircraft against the horizontal coordinate system (connected with the Earth, beginning on the aircraft),

Θ_{PO}, Φ_{PO} – calculated aircraft attitude and tilt in the horizontal coordinate system (connected with the Earth, beginning on the pilot's helmet). It is possible to specify current elevation angles basing on the above information, and the azimuth of the pilot's helmet in relation to the aircraft cockpit due to the following dependencies [9]:

$$A_{\text{PO-SP}} = [\Psi_{\text{PO}} \cos\Phi_{\text{PO}} - \Theta_{\text{PO}} \sin\Phi_{\text{PO}}] - [\Psi_{\text{SP}} \cos\Phi_{\text{SP}} - \Theta_{\text{SP}} \sin\Phi_{\text{SP}}], \quad (3)$$

$$E_{\text{PO-SP}} = [\Theta_{\text{PO}} \cos\Phi_{\text{PO}} + \Psi_{\text{PO}} \sin\Phi_{\text{PO}}] - [\Theta_{\text{SP}} \cos\Phi_{\text{SP}} + \Psi_{\text{SP}} \sin\Phi_{\text{SP}}], \quad (4)$$

where:

$A_{\text{PO-SP}}$, $E_{\text{PO-SP}}$ – calculated azimuth and the elevation of the pilot's helmet in relation to the aircraft main axes (for the set angular position of the pilot's helmet against the cockpit).

Despite the knowledge of mathematical dependencies, allowing to calculate the current course of the pilot's helmet and of the aircraft, it is problematic to reduce the influence of the aircraft's own magnetic field (coming from the so-called hard irons and soft irons as well as the field generated from on-board electrical circuits), and also an influence of linear accelerations (from aircraft manoeuvres), which lower the accuracy of calculating tilt and attitude angles of the pilot's helmet [11].

In order to dispose of the above limitations, it is possible to apply the magnetic method for determining the angular position of the pilot's helmet in relation to the aircraft, using the so-called calibrated magnetic field (artificially generated in the cockpit). For this method, we suggested an algorithm of calculating an azimuth and elevation of the pilot's helmet because of direction cosine matrices, obtained from the magnetic field matrix, generated by a system of three magnetic coils, according to the information presented in [11].

4. Using artificial magnetic field in the cockpit in order to determine the angular position of the pilot's helmet

The principle of determining the angular position of the pilot's helmet relies on measuring the components of the magnetic field, artificially generated on board the aircraft (similarly to the F-16 aircraft).

In order to facilitate the understanding of the principle of using the magnetic method to determine the angular position of the pilot's helmet in relation to the aircraft cockpit [10], we accepted (Fig. 5), that the magnetic field is generated by three mutually orthogonal transmitters: coil A (the vector of the field overlaps the longitudinal axis of the aircraft), coil B (the vector of the field overlaps the horizontal axis of the aircraft), and coil C (the vector of the field overlaps the vertical axis of the aircraft).

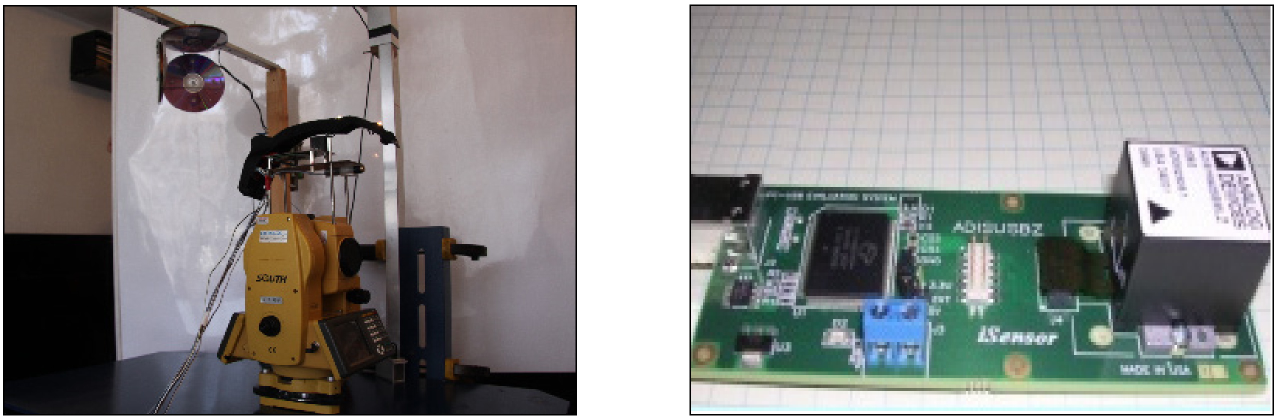

Fig. 5. View of systems to generate and measure magnetic field with flat coils [9]

The measurement system mounted on the pilot's helmet, used for the investigation, contains three ADIS-16405 magnetic field sensors [7], placed orthogonally on a joint panel (Fig. 5).

The operations of the helmet-mounted cueing system in the presented magnetic method means that [11] in each measurement cycle there are four phases: measurement of reference field (of the Earth's magnetic field and the magnetic field generated by the equipment of the aircraft), measurement of the magnetic field generated by coil A (with the reference field), measurement of the magnetic field generated by coil B (with the reference field), and measurement of the magnetic field generated by coil C (with the reference field). The data of the measurement system in the form of 12 components of magnetic field vectors (obtained from the measurement of the impulse magnetic field, generated by the particular coils, in the set order, in four successive periods of the measurement cycle) are transmitted to the computational block (system computer). The aim of its implemented software (e.g. with the algorithm based on the direction cosine matrix, suggested in this paper) is to determine the current angles of azimuth and elevation of the pilot's helmet in relation to the aircraft axes, based on the obtained measurement data.

The fundamental problem occurring in the realization of the magnetic method [11] is the difficulty to determine the angular position of the pilot's helmet with large tilts of the pilot's head and changes of his sitting posture, owing to non-linearity of the magnetic field, generated by real systems (e.g. flat coils).

The vector of the magnetic field components present within the area of the pilot's head, in particular moments of its generation by the coils, may be shown as:

$$[H_{\mathrm{SP}}(A)] = [H_{\mathrm{SP\text{-}X}}(A)\,,\, H_{\mathrm{SP\text{-}Y}}(A)\,,\, H_{\mathrm{SP\text{-}Z}}(A)], \tag{5}$$

$$[H_{\mathrm{SP}}(B)] = [H_{\mathrm{SP\text{-}X}}(B)\,,\, H_{\mathrm{SP\text{-}Y}}(B)\,,\, H_{\mathrm{SP\text{-}Z}}(B)], \tag{6}$$

$$[H_{\mathrm{SP}}(C)] = [H_{\mathrm{SP\text{-}X}}(C)\,,\, H_{\mathrm{SP\text{-}Y}}(C)\,,\, H_{\mathrm{SP\text{-}Z}}(C)], \tag{7}$$

where:

$H_{\mathrm{SP\text{-}X}}(A)$, $\mathrm{H}_{\mathrm{SP\text{-}Y}}(A)$, $H_{\mathrm{SP\text{-}Z}}(A)$ – magnetic field components, present in the area of the pilot's head, at the time of its generation by coil A, in the coordinate system connected with the main axes of the aircraft,

$H_{\mathrm{SP\text{-}X}}(B)$, $\mathrm{H}_{\mathrm{SP\text{-}Y}}(B)$, $H_{\mathrm{SP\text{-}Z}}(B)$ – magnetic field components, present in the area of the pilot's head, at the time of its generation by coil B, in the coordinate system connected with the main axes of the aircraft,

$H_{SP\text{-}X}(C)$, $H_{SP\text{-}Y}(C)$, $H_{SP\text{-}Z}(C)$ – magnetic field components, present in the area of the pilot's head, at the time of its generation by coil C, in the coordinate system connected with the main axes of the aircraft.

The vector of the components of the magnetic field measured by the sensors present in the pilot's helmet, in particular moments of its generation by the coils, may be expressed as follows:

$$[H_{PO}(A)] = [H_{PO\text{-}X}(A)\,,\, H_{PO\text{-}Y}(A)\,,\, H_{PO\text{-}Z}(A)], \tag{8}$$

$$[H_{PO}(B)] = [H_{PO\text{-}X}(B)\,,\, H_{PO\text{-}Y}(B)\,,\, H_{PO\text{-}Z}(B)], \tag{9}$$

$$[H_{PO}(C)] = [H_{PO\text{-}X}(C)\,,\, H_{PO\text{-}Y}(C)\,,\, H_{PO\text{-}Z}(C)], \tag{10}$$

where:

$H_{PO\text{-}X}(A)$, $H_{PO\text{-}Y}(A)$, $H_{PO\text{-}Z}(A)$ – components of the magnetic field, present in the measurement axes of the sensor mounted on the pilot's helmet at the moment of its generation by coil A, in the system of coordinates which are linked to the main axes of the aircraft,

$H_{PO\text{-}X}(B)$, $H_{PO\text{-}Y}(B)$, $H_{PO\text{-}Z}(B)$ – components of the magnetic field, present in the measurement axes of the sensor mounted on the pilot's helmet at the moment of its generation by coil B, in the system of coordinates which are linked to the main axes of the aircraft,

$H_{PO\text{-}X}(C)$, $H_{PO\text{-}Y}(C)$, $H_{PO\text{-}Z}(C)$ – components of the magnetic field, present in the measurement axes of the sensor mounted on the pilot's helmet at the moment of its generation by coil C, in the system of coordinates which are linked to the main axes of the aircraft.

Basing upon the above-mentioned data, we prepared a mathematical model which describes determining the angular position of the pilot's helmet on the basis of measurement of the magnetic field components, which are present in the particular moments of powering the orthogonally fixed magnetic coils, with the assumption that both generation and measurement occur fast enough in relation to the angular movement of the pilot's head that it is possible to accept that the direction cosine matrix is also constant in a given measurement cycle (during the generation of the magnetic field for coil A, B and C).

This is when the following dependency occurs, enabling to determine coefficients of the direction cosine matrices for the selected angular position of the pilot's helmet in relation to the aircraft cockpit, for one cycle of the magnetic field generation by coils A, B and C.

$$[H_{PO}(A,B,C)] = [M(A,B,C)] \times [H_{SP}(A,B,C)], \tag{11}$$

where:

$[H_{PO}(\mathrm{A,B,C})]$ – matrix of magnetic field components, present in measurement axes of the sensor, for the set angular position of the pilot's helmet in relation to the aircraft cockpit, for coil A, B and C, respectively, (with matrix measuring 3×3);

$[M(\mathrm{A,B,C})]$ – direction cosine matrix for the set angular position of the helmet in relation to the aircraft cockpit (with matrix measuring 3×3);

$[H_{SP}(\mathrm{A,B,C})]$ – matrix of the magnetic field components, generated in the cockpit, which are present in the aircraft axes for the set angular position of the pilot's helmet, in relation to the aircraft cockpit, for coil A, B and C, respectively, (with matrix measuring 3×3).

The above dependency may be expressed as follows [11]:

$$\begin{bmatrix} H_{PO\text{-}X}(A) & H_{PO\text{-}X}(B) & H_{PO\text{-}X}(C) \\ H_{PO\text{-}Y}(A) & H_{PO\text{-}Y}(B) & H_{PO\text{-}Y}(C) \\ H_{PO\text{-}Z}(A) & H_{PO\text{-}Z}(B) & H_{PO\text{-}Z}(C) \end{bmatrix} = \begin{bmatrix} M11 & M12 & M13 \\ M21 & M22 & M23 \\ M31 & M32 & M33 \end{bmatrix} \times \begin{bmatrix} H_{SP\text{-}X}(A) & H_{SP\text{-}X}(B) & H_{SP\text{-}X}(C) \\ H_{SP\text{-}Y}(A) & H_{SP\text{-}Y}(B) & H_{SP\text{-}Y}(C) \\ H_{SP\text{-}Z}(A) & H_{SP\text{-}Z}(B) & H_{SP\text{-}Z}(C) \end{bmatrix}. \tag{12}$$

Thus, the direction cosine matrix $[M]$ may be determined on the basis of the above dependency through determining the matrix which opposes the matrix of the components generated by the magnetic field [H_{SP}]:

$$[M(A,B,C)] = [H_{PO}(A,B,C)] \times [H_{SP}(A,B,C)]^{-1}, \tag{13}$$

which may be shown in a detailed way for the particular elements of the matrix:

$$\begin{bmatrix} M11 & M12 & M13 \\ M21 & M22 & M23 \\ M31 & M32 & M33 \end{bmatrix} = \begin{bmatrix} H_{PO\text{-}X}(A) & H_{PO\text{-}X}(B) & H_{PO\text{-}X}(C) \\ H_{PO\text{-}Y}(A) & H_{PO\text{-}Y}(B) & H_{PO\text{-}Y}(C) \\ H_{PO\text{-}Z}(A) & H_{PO\text{-}Z}(B) & H_{PO\text{-}Z}(C) \end{bmatrix} \times \begin{bmatrix} H_{SP\text{-}X}(A) & H_{SP\text{-}X}(B) & H_{SP\text{-}X}(C) \\ H_{SP\text{-}Y}(A) & H_{SP\text{-}Y}(B) & H_{SP\text{-}Y}(C) \\ H_{SP\text{-}Z}(A) & H_{SP\text{-}Z}(B) & H_{SP\text{-}Z}(C) \end{bmatrix}^{-1}. \tag{14}$$

Below, we specified selected issues within the possibilities to model the helmet-mounted operation of the cueing system, which exploits the magnetic method to determine the angular position of the pilot's helmet, according to the above-mentioned dependency.

5. Possibilities of modelling the magnetic method used to determine the angular position of the pilot's helmet

With regard to modelling the magnetic method, it was proved that it is possible to use the direction cosine method, determined on the basis of the matrix created from the magnetic field components, which occur in particular moments of powering orthogonally mounted magnetic coils, in order to determine the angular position of the pilot's helmet. Determining the components of direction cosine matrices enables to determine angles of the helmet's position against the aircraft cockpit (as for the azimuth and elevation), in accordance with the generally known dependencies, e.g. [1, 8, 10]. For conclusions stemming from the conducted simulation tests, we specified an outline of simulation research that allowed determining the error of the helmet-mounted cueing system, using such a method.

6. Modelling the method of magnetic field, generated by an ideal flat coil

According to [2], for the ideal flat coil (flat plate with an infinite surface), the field generated by it has got a constant value both with regard to the direction and shifts, as well as the module, regardless of the distance of the measurement system (helmet-mounted sensor) from the surface of the magnetic field transmitter (coil).

In the case of an ideal flat coil (in the form of a flat plate with an endless surface),the matrix of the components of the magnetic field, generated by coils A, B and C respectively in one measurement cycle, is determined in the coordinate system of the aircraft as:

$$\begin{bmatrix} H_{SP\text{-}X}(A) & H_{SP\text{-}X}(B) & H_{SP\text{-}X}(C) \\ H_{SP\text{-}Y}(A) & H_{SP\text{-}Y}(B) & H_{SP\text{-}Y}(C) \\ H_{SP\text{-}Z}(A) & H_{SP\text{-}Z}(B) & H_{SP\text{-}Z}(C) \end{bmatrix} = \begin{bmatrix} H_{SP\text{-}X}(A) & 0 & 0 \\ 0 & H_{SP\text{-}Y}(B) & 0 \\ 0 & 0 & H_{SP\text{-}Z}(C) \end{bmatrix}. \tag{15}$$

Thus, for the helmet-mounted system, which uses such a coil, determining the angular position, accoring to the suggested method, is linked with solving a matrix equation, shown as:

$$\begin{bmatrix} M11 & M12 & M13 \\ M21 & M22 & M23 \\ M31 & M32 & M33 \end{bmatrix} = \begin{bmatrix} H_{PO\text{-}X}(A)\cdot H_{SP\text{-}X}(A) & H_{PO\text{-}X}(B)\cdot H_{SP\text{-}Y}(B) & H_{PO\text{-}X}(C)\cdot H_{SP\text{-}Z}(C) \\ H_{PO\text{-}Y}(A)\cdot H_{SP\text{-}X}(A) & H_{PO\text{-}Y}(B)\cdot H_{SP\text{-}Y}(B) & H_{PO\text{-}Y}(C)\cdot H_{SP\text{-}Z}(C) \\ H_{PO\text{-}Z}(A)\cdot H_{SP\text{-}X}(A) & H_{PO\text{-}Z}(B)\cdot H_{SP\text{-}Y}(B) & H_{PO\text{-}Z}(C)\cdot H_{SP\text{-}Z}(C) \end{bmatrix}. \tag{16}$$

As it can be observed, the calculations are made for each angular position of the pilot's helmet. The problem is technical realization of an „ideal" transmitter of the magnetic field in a situation of a limited surface of the aircraft cockpit.

Therefore, for further analysis, we accepted a model of a magnetic field transmitter, in the form of a flat coil with a finite surface (real coil).

7. Modelling the method for the magnetic field generated by the real coil

In the case of a flat real coil in the form of a flat plate with a finite surface [9], the matrix of the components of the magnetic field, generated by coil A, B and C respectively, is determined in the coordinate system of the aircraft as:

$$\begin{bmatrix} H_{\text{SP-X}}(A) & H_{\text{SP-X}}(B) & H_{\text{SP-X}}(C) \\ H_{\text{SP-Y}}(A) & H_{\text{SP-Y}}(B) & H_{\text{SP-Y}}(C) \\ H_{\text{SP-Z}}(A) & H_{\text{SP-Z}}(B) & H_{\text{SP-Z}}(C) \end{bmatrix} = \begin{bmatrix} H_{\text{SP-X}}(A,x,y,z) & H_{\text{SP-X}}(B,x,y,z) & H_{\text{SP-X}}(C,x,y,z) \\ H_{\text{SP-Y}}(A,x,y,z) & H_{\text{SP-Y}}(B,x,y,z) & H_{\text{SP-Y}}(C,x,y,z) \\ H_{\text{SP-Z}}(A,x,y,z) & H_{\text{SP-Z}}(B,x,y,z) & H_{\text{SP-Z}}(C,x,y,z) \end{bmatrix}, \quad (17)$$

where $H_{\text{SP-X}}(A, x, y, z)$, …, $H_{\text{SP-Z}}(C, x, y, z)$ are components of the magnetic field present in the main axes of the aircraft, with the values depending on the set angular and linear position (linear coordinates x, y, z) of the pilot's helmet in relation to the aircraft cockpit, for coils A, B and C, respectively (matrix measuring 3×3).

In order to determine the distribution of the magnetic field generated by the flat coil, the authors have made their own model of the coil and conducted preliminary research (Fig. 6). It could enable to determine the values of the components of the field, which are present around the axis of symmetry of the coil.

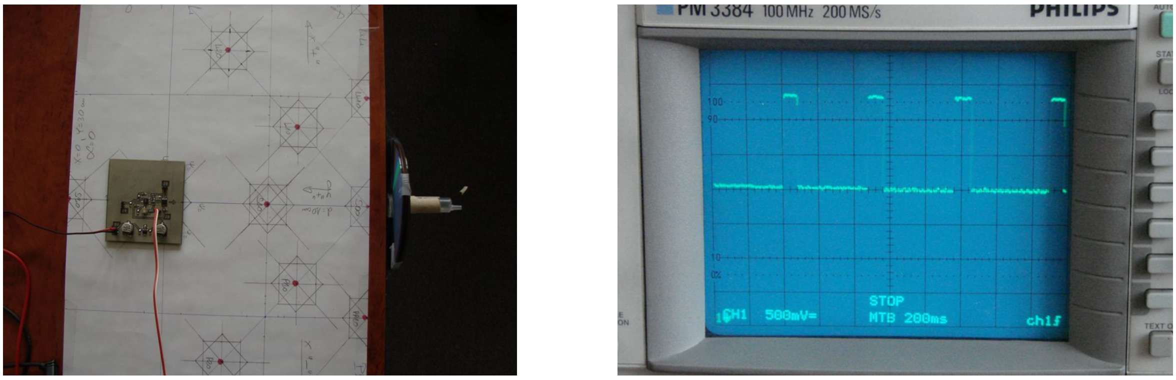

Fig. 6. View of systems to generate and measure magnetic field with flat coil

Thus, for the helmet-mounted system, which uses such a coil, determining the angular position is linked, according to the proposed method, with solving the matrix equation as:

$$\begin{bmatrix} M11 & M12 & M13 \\ M21 & M22 & M23 \\ M31 & M32 & M33 \end{bmatrix} = \begin{bmatrix} H_{\text{PO-X}}(A) & H_{\text{PO-X}}(B) & H_{\text{PO-X}}(C) \\ H_{\text{PO-Y}}(A) & H_{\text{PO-Y}}(B) & H_{\text{PO-Y}}(C) \\ H_{\text{PO-Z}}(A) & H_{\text{PO-Z}}(B) & H_{\text{PO-Z}}(C) \end{bmatrix} \times \begin{bmatrix} H_{\text{SP-X}}(A) & H_{\text{SP-X}}(B) & H_{\text{SP-X}}(C) \\ H_{\text{SP-Y}}(A) & H_{\text{SP-Y}}(B) & H_{\text{SP-Y}}(C) \\ H_{\text{SP-Z}}(A) & H_{\text{SP-Z}}(B) & H_{\text{SP-Z}}(C) \end{bmatrix}^{-1}. \quad (18)$$

As it possible to observe, the components of the magnetic field measured by helmet-mounted sensors depend not only on the angular position of the pilot's helmet against the aircraft cockpit, but also on its linear shifts with regard to the central positioning point (determined in the process of calibration of the measurement system, within the helmet-mounted cueing system). Detailed error estimation, caused by such movements of the pilot's head with the helmet-mounted system, requires additional research.

The effect of such research in the first stage (minimal plan) might be the so-called mapping (measurement) of the components of the magnetic field in the accepted area of changes of linear positioning of the field's sensor, mounted on the pilot's helmet as well as making charts (matrix form). The more advanced version assumes determining analytical dependencies (formulas) for the obtained spatial distributions of the magnetic field.

The sample dependencies for component matrices of the magnetic field, determined on the basis of laboratory investigation for the symmetrical coil (flat coil) made by the authors, may be expressed as:

$$\begin{bmatrix} \frac{H_0(A)}{R_X+\Delta x}\cos\left(\frac{k_Y\Delta y}{R_X}\right)\cos\left(\frac{k_Z\Delta z}{R_X}\right) & \frac{H_0(B)}{R_Y+\Delta y}\cos\left(\frac{k_X\Delta x}{R_Y}\right)\cos\left(\frac{k_Z\Delta z}{R_Y}\right) & \frac{H_0(C)}{R_Z+\Delta z}\cos\left(\frac{k_X\Delta x}{R_Z}\right)\cos\left(\frac{k_Y\Delta y}{R_Z}\right) \\ \frac{H_0(A)}{R_X+\Delta x}\sin\left(\frac{k_Y\Delta y}{R_X}\right)\cos\left(\frac{k_Z\Delta z}{R_X}\right) & \frac{H_0(B)}{R_Y+\Delta y}\sin\left(\frac{k_X\Delta x}{R_Y}\right)\cos\left(\frac{k_Z\Delta z}{R_Y}\right) & \frac{H_0(C)}{R_Z+\Delta z}\sin\left(\frac{k_X\Delta x}{R_Z}\right)\cos\left(\frac{k_Y\Delta y}{R_Z}\right) \\ \frac{H_0(A)}{R_X+\Delta x}\cos\left(\frac{k_Y\Delta y}{R_X}\right)\sin\left(\frac{k_Z\Delta z}{R_X}\right) & \frac{H_0(B)}{R_Y+\Delta y}\cos\left(\frac{k_X\Delta x}{R_Y}\right)\sin\left(\frac{k_Z\Delta z}{R_Y}\right) & \frac{H_0(C)}{R_Z+\Delta z}\cos\left(\frac{k_X\Delta x}{R_Z}\right)\sin\left(\frac{k_Y\Delta y}{R_Z}\right) \end{bmatrix}, \quad (19)$$

where:

$H_0(A)$, $H_0(B)$, $H_0(C)$ – modules of magnetic field components present in the measurement axes of the sensor for the central (calibrated) linear and angular position of the pilot's helmet in relation to the aircraft for coils A, B and C, respectively,

R_X, R_Y, R_Z – linear distances between the front of the measurement system of the sensor for the magnetic field (mounted on the pilot's helmet) and the coil for the central (calibrated) linear and angular position of the pilot' helmet against the aircraft, for coil A, B and C, respectively,

Δx, Δy, Δz – linear shifts of the front of the measurement system of the sensor for the magnetic field (mounted on the pilot's helmet) against the central (calibrated) position of the pilot's helmet in relation to the aircraft, for the set angular position of the pilot's helmet against the aircraft cockpit, for A, B and C coil, respectively,

k_X, k_Y, k_Z – coefficients of changes in velocity of the amplitude of the magnetic field components, present in measurement axes of the sensor, for the set angular position of the pilot's helmet against the aircraft cockpit for coil A, B and C, respectively.

The above research approach adopted in the presented algorithm in the realization of the magnetic method for the helmet-mounted cueing system enables to specify the errors in determining the angular position of the pilot's helmet for the accepted matrix of the generated magnetic field, depending upon the present linear position of the pilot's helmet.

8. Conclusions

The algorithm of determining the angular position of the pilot's helmet, proposed in this paper, which relies on determining component matrices of the magnetic field, generated cyclically, using three orthogonal flat coils, forms the basis for further detailed research (including dissertations) within the scope of exploiting the magnetic method and a manner of its technical realization in helmet-mounted cueing systems, manufactured at home for military aircraft, for instance for the multirole helicopter W-3PL. We assume that detailed testing of this algorithm, planned for selected jamming sources (such as errors of component generations of the magnetic field by means of a system of flat coils, measurement errors by means of an electronic sensor, computation errors performed by the on-board computer), will enable to assess the possibilities of the magnetic method in determining the angular position of the pilot's helmet.

Among a number of other problems which occur during a manufacture and testing of the system for generating the magnetic field, the most relevant ones, from the point of view of their applications in helmet-mounted cueing systems are preliminary measurements of the movements of the pilot's helmet which are essential to specify the extent of research of the magnetic method, calculating inaccuracies in determining the helmet's position for the magnetic method as well as verifying the obtained findings within modelling the errors of determining the helmet's position for the magnetic method.

The initial measurements embrace e.g. determining maximum angular tilts of the pilot's head (degree of changes of the azimuth angles and elevation angles), maximum angular velocities of the pilot's head movements while tracing the target (scope of changes in dynamics of the angular movement and changes in the components of the magnetic field, generated in the helmet-mounted cueing system).

Calculating the inaccuracies in determining the helmet's position for the magnetic method covers specifying for instance maximum errors of determining the helmet's position for the accepted inaccuracies of the computer calculations (so-called rounding errors), maximum errors of determining the helmet's position for the inaccuracies of the used field sensor (sensor errors) and maximum errors of determining the helmet's position with regard to the influence of the magnetic environment (generated by the cockpit equipment).

The last phase in the suggested research approach is verification of the calculations in inaccuracies of determining the helmet's position for the magnetic method, which includes specifying e.g. the maximum errors in determining the helmet's position for the inaccuracies of the computer calculations and own errors of the exploited electronic sensor as well as the influence of the selected magnetic jamming (in compliance with meeting the requirements of electromagnetic compatibility of on-board instruments).

The problems require detailed research, both through investigations in research centres as well as verification in industrial laboratories. The findings may indicate a way to build an effective system of determining the angular position of the pilot's helmet in the conditions of the available technology. The conducted analyses may enable to estimate the achieved accuracies in determining this position.

References

[1] Adamski, M., Vogt, R., Ćwiklak, J., *Integrated navigation and pilotage systems*, 2014 IEEE Chinese Guidance, Navigation and Control Conference, Yantai, China 2014.

[2] Figiel, H., Proniewski, B., *Projektowanie i konstrukcja cewek nadawczo-odbiorczych do obrazowania magnetyczno-rezonansowego*, Postępy Nauki i Techniki, Nr 6, Warszawa 2011.

[3] Grzesik, N., Picher, S., *Wyposażenie specjalne wybranych statków powietrznych*, Wyd. WSOSP, Dęblin 2012.

[4] Materiały reklamowe firmy Vision Systems International: *Worldwide leader in tactical aircraft helmet-mounted display systems*, 2012.

[5] Materiały reklamowe firmy Lockheed Martin: *A new technology joint helmet-mounted system for F-35 aircraft*, 2009.

[6] Materiały reklamowe firmy Lockheed Martin: *F-16 Fighting Falcon – Introduction to F-16 maintenance – Avionics*, 2006.

[7] Materiały reklamowe firmy Analog Devices: *Triaxial inertial sensor with magnetometer ADIS-16400 / ADIS-16405*, 2010.

[8] Ortyl, A., Gosiewski, Z., *Algorytmy inercjalnego bezkardanowego systemu orientacji i położenia obiektu o ruchu przestrzennym*, Wyd. Instytutu Lotnictwa, Warszawa 1999.

[9] Rash, C., *Helmet displays in aviation. Mounted display. Design issues for rotary-wing aircraft*, Fort Rucker, USA 2009.

[10] Szelmanowski, A., *Nahełmowy system celowniczy NSC-1 Orion dla śmigłowców wojskowych ze zintegrowanym systemem awionicznym*, Wyd. ITWL, Warszawa 2013.

[11] Szelmanowski, A., Borowski, J., Milewski, W., *Wykorzystanie nahełmowego systemu prezentacji danych do sterowania uzbrojeniem śmigłowców wojskowych*, Zeszyty Naukowe Politechniki Rzeszowskiej, Nr 12, Rzeszow 2010.