EVALUATION OF THE EFFECTS OF THE WATER-FLAT-PANEL ILLUMINATOR-AIR OPTICAL SYSTEM ON THE SIZE OF THE PHOTOGRAPHED OBJECT

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ABSTRACT

The paper discusses the problem of the effect of the water - flat-panel illuminator - air optical system on the size of an object photographed in an underwater environment as well as presents an analysis of the function describing the angular size of an object photographed with this type of system along with the results of computer simulations. It has been shown that when using this type of an optical system in practice, the value of the angle of incidence of the rays from the photographed object on the illuminator plane has the major influence on output object dimensions.
Keywords: mechanical engineering, underwater technology, underwater engineering photogrammetry.

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INTRODUCTION

In order to realise efficient activities in the aquatic environment, it is necessary to adjust one's activities strictly to the hydrospheric requirements. A significant element of human functioning in any environment is the ability to carry out observations, usually by means of the natural sense of sight. If this is not possible it is implemented through technical observation. In the hydrosphere, light is subject to different phenomena than in the atmosphere, resulting in blurred vision for the unaided human eye or a photographic camera without a dedicated design [1,2,3]. These issues are extensively described, inter alia, in the work of J. Williams [4]. The simplest way to ensure sharp vision for the human eye or a camera in an underwater environment is to isolate it from the surrounding hydrosphere. In the case of a photographic camera, it is also necessary to isolate its sensitive components with a sealed casing. This creates a water-illuminator-air optical system, which results in a distortion in the received image of the photographed object. This distortion can be minimised in the case of a diver by the refraction of light on the mask or helmet illuminator. The problem arises with an image obtained with a photographic camera. An image that has been obtained by taking a photograph of an object in the hydrosphere can be misinterpreted. The determination of the influence that the water-illuminator-air optical system has on the images obtained is therefore a key issue necessary for the effective use of the material collected with the camera, for instance to diagnose the surface of underwater objects [5].

Two types of camera illuminators are most commonly used in underwater technology: spherical and flat-panel illuminators [6,7,8]. The spherical illuminator is characterised by a large viewing angle of the camera, although good image quality is obtained only when the incidence angle of light reflected from the object is small [9,10]. For these reasons, this type of solution requires a special design of the optical system with a compensating lens if the digital camera matrix has dimensions close to a 35 mm film frame as well as precise positioning of the illuminator in relation to the lens. Such an illuminator may also cause slight distortion of the image [6,10]. In the case of flat-panel illuminators, they are firstly much simpler to make and do not require precise positioning relative to the lens. In addition, they are characterised by so-called zero optical power - they do not change the scale of the image when taken at an infinite photographic distance [5]. However, it should be remembered that the use of such an illuminator with a wide-angle lens causes chromatic aberration and image distortion [6]. It follows that for visual diagnostics of underwater objects, it is best to use a water-illuminator-air optical system with a flat-panel illuminator without a wide-angle lens, which will result in the minimum degradation of the collected vision data [5]. The influence of such an optical system on the angular size of the photographed object was the subject of an engineering diploma thesis carried out at the Department of Underwater Works Technology of the Naval Academy in Gdynia, by Officer Cadet Łukasz Sokół under the supervision of Adam Olejnik, Ph.D., Eng [11]. The thesis was successfully defended at the beginning of 2021, and the following material will present its results.

THE SIZE OF THE OBJECT PHOTOGRAPHED WITH THE WATER – FLAT-PANEL ILLUMINATOR – AIR OPTICAL SYSTEM

The path of the rays passing through the water – flat-panel illuminator – air optical system is as shown in Figure 1. The rays that pass from the object represented in the figure by the segment $\overline{AB}$ run in the water environment from the object to the camera lens O. In front of the lens, they hit the edge of the plane separating the hydrosphere and the air, i.e. the flat-panel illuminator at an angle $2\beta_w$. . At the edge of the illuminator, rays are refracted in the normal direction, reaching the lens at an angle $2\beta_p$.

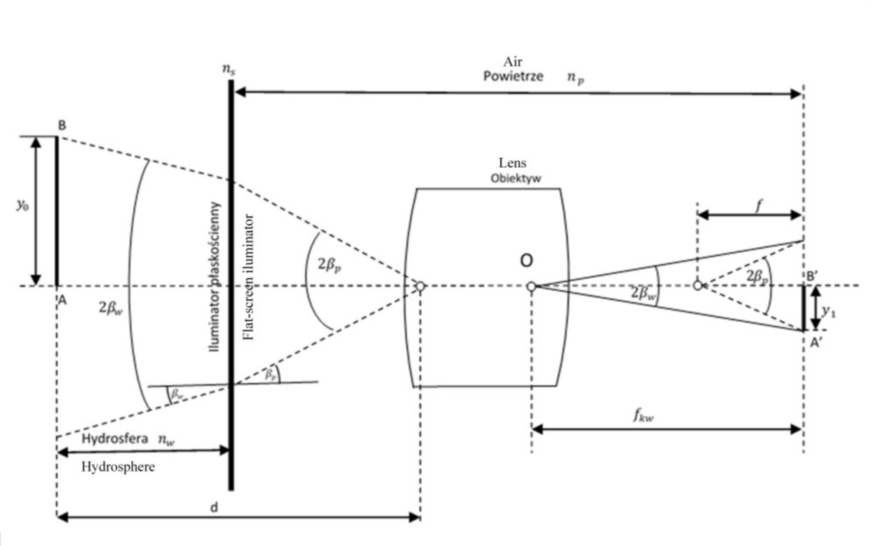

Fig. 1 The path of the rays in the water - flat-panel illuminator - air system, based on [5,6].

Thus, the object is seen through the lens at a different angular size from the actual object. The rays pass through the lens in the image plane π' where an image ($\overline{A'B'} = y_i$ of the actual object marked as $\overline{AB} = y_0$ is formed. In the situation when point A is on the optical axis of the system, the point marked as B' is the end of the radius r' in the image plane, then [5,6,11]:

$$r' = f_{kp} \cdot tg\beta_p \tag{1}$$

$$r' = f_{kw} \cdot tg\beta_w \tag{2}$$

where:

r'	-	radial size of the photographed object [rad],
f_{kp}	-	focal length of photographic camera in air [m],
f_{kw}	-	Focal length of photographic camera in water [m],
β_p	-	angle of incidence of light on the illuminator in air [^{0}],
β_w	-	angle of incidence of light on the illuminator in water [^{0}].

Equations (1) and (2) constitute a system that can be transformed to the form of:

$$r' = f_{kp} \cdot tg\beta_p \Rightarrow f_{kp} = \frac{r'}{tg\beta_p} \tag{3}$$

$$r' = f_{kw} \cdot tg\beta_w \tag{4}$$

then

$$f_{kp} = \frac{f_{kw} \cdot tg\beta_w}{tg\beta_p} = f_{kw} \cdot \frac{tg\beta_w}{tg\beta_p} \tag{5}$$

On the basis of trigonometric relationships and based on Snell's law, the following relation can be formulated [2,6,10]:

$$tg\beta_p = \frac{sin\beta_p}{cos\beta_p} \tag{6}$$

And also,

$$\frac{sin\beta_w}{sin\beta_p} = \frac{n_p}{n_w} \tag{7}$$

where:

n_p	-	index of refraction in air,
n_w	-	index of refraction in water.

From equation (7) it results that

$$sin\beta_p = \frac{n_w}{n_p} sin\beta_w \tag{8}$$

Because

$$cos^2\beta_p + sin^2\beta_p = 1 \Rightarrow cos^2\beta_p = 1 - sin^2\beta_p \tag{9}$$

then

$$cos\beta_p = (1 - sin^2\beta_p)^{\frac{1}{2}} \tag{10}$$

Then, taking into account equation (8), we may write:

$$sin^2\beta_p = (\frac{n_w}{n_p})^2 sin^2\beta_w \tag{11}$$

Because

$$n_p = 1 \Rightarrow \frac{n_w}{n_p} = n_w \tag{12}$$

Next, taking into account relations (11) and (12) equation (6) may take the following form:

$$cos\beta_p = [1 - n_w^2 sin^2\beta_w]^{\frac{1}{2}} \tag{13}$$

In considering equations (8) and (13) in (6) we obtain:

$$tg\beta_p = n_w sin\beta_w [1 - n_w^2 sin^2\beta_w]^{\frac{1}{2}} \tag{14}$$

Finally, after taking into account the relation (2) in (14), we obtain the final form of the equation for the angular size of the object photographed with the optical system water - flat-panel illuminator - air:

$$r' = f_{kp} \cdot n_w \cdot sin\beta_w \cdot [1 - n_w^2 \cdot sin^2\beta_w]^{-\frac{1}{2}} \tag{15}$$

Wherefrom it results that

$$r' = f(f_{kp}; n_w; \beta_w) \tag{16}$$

In the case of a spherical illuminator, the angular size of the object (r') will further depend on the radius of curvature of the illuminator (R) and the focal length of the compensating lens (f_s) and the angle of incidence of the rays in air, then

$$r' = f(R; f_s; \beta_p; n_w; \beta_w) \tag{17}$$

Comparison of the relations (17) and (16) clearly shows that the angular size of the object photographed with the optical system water – flat-panel illuminator – air depends on three variables only: internal orientation of the camera – its focal length in air (k_p), the refractive index in water (n_w) and the angle of incidence of light on the illuminator (β_w).

EVALUATION OF THE EFFECTS OF THE WATER – FLAT-PANEL ILLUMINATOR – AIR OPTICAL SYSTEM ON THE SIZE OF THE PHOTOGRAPHED OBJECT

The evaluation of the effects of the analysed optical system on the angular size of the object photographed in the underwater environment was carried out according to the algorithm presented in the figure below.

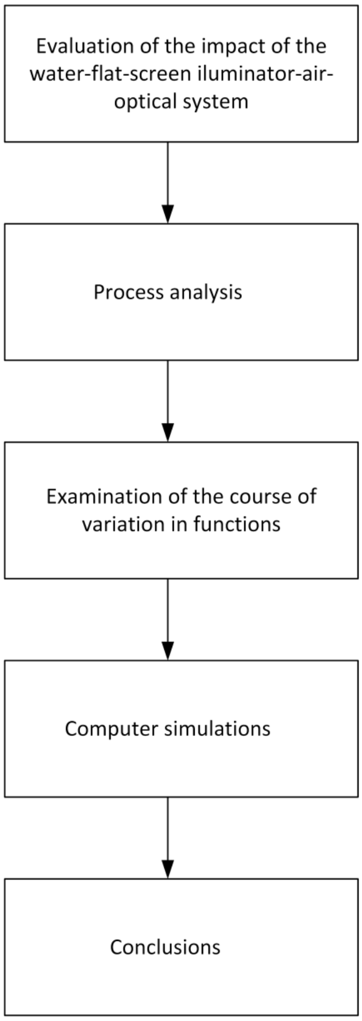

Fig. 2 Algorithm for the evaluation of the effects of the analysed optical system on the angular size of the photographed object.

In the course of the process analysis, the input and output quantities, as well as the interference quantities and process constants, were defined (Fig. 3). According to equation (16), the input quantities for the process under investigation are the focal length of the camera (f_{kp}) and the value of the angle at which the light is projected onto the flat-panel illuminator, while the refractive index in water (n_w) is a constant quantity of the process and equals 1.33. The interfering quantities analysed are the absorption of light by the aquatic environment (I_z), the mechanical and molecular diffraction of light in water(I_α) and the absorption of light (L). The output quantity is the angular size of the photographed object (r'). The study of the function course was performed by adopting the initial assumptions.

In the first case, the effect of changing the focal size of the camera at a constant value of the angle of incidence of light on the illuminator was studied, while in the second case, the study investigated the effect of changing the angle at a constant value of the focal length (Fig. 4). Prior to the study commencement, an analysis was made of the extent to which the angle of incidence of light on the illuminator could change.

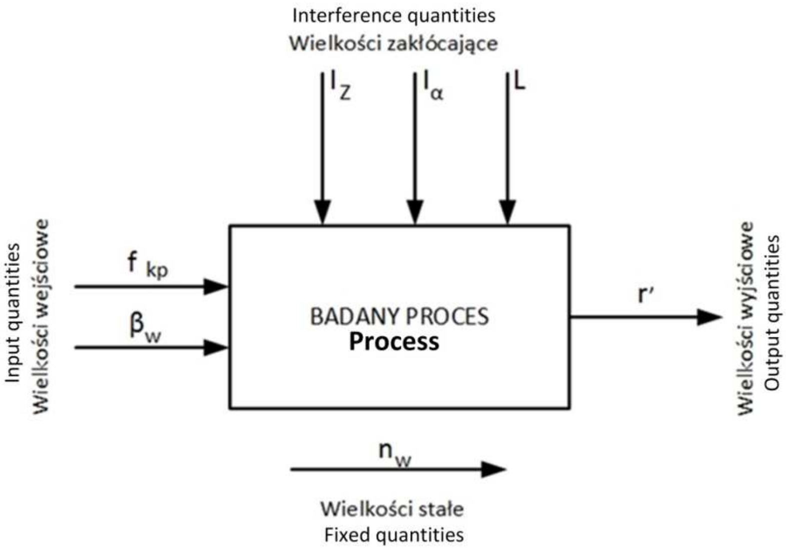

Fig. 3 Diagram of the process analysed (indications in the text).

According to the law of refraction at the boundary between two media, and assuming that the maximum value of the incident light is 90^0, it is possible to calculate the angle β_w. The light ray in the system under consideration is first refracted at the boundary between water and the illuminator, then, after passing through the illuminator, it refracts at the boundary between the illuminator and the air. Therefore, there are three angles of incidence - B_w – the angle of refraction at the boundary between water and the illuminator, α – the angle of incidence in the illuminator and β_P – the angle of refraction at the boundary between the illuminator and air. Also, there are three refractive indices as the ray passes through three media: n_w – refractive index in water (1.33); n_s – refractive index in glass (1.60) and n_p – refractive index in air (1.0). Then, applying the law of refraction, we can write

$$\frac{sin\alpha}{sin\beta_p} = \frac{n_p}{n_s} \tag{18}$$

Since we assume that the maximum value of β_p is 90^0 then $sin\beta_p = 1.0$ in which case equation (18) becomes

$$\frac{sin\alpha}{1,0} = \frac{1,0}{1,60} \Longrightarrow sin\alpha = 0,625 \tag{19}$$

Similarly, using the law of refraction, we can write down the following:

$$\frac{sin\beta_w}{sin\alpha} = \frac{n_s}{n_w} \tag{20}$$

Which, given equation (19), can be written down as:

$$\frac{sin\beta_w}{0,625} = \frac{1,60}{1,33} \Longrightarrow sin\beta_w = 0,751 \Longrightarrow \beta_w \cong 48^0 \tag{21}$$

From equation (21) it results that the maximum value for angle β_w is 48^0.

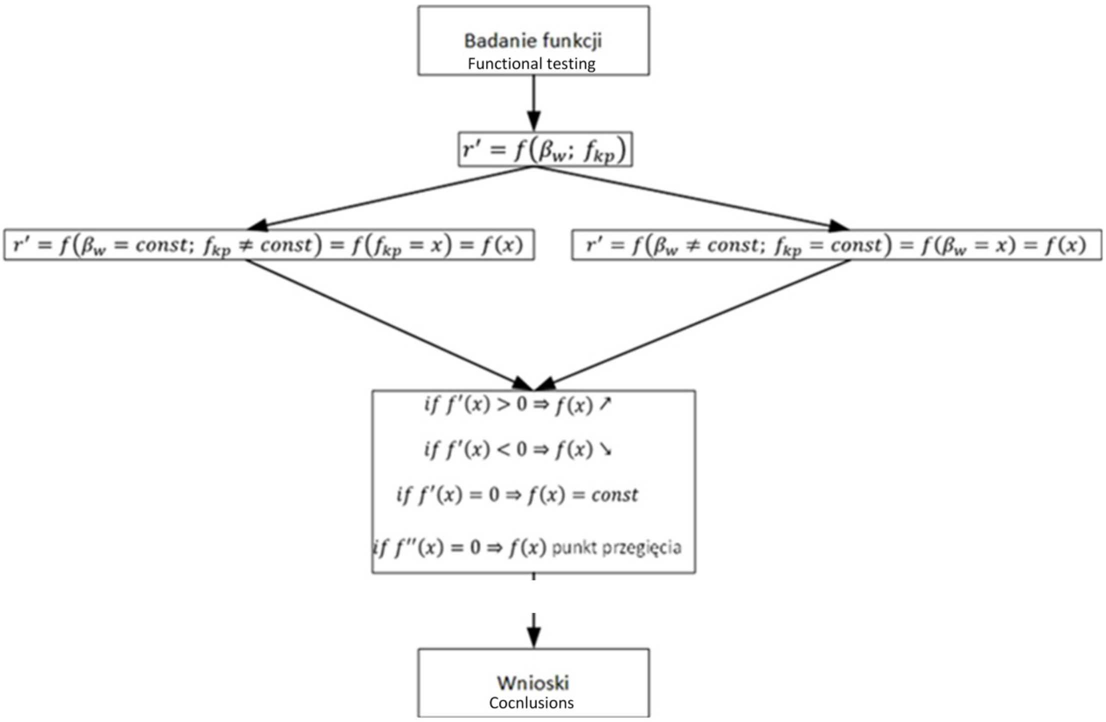

Fig. 4 The adopted algorithm of function evaluation.

The function in the form described by equation (15) was tested using standard procedures based on mathematical analysis, checking the following conditions:

1. $f'(x) > 0 \Rightarrow f(x) \nearrow$ (22)

2. $f'(x) < 0 \Rightarrow f(x) \searrow$ (23)

3. $f'(x) = 0 \Rightarrow f(x) = const;\ f(x)\ ma\ ekstremum$ (24)

According to Fig. 4, the study of the function started with the assumption that only one of the input quantities changes - the angle of incidence of the light on the illuminator at the water-illuminator interface (β_w), with the remaining quantities being constant. Assuming that $x = \beta_w; a = f_{kp}; b = n_w$, he studied function described by the relation (15) takes the following form:

$$f(x) = a \cdot b \cdot sinx\ \ (1 - b^2 sin^2 x)^{-\frac{1}{2}} \quad (25)$$

Then:

$$f'(x) = \frac{abcosx}{(1 - b^2 sin^2 x)^{\frac{1}{2}}} + \frac{ab^3 sin^3 xcosx}{(1 - b^2 sin^2 x)^{\frac{3}{2}}} \quad (26)$$

For condition (22) $f'(x) > 0$, equation (27) assumes the form:

$$f'(x) > 0 \Longrightarrow \frac{abcosx}{(1 - b^2 sin^2 x)^{\frac{1}{2}}} + \frac{ab^3 sin^3 xcosx}{(1 - b^2 sin^2 x)^{\frac{3}{2}}} > 0 \quad (27)$$

which, after calculation, can be written down as:

$$1 - b^2 sin^2 x > 0 \quad (28)$$

For condition (23) $f'(x) < 0$, we can write:

$$1 - b^2 sin^2 x > 0 \quad (29)$$

Whereas for condition $f'(x) = 0$, equation (26) assumes the following form:

$$1 - b^2 sin^2 x = 0 \quad (30)$$

Bearing in mind that $b = n_w = const = 1{,}33$ and that $x = \beta_w$, and that theoretically the value of the angle can range from 0^0 to 360^0, it is possible to calculate that course of variation of the function $f'(x)$ and examine the conditions described by relations (28), (30) and graphically by (31) – Fig. 5.

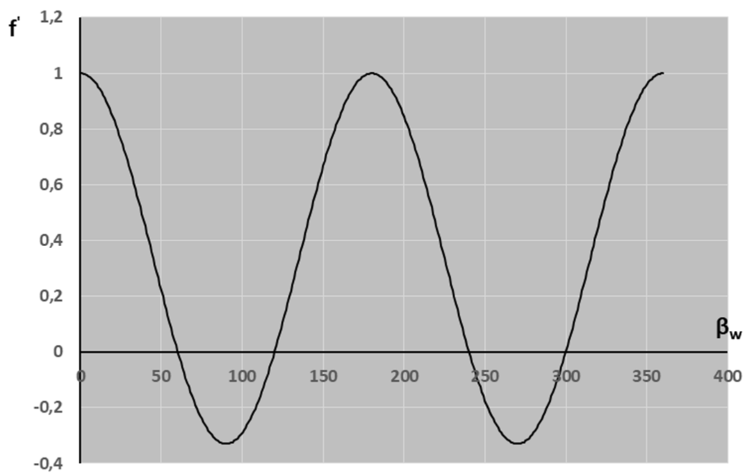

Fig. 5 Function f^' (x) variability course, where x=β_w.

According to relation (21), the maximum value of the angle β_w cannot exceed the value of 48^0, given the date from Fig. 5 and Tab.1 the derivative $f'(x)$ in the range from 0^0 to 61^0 is greater than zero, therefore function $f(x)$ will be increasing in this range.

In the next step of the function study, it was assumed that only the value of the focal length of the photogrammetric camera changes in equation (15) and that the other quantities are constant. Assuming that $f_{kp} = x; a = n_w; b = \beta_w$ equation (15) takes the following form:

$$f(x) = x \cdot a \cdot sinb(1 - a^2 sin^2 b)^{-\frac{1}{2}} \tag{36}$$

During the study the same conditions (22), (23), (24) were applied.

Then:

$$f'(x) = a \cdot sinb(1 - a^2 sin^2 b)^{-\frac{1}{2}} \tag{31}$$

For condition (22) $f'(x) > 0$, equation (39) takes the form of:

$$a \cdot sinb(1 - a^2 sin^2 b)^{-\frac{1}{2}} > 0 \tag{32}$$

Similarly, for condition (23) $f'(x) < 0$, we can write down:

$$a \cdot sinb(1 - a^2 sin^2 b)^{-\frac{1}{2}} < 0 \tag{33}$$

For condition (24), on the other hand, we can write down the following:

$$a \cdot sinb(1 - a^2 sin^2 b)^{-\frac{1}{2}} = 0 \tag{34}$$

Again, as can be seen from the form of equations (32), (33) and (34) the value of the derivative $f'(x)$, despite the fact that in this case $x = f_{kp}$ will nevertheless depend on the value of the angle b (β_w). As in the previous case, the problem can be solved graphically because the value of a and b constitute a closed set. In this case $a = 1{,}33$, and the value of b lies in the range from 0^0 to 360^0 – Fig. 6.

In accordance with relation (21), the maximum value of the angle β_w cannot exceed the value 48^0, taking into account the data from Fig. 6 and Tab.2 the derivative $f'(x)$ in the range from 0^0 to 48^0 is greater than zero, therefore the function $f(x)$ will be increasing in this interval.

The next step involved simulation calculations according to the algorithm shown in Fig. 5. Firstly, assuming a constant value of the camera focal length $f_{kp} = const = 0{,}035\ [m]$ and angle changes according to the inference resulting from equation (21) in the range from 0^0 to 48^0 ($\beta_w \in (o^0 \div 48^0)$, as well as $n_w = 1{,}33$. For such selected values, the values of the function described by equation (15) were calculated - the results are shown in the following figure.

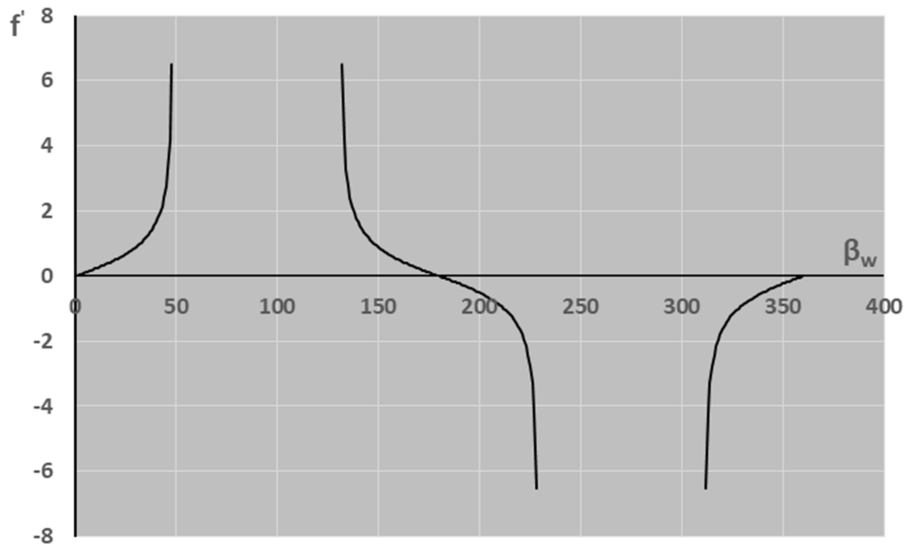

Fig. 6 Function variability course $f'(x)$ where $x = f_{kp}$.

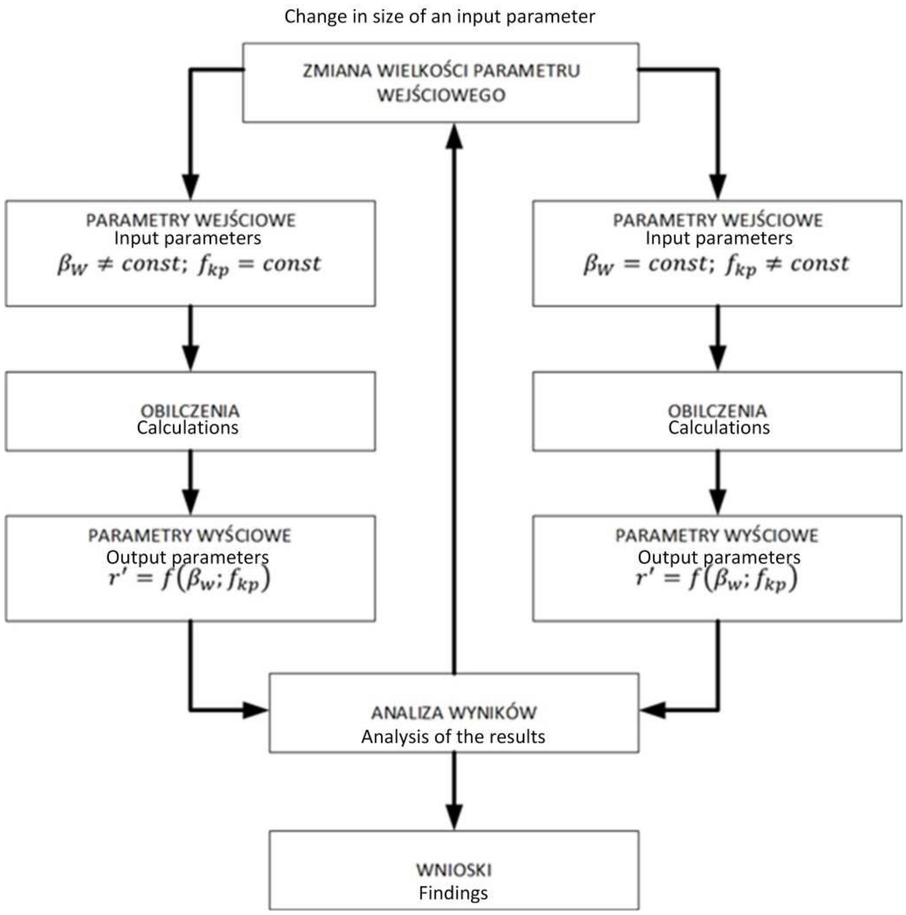

Fig. 7 Algorithm for the performer simulation calculations.

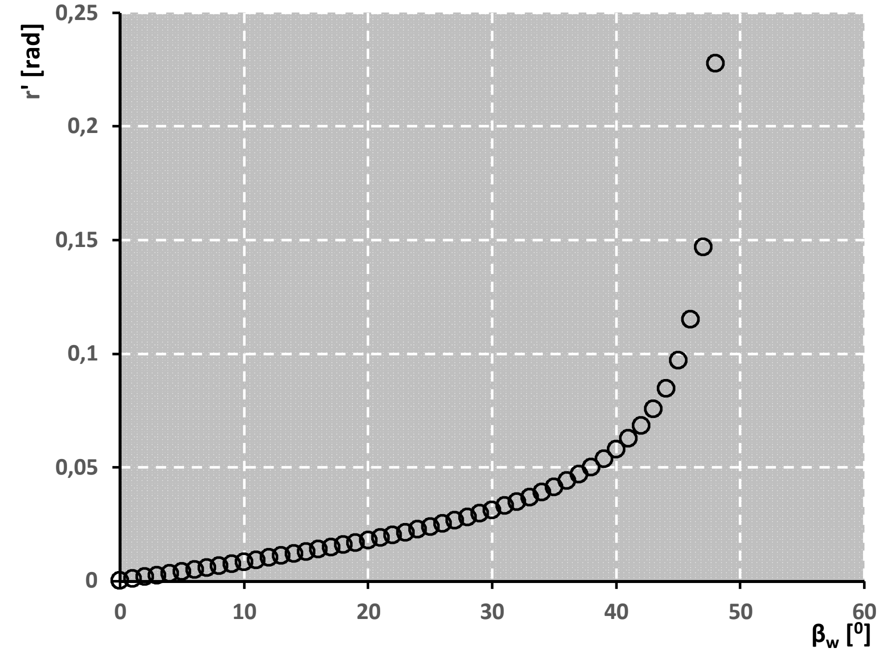

Fig. 8 Calculations results for f_kp=0,035 [m],n_w=1,33 and B_w∈(0^0÷ 〖48〗 ^0).

Next, calculations were carried out assuming that $\beta_w = const = 11,0\, [^0]$, $n_w = 1,33$ and $f_{kp} \in (0,035 \div 0,083)[m]$. The results are presented in the figure below.

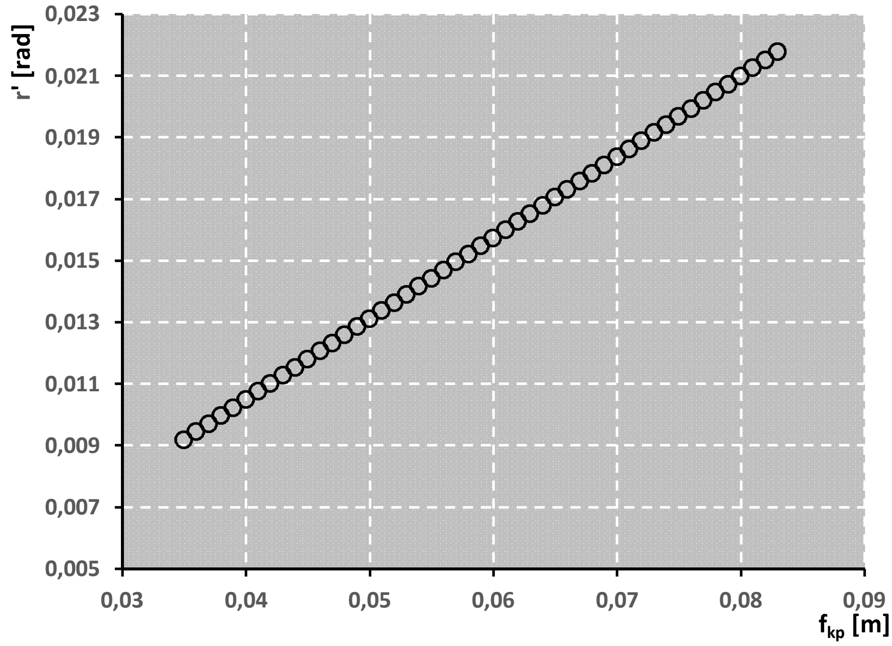

Fig. 9 Calculations results for $\beta_w = 11,0$, $n_w = 1,33$ and $f_{kp} \in (0,035 \div 0,083)$.

CONCLUSIONS

The analysis was performed on the function describing the angular size of the object photographed (r') with the optical system water - flat-panel illuminator - air described by equation (15). Based on this equation, the output quantity depends on the variation of three parameters: the angle of incidence of the rays on the illuminator, the focal length of the camera and the refractive index of the water. Since the value of the index is a constant quantity, it is evident from the above that the angle of incidence (β_w) and the camera focal length (f_{kp}) have a direct effect on the size of the photographed object. For the above reasons, the effect of changes in these quantities on the output size was analysed during the function study. The course of the variation of the functions $f'(\beta_w)$ and $f'(f_{kp})$ are shown in Fig. 5 and Fig. 6. In both cases, it was found that the values of the derivative show a significant dependence on the value $\measuredangle\beta_w$. Moreover, according to the result of equation (21), the maximum value of this angle cannot exceed the value of 48^0. Both the derivative of the function $f'(\beta_w)$ and $f'(f_{kp})$ in the range $\measuredangle\beta \in (0^0 \div 48^0)$ take positive values $f'(x) > 0 \Rightarrow f(x) \nearrow$, meaning the an increase in the values β_w and f_{kp} will translate into an increase in value r'. The conclusions from the evaluation of function $r' = f(\beta_w; f_{kp})$ were confirmed by the results of computer simulations. Using equation (15), function calculations were performer assuming $f_{kp} = 0{,}035\ [m]$; $n_w = 1{,}33$ and $\beta_w \in (0^0 \div 48^0)$ and with the assumption that $\measuredangle\beta_w = 11{,}0^0$; $n_w = 1{,}33$ and $f_{kp} \in (0{,}035[m] \div 0{,}083[m])$. The results of the calculations are shown in Fig. 8 and Fig. 9. Both figures explicitly demonstrate the existence of a correlation between the variables. Fig. 8 shows a curvilinear correlation and Fig. 9 a linear correlation. This is confirmed by the Pearson correlation coefficients calculated for these courses. For Fig. 8, it equals $e_{r\beta_w} = 0{,}7933$, whereas for the course from Fig. 9 - $e_{rf_{kp}} = 1{,}0$. The determination coefficients calculated from these show that, in the case of the function $r' = f(\beta_w)$ 63% of the changes in the value of the independent variable ha dan impact on changes in the dependent variable ($e^2_{r\beta_w} = 0{,}6294$), and for the function $r' = f(f_{kp})$ 100% of changes in the independent variable had an impact on changes in the dependent variable.

As can be seen from the performed analyses and calculations, theoretically the angular magnitude of the photographed object is most sensitive to changes in the focal length of the photographic camera. In practical conditions, however, the situation emerges where this magnitude is a constant value, which, with a constant value of the refractive index in water, means that in practice the value of r^' is dependent on the value of $\measuredangle\beta_w$. The results of the calculations for the function $r' = f(\beta_w)$ clearly show that more than 60% of the changes in angle had a direct effect on the changes in the magnitude of r'. Whereas in the range from 0^0 to 30^0 the value of r' increases by an average of 0.1% per 1^0, and in the range from 30^0 to 48^0 it increases by an average of 1.05% per 1^0. From the above, it can be seen that as the angle of incidence on the illuminator increases, the scale of the image we would like to use to size the photographed object changes. The results of the presented analyses are consistent with the theoretical assumptions provided in the publication by Bekier and Kaczyński (Fig. 3.29 p. 54) [2]. In the further course of work, a number of experiments are planned in the test pool towards confirming the above conclusions. For the purposes of the planned experiment, a suitable photographic camera was selected and a casing was designed to enable its operation in an aquatic environment (Fig. 10).

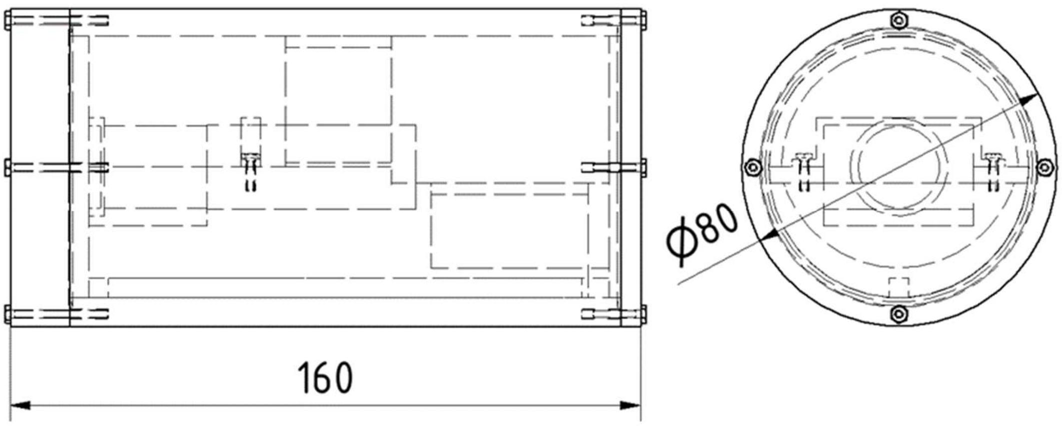

Fig. 10 Design of the casing for the photographic camera planned for use in the test pool experiments.

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