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DYNAMICS MODEL OF STABILIZATION MECHANISM FOR HELICOPTER PAD

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Abstract

Helipad located on ships greatly increases their ability to perform tactical and logistical abilities. They allow performing reconnaissance from the air, transportation of cargos and people to and from the ship. Landing on a moving ship particularly small size during bad weather is not a safe manoeuvre. Article provides an overview of existing solutions that improve safety during the landing manoeuvre of the helicopter to the ship and describes an innovative mechanism with can stabilize helicopter pad in four degrees of freedom. This solution is characterized in that the landing plate is movable and actuated simultaneously by two support plates and two levers. Plates and levers are driven by separate linear motors that move along the guides connected to the base. The main feature of the mechanism is that when the base is not stable, it can reduce the linear movement of the landing platform in the vertical and transverse direction and angular displacement around an axis perpendicular and parallel to the axis of the ship. A preferred feature of the mechanism is that in folded position it occupies relatively little space. In addition, advantageous attribute of the mechanism is its large working area, enabling the reduction of high amplitude vibration. The article contains a calculation of the kinematics for the proposed structure of the mechanism. It also includes speed drives waveforms, which are the result of simulations for the input parameters of the ship movement.

Keywords: *maritime engineering, kinematic and dynamic analysis, mechanism design, safety*

1. Introduction

Safe flight of helicopters is possible at wind speeds up to 8 on the Beaufort scale. This type of wind generates waves up to 4 m. Waves of this height cause significant rocking of medium size naval unit such as ship ORP General Kazimierz Pulaski guided missile frigate type Oliver Hazard Perry. Greatly complicates the safe landing of the helicopter on the helipad located at the stern of the ship. It should also consider the situation in which weather conditions after the start of the helicopter get worse, preventing its further safe landing Fig. 1. There are solutions to support the landing of helicopters on the ship. The most widely used system is “CILAS HVLAS Helicopter Visual Landing Aid System” [9], which by means of gyro-stabilized helicopter indicator lights guides the helicopter on the correct approach path. There are also prototype systems such as the Prism Defence [11] system, which monitors the movement of the ship and now when the conditions are right it gives a signal to the pilot to land.

Another solution is a conceptual system proposed by J. L. Sánchez López in 2012 [5]. Using a camera mounted on the helicopter system is observing the “H” symbol on the landing pad and without the participation of the pilot controls the helicopter during landing. There are also mechanical solutions. Patent US 2010 / 0224118A1 [10] describes a system which is able to move the landing pad along the transverse axis of the ship. This system however does not compensate in any way the angular oscillation.

Fig. 1. Helicopter land attempt in storm conditions (Prism Defence [11])

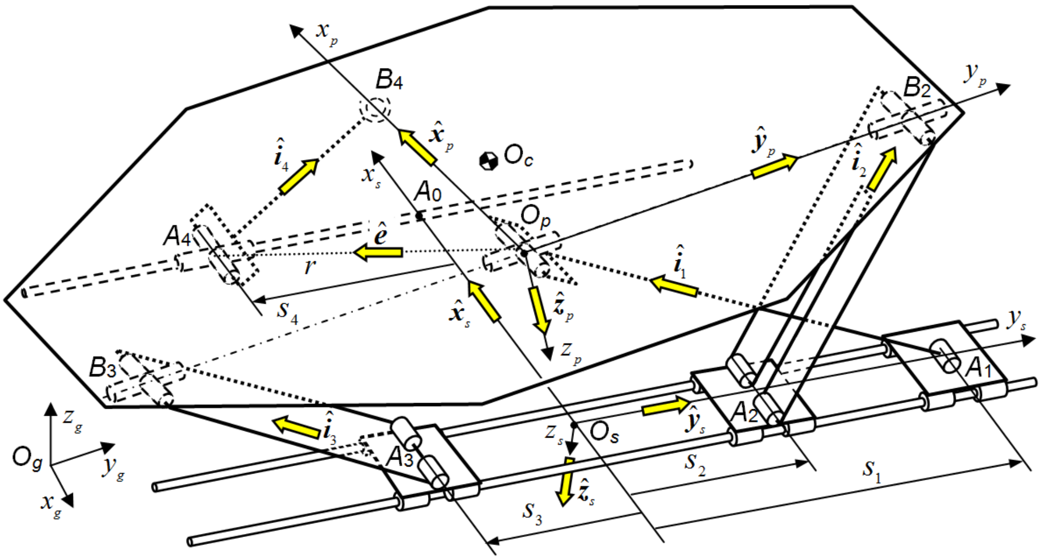

Fig. 2. Scheme of the stabilization mechanism for helicopter pad with four degrees of freedom

2. The helipad position stabilization system

The proposed helicopter pad position stabilization system [6] consists of the following subsystems: measuring, control, drive and executive mechanism (Fig. 2). The measurement system is designed to measure the real-time movement of the ship caused by water waving. Measurements of temporary position, drives speeds, angles and angular velocities of the rolling of the ship and the linear speed of the ship base point are required. The measured parameters are the basis for calculations in real time by the control system, which sends signals to the electric motors located under the ship deck [1]. Motors through gears, pulleys and ropes move four trolleys along guides arranged transverse to the longitudinal axis of the ship. On each trolley lever, supporting helipad is located. During the roll of the ship, drives cause movement of trolleys that through the support levers set landing plate in a horizontal position [2]. Further, in the operating space of mechanism, the height of the helicopter pad remains constant and the plate does not move in a direction transverse to the ship course.

3. Kinematics of the helicopter pad stabilization mechanism

Kinematics of the considered system is described in three different reference systems. The measurement of ships reference system movement $\{O_s, x_s, y_s, z_s\}$ is performed relative to the stationary reference system $\{O_g, x_g, y_g, z_g\}$ in which is assumed behaviour of the helipad and the associated reference system $\{O_p, x_p, y_p, z_p\}$. Kinematics equations are presented in the reference system of the ship, therefore unit vectors of the stationary and helipad reference system should be expressed according to the versors: $\hat{\boldsymbol{x}}_s = [1 \quad 0 \quad 0]^T$, $\hat{\boldsymbol{y}}_s = [0 \quad 1 \quad 0]^T$, $\hat{\boldsymbol{z}}_s = [0 \quad 0 \quad 1]^T$.

3.1. Calculations of the links positions

Based on measurements of ship tilts angles α_x and α_y around the axis x_s and y_s it is possible to calculate unit vector expressed in ship reference system:

$$\hat{\boldsymbol{z}}_g = [\sin\alpha_x \cos\alpha_y \quad -\sin\alpha_y \quad \cos\alpha_x \cos\alpha_y]^T . \tag{1}$$

Assuming that the axis y_g is perpendicular to the plane containing axes $\hat{\boldsymbol{z}}_g$ and $\hat{\boldsymbol{x}}_s$, then:

$$\hat{\boldsymbol{y}}_g = \frac{\hat{\boldsymbol{z}}_g \times \hat{\boldsymbol{x}}_s}{\left|\hat{\boldsymbol{z}}_g \times \hat{\boldsymbol{x}}_s\right|} . \tag{2}$$

The third unit vector of fixed reference system is equal: $\hat{\boldsymbol{x}}_g = \hat{\boldsymbol{y}}_g \times \hat{\boldsymbol{z}}_g$. Calculation of unit vectors of the helicopter pad reference system was based in Fig. 2. It contains part of the mechanism operating in the plane of axes y_s and z_s. Adopted variable: $i_{1y} = \hat{\boldsymbol{i}}_1 \cdot \hat{\boldsymbol{y}}_s$, which was used in the triangles equations $A_2A_1O_p$ and $A_3A_1O_p$:

$$(s_1 - s_2)\hat{\boldsymbol{y}}_s + l_1\hat{\boldsymbol{i}}_1 = r_2\hat{\boldsymbol{e}}_2 , \tag{3}$$

$$(s_1 - s_3)\hat{\boldsymbol{y}}_s + l_1\hat{\boldsymbol{i}}_1 = r_3\hat{\boldsymbol{e}}_3 , \tag{4}$$

where: $\hat{\boldsymbol{i}}_1 = i_{1y}\hat{\boldsymbol{y}}_s - \sqrt{1 - i_{1y}^2}\,\hat{\boldsymbol{z}}_s$.

Based on (3) and (4):

$$r_2 = \sqrt{l_1^2 + (s_1 - s_2)^2 - 2l_1(s_1 - s_2)i_{1y}} , \; r_3 = \sqrt{l_1^2 + (s_1 - s_3)^2 + 2l_1(s_1 - s_3)i_{1y}} ,$$

$$\hat{\boldsymbol{e}}_2 = \frac{l_1\hat{\boldsymbol{i}}_1 + (s_1 - s_2)\hat{\boldsymbol{y}}_s}{r_2} , \; \hat{\boldsymbol{e}}_3 = \frac{l_1\hat{\boldsymbol{i}}_1 + (s_1 - s_3)\hat{\boldsymbol{y}}_s}{r_3} .$$

On the basis of Fig. 3 formulated following triangles equation $A_2B_2O_p$ and $A_3B_3O_p$:

$$l_2\hat{\boldsymbol{i}}_2 - l_{py}\hat{\boldsymbol{y}}_{p2} = r_2\hat{\boldsymbol{e}}_2 , \tag{5}$$

$$l_3\hat{\boldsymbol{i}}_3 + l_{py}\hat{\boldsymbol{y}}_{p3} = r_3\hat{\boldsymbol{e}}_3 . \tag{6}$$

The solution of the equation (5) is:

$$-\hat{\boldsymbol{y}}_{p2} = \pm\sqrt{1 - \left(\frac{l_{py}^2 - l_2^2 + r_2^2}{2r_2 l_{py}}\right)^2}\,\hat{\boldsymbol{j}}_2 + \frac{l_{py}^2 - l_2^2 + r_2^2}{2r_2 l_{py}}\hat{\boldsymbol{e}}_2 , \tag{7}$$

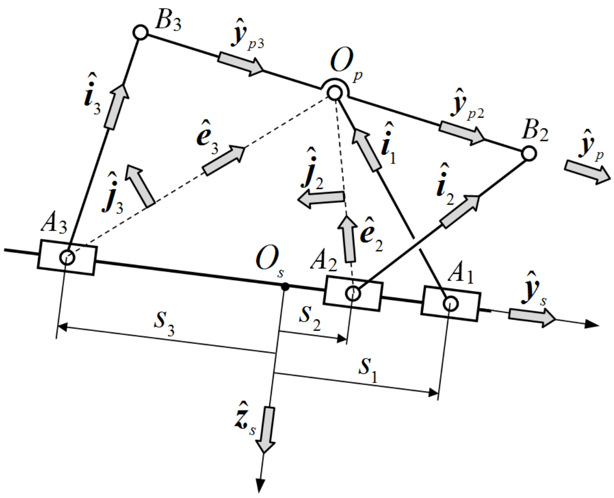

Fig. 3. Unit vectors of flat part of the mechanism

where: $\hat{\boldsymbol{j}}_2 = \hat{\boldsymbol{e}}_2 \times \hat{\boldsymbol{x}}_s$.

The solution of the equation (6) is:

$$\hat{\boldsymbol{y}}_{p3} = \pm\sqrt{1-\left(\frac{l_{py}^2 - l_3^2 + r_3^2}{2r_3 l_{py}}\right)^2}\,\hat{\boldsymbol{j}}_3 + \frac{l_{py}^2 - l_3^2 + r_3^2}{2r_3 l_{py}}\hat{\boldsymbol{e}}_3\,, \tag{8}$$

where: $\hat{\boldsymbol{j}}_3 = \hat{\boldsymbol{e}}_3 \times \hat{\boldsymbol{x}}_s$.

Unit vectors $\hat{\boldsymbol{y}}_{p2}$, $\hat{\boldsymbol{y}}_{p3}$ should have the same direction (Fig. 3). On this basis function of bonds is formulated:

$$f(i_{1y}) = \left|(\hat{\boldsymbol{y}}_{p3} - \hat{\boldsymbol{y}}_{p2})\cdot\hat{\boldsymbol{y}}_s\right| + \left|(\hat{\boldsymbol{y}}_{p3} - \hat{\boldsymbol{y}}_{p2})\cdot\hat{\boldsymbol{z}}_s\right|, \tag{9}$$

the place of zero corresponds to the current value i_{1y}, allowing the identification of all unit vectors of Fig. 3.

Using the pattern of three versors, received the following:

$$\hat{\boldsymbol{x}}_p = -\frac{c_{ye}\,c_{ex}}{1-c_{ye}^2}\hat{\boldsymbol{y}}_p + \frac{c_{ex}}{1-c_{ye}^2}\hat{\boldsymbol{e}} + \sqrt{\frac{1-c_{ye}^2-c_{ex}^2}{1-c_{ye}^2}}(\hat{\boldsymbol{y}}_p \times \hat{\boldsymbol{e}})\,, \tag{10}$$

where:

$$c_{ye} = \hat{\boldsymbol{y}}_p\cdot\hat{\boldsymbol{e}}\,,\; c_{ex} = \frac{r^2 + l_{px}^2 - l_4^2}{2rl_{px}}\,,\; \hat{\boldsymbol{e}} = \frac{\hat{\boldsymbol{y}}_s(s_4 - s_1) - l_1\hat{\boldsymbol{i}}_1 + l_{sx}\hat{\boldsymbol{x}}_s}{r}\,,\; r = \left|\hat{\boldsymbol{y}}_s(s_4 - s_1) - l_1\hat{\boldsymbol{i}}_1 + l_{sx}\hat{\boldsymbol{x}}_s\right|.$$

Based on the polygon $O_sA_1O_pB_4A_4A_0$ (Fig. 1) is achieved:

$$\hat{\boldsymbol{i}}_4 = \frac{s_1\hat{\boldsymbol{y}}_s + l_1\hat{\boldsymbol{i}}_1 + l_{px}\hat{\boldsymbol{x}}_p - s_4\hat{\boldsymbol{y}}_s - l_{sx}\hat{\boldsymbol{x}}_s}{l_4}\,. \tag{11}$$

3.2. Calculations of the links speeds

Kinematic relations in considered mechanism are represented by a matrix $\boldsymbol{J}_\omega$ transformation trolleys speeds; $\dot{\boldsymbol{s}} = [\dot{s}_1 \quad \dot{s}_2 \quad \dot{s}_3 \quad \dot{s}_4]^T$ in the angular velocity of the helipad; $\boldsymbol{\omega}_{p,s} = [\omega_{p,s}^x \quad \omega_{p,s}^y \quad \omega_{p,s}^z]^T$ calculated relative to the ship reference system:

$$\boldsymbol{\omega}_{p,s} = \boldsymbol{J}_{\omega}\,\dot{\boldsymbol{s}} \,. \tag{12}$$

The source of obtaining matrix $\boldsymbol{J}_{\omega}$ elements are vector polygons equations from the flat part of the mechanism, formulated on the basis of Fig. 2:

$$s_j\hat{\boldsymbol{y}}_s + l_j\hat{\boldsymbol{i}}_j + p_j\hat{\boldsymbol{y}}_p = \boldsymbol{r}_{O_sO_p}\,, \quad j = 1, 2, 3, \tag{13}$$

where: $p_1 = 0$, $p_2 = -p_3$, and vectors polygon equation O_sJGFO_p:

$$l_{sx}\hat{\boldsymbol{x}}_s + s_4\hat{\boldsymbol{y}}_s + l_4\hat{\boldsymbol{i}}_4 - p_4\hat{\boldsymbol{x}}_p = \boldsymbol{r}_{O_sO_p}\,. \tag{14}$$

Equations (13) and (14) after differentiation over time, supplant $\mathrm{d}/\mathrm{d}t(\boldsymbol{r}_{O_sO_p})$ and projected for directions: $\hat{\boldsymbol{i}}_1$, $\hat{\boldsymbol{i}}_2$, $\hat{\boldsymbol{i}}_3$, $\hat{\boldsymbol{i}}_4$ are the basis of getting matrix elements:

$$\boldsymbol{J}_{\omega} = \begin{bmatrix} q_{11} & q_{12} & q_{13} & 0 \\ q_{21} & q_{22} & q_{23} & q_{24} \\ q_{31} & q_{32} & q_{33} & q_{34} \end{bmatrix}, \tag{15}$$

depending on the trolleys location and dimensions of the mechanism links.

The linear motion of the landing in terms of speed is represented by a matrix $\boldsymbol{J}_v$ transformation trolleys speed in linear velocity of joint centre of mass of the landing and the helicopter O_c calculated relative to the centre of the ship reference system O_s ; $\boldsymbol{v}_{O_cO_s} = [v^x_{O_cO_s} \quad v^y_{O_cO_s} \quad v^z_{O_cO_s}]^T$:

$$\boldsymbol{v}_{O_cO_s} = \boldsymbol{J}_v\dot{\boldsymbol{s}} \,. \tag{16}$$

The source of obtaining matrix $\boldsymbol{J}_v$ elements is vector from O_c to O_s:

$$\boldsymbol{r}_{O_sO_c} = s_1\hat{\boldsymbol{y}}_s + l_1\hat{\boldsymbol{i}}_1 + p^x_{O_c}\hat{\boldsymbol{x}}_p + p^z_{O_c}\hat{\boldsymbol{z}}_p \,. \tag{17}$$

Time derivative relations and projecting vectors for the axes of the ship reference system are the basis to determine the matrix elements:

$$\boldsymbol{J}_v = \begin{bmatrix} f_{11} & f_{12} & f_{13} & f_{14} \\ f_{21} & f_{22} & f_{23} & f_{24} \\ f_{31} & f_{32} & f_{33} & f_{34} \end{bmatrix}, \tag{18}$$

depending on the trolleys location and dimensions of the mechanism links and O_c position in helipad reference system.

3.3. Kinematic operating conditions of the helipad position stabilization mechanism

The basic equation of kinematics deployed to control the drives is the dependence on the angular velocity of the helipad relative to the fixed reference system:

$$\boldsymbol{\omega}_{p,g} = \boldsymbol{\omega}_{s,g} + \boldsymbol{\omega}_{p,s}\,, \tag{19}$$

where:

$\boldsymbol{\omega}_{s,g}$ – measured in real time the angular velocity of the ship relative to a fixed reference system,
$\boldsymbol{\omega}_{p,s}$ – the angular velocity of the helipad relative to the ship, which can be influenced by drives.

The second basic equation of kinematics deployed to control the drives is the dependence on the linear velocity of the point of helicopter pad O_p relative to the O_g:

$$\boldsymbol{v}_{O_pO_g} = \boldsymbol{v}_{O_sO_g} + \boldsymbol{v}_{O_pO_s} + \boldsymbol{\omega}_{p,s} \times \boldsymbol{r}_{O_sO_p}\,, \tag{20}$$

where:

$\boldsymbol{v}_{O_sO_g}$ – measured in real-time velocity of the point O_s of the ship relative to the O_g,

$\boldsymbol{v}_{O_pO_s}$ – linear velocity of the helipad point O_p relative to the O_s.

Although the mechanism can operate in four degrees of freedom for the effective and simplified control may be taken: $\boldsymbol{\omega}_{p,g} = \mathbf{0}$ and $\boldsymbol{v}_{O_pO_g} = \mathbf{0}$, then the equations (19) and (20) results:

$$\boldsymbol{v}_{O_pO_s} = \boldsymbol{\omega}_{s,g} \times \boldsymbol{r}_{O_sO_p} - \boldsymbol{v}_{O_sO_g} \,. \tag{21}$$

Based on the derived of equations (13) and (14) and after project their vectors on directions: $\hat{\boldsymbol{i}}_1$, $\hat{\boldsymbol{i}}_2$, $\hat{\boldsymbol{i}}_3$, $\hat{\boldsymbol{i}}_4$ correlation for the momentary drives speed can be formulated:

$$\dot{s}_j = \frac{\boldsymbol{v}_{O_pO_s} \cdot \hat{\boldsymbol{i}}_j - s_j(\hat{\boldsymbol{y}}_s \times \hat{\boldsymbol{i}}_j) \cdot \boldsymbol{\omega}_{s,g}}{\hat{\boldsymbol{y}}_s \cdot \hat{\boldsymbol{i}}_j}, \quad j = 1, 2, 3, \tag{22}$$

$$\dot{s}_4 = \frac{\boldsymbol{v}_{O_pO_s} \cdot \hat{\boldsymbol{i}}_4 - [(s_4\hat{\boldsymbol{y}}_s + l_{sx}\hat{\boldsymbol{x}}_s) \times \hat{\boldsymbol{i}}_4] \cdot \boldsymbol{\omega}_{s,g}}{\hat{\boldsymbol{y}}_s \cdot \hat{\boldsymbol{i}}_4} \,. \tag{23}$$

The implementation of these speeds provides the desired behaviour of the landing, as shown in Fig. 4 and 5.

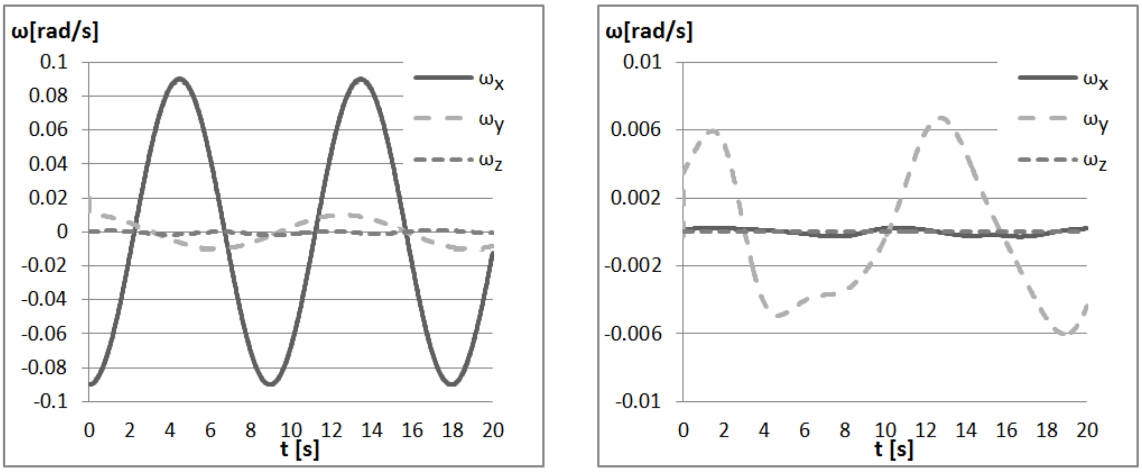

Fig. 4. Comparison of the angular velocity of the ship (left graph) and the helipad (right graph)

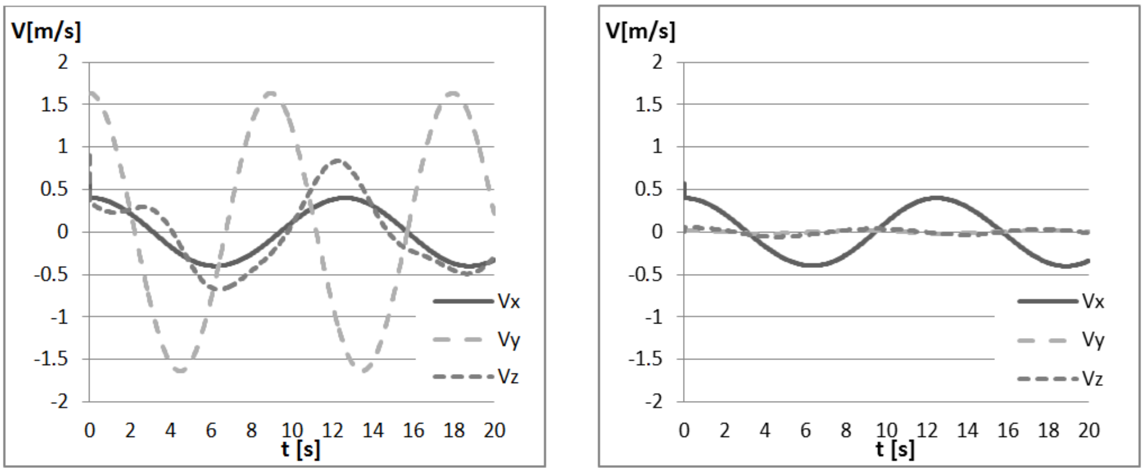

Fig. 5. Comparison of ship point O_s speed (left graph) and speed of corresponding point associated with the helipad (right graph)

4. Dynamics of the helicopter pad stabilization mechanism

Dynamics model of considered system takes into account the following assumptions. Weight of supports and trolleys are negligible in relation to the weight of the landing and the helicopter. Helipad and links forming mechanism are ideally rigid. Skips the influence of friction. In kinematic pairs, there is no looseness. Drives are reduced to four trolleys that move at speeds: $\dot{\boldsymbol{s}} = [\dot{s}_1 \quad \dot{s}_2 \quad \dot{s}_3 \quad \dot{s}_4]^T$ and develop forces along their guides equal $\boldsymbol{F} = [F_1 \quad F_2 \quad F_3 \quad F_4]^T$.

Matrix dynamics equation derived from the temporary power balance developed by the gravity forces, inertia forces and forces from the trolleys [8]:

$$m_p \boldsymbol{v}_{O_cO_s}^T (\boldsymbol{g} - \boldsymbol{a}_{O_cO_g}) + \boldsymbol{\omega}_{p,s}^T (-\boldsymbol{I}_p \boldsymbol{\varepsilon}_{p,g} - \tilde{\boldsymbol{\omega}}_{p,g} \boldsymbol{I}_p \boldsymbol{\omega}_{p,g}) + \dot{\boldsymbol{s}}^T \boldsymbol{F} = 0, \tag{24}$$

where:

m_p – mass of the helipad and the helicopter,
$\boldsymbol{I}_p$ – tensor of helipad inertia with helicopter,
$\boldsymbol{a}_{O_cO_g}$ – absolute acceleration of the mass centre of helipad with helicopter,
$\boldsymbol{\omega}_{p,g}$, $\boldsymbol{\varepsilon}_{p,g}$ – the absolute velocity and angular acceleration of the helipad with helicopter.

Usage in (24) dependence (12) and (16) allows determining the force developed by the trolleys:

$$\boldsymbol{F} = m_p \boldsymbol{J}_v^T \boldsymbol{v}_{O_cO_s}^T (\boldsymbol{a}_{O_cO_g} - \boldsymbol{g}) + \boldsymbol{J}_\omega^T (\boldsymbol{I}_p \boldsymbol{\varepsilon}_{p,g} + \tilde{\boldsymbol{\omega}}_{p,g} \boldsymbol{I}_p \boldsymbol{\omega}_{p,g}). \tag{25}$$

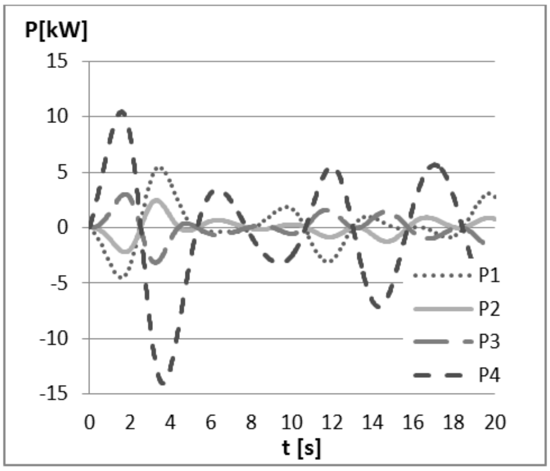

Fig. 6. Powers developed by the trolleys movements

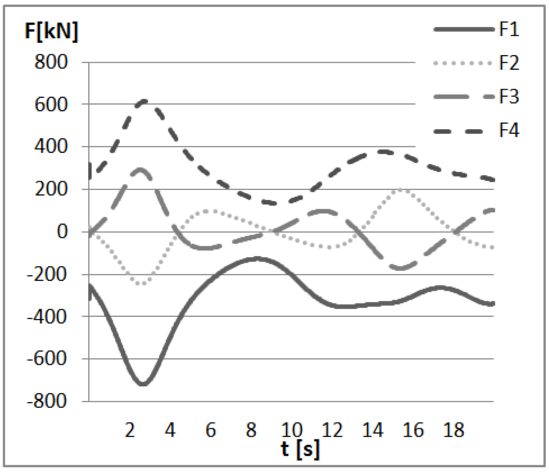

Fig. 7. Forces developed on the direction of trolleys

Simulations show that for adopted helipad and helicopter mass 25800 [kg] power consumption by trolleys is in 15 [kW] range and the forces, which they are charged, are in 10^3 [kN] range.

5. Conclusions

The helicopter pad mechanism fulfils the tasks for which it was designed. Helipad point moves in the longitudinal direction to the axis of the ship. This is due to the structure and orientation of the helipad stabilization mechanism on the ship. In other directions: vertical and transverse achieved almost complete reduction in point of helipad movement. There is very good reduction of landing tilting about ship longitudinal axis and weaker tilting reducing about the transverse axis.

The adopted dynamics model of the mechanism allows the calculation of maximum loads of mechanism elements. It also allows to detailed design of the cable drive system with motors and to determining boundary conditions for proper operation.

Helipad stabilization system requires the development of control system, which takes into account the approach to its extreme positions, and the adoption of strategies behaviour during helicopter landing sequence.

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