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MATHEMATICAL MODEL OF STABILISING AND TRACKING CONTROL SYSTEM IN MAIN BATTLE TANK

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Abstract

The aim of this researches was to identify all functional blocks of tank gun stabiliser 2E28M (installed in tanks T-72 and PT-91 Twardy) in order to build mathematical model of the system.
The tank gun stabiliser is an electro-hydraulic control system, which makes possible aiming at a target, tracking of a target and stabilise of a given gun and turret angular position. The two-axial stabiliser consists of two separate control systems to stabilise the gun in elevation and the turret (with gun) in azimuth.
After detailed analysis of construction and work principles, functional schemes of investigated systems were build. Afterwards, static and dynamic characteristics of functional parts of the system were determined. Because of obtained characteristics and based on the knowledge about the system feedbacks, structural schemes and mathematical models of foregoing stabiliser were derived.
The results of numerical computations were compared with the existing results of experimental tests carried-out on a real plant. The results of experimental and model simulation investigations showed that the mathematical model and its numerical implementation were correctly developed.

Keywords: *main battle tank, stabilising and tracking control system, tank gun stabiliser*

1. Introduction

The T-72 battle tank (and its' derivative PT-91 Twardy) are equipped with 2E28M two-axis stabilisation system and monoaxially (in elevation) stabilised gunner's sight system. The stabilisation system compensates the velocities of the vehicle. The stabilisation system automatically maintains a position of the gun at a fixed bearing in space. In spite of any motion of the vehicle in roll (γ_K-rotation round axis y_K), in pitch (ϕ_K-rotation round axis x_K) or in yaw (ψ_K-rotation round axis z_K), the tank gun stabiliser minimises the effects of vehicle motion on the main armament of the tank under typical conditions of tank operation over rough ground (see Fig. 1) [1, 2, 4, 12, 19, 27, 31]. The gun is rotated in pitch (ϕ_A) relative to the turret by an elevation drive system. A hydraulic servomotor (actuator), fixed to the gun and turret drives the gun [3, 15, 25]. The turret is rotated in yaw (ψ_W) relative to the hull by an azimuth drive system. A hydraulic servomotor, fixed to the hull drives the turret.

The power for the drive is taken from the on board 24 V system. The power is taken from the generator buffered over a set of batteries. It is fed to the electric motor. This electric motor is turn drives a pump. The electric power is thus converted into hydraulic power. The flow of hydraulic fluid through to the drive unit is controlled by a servo valve. An electronic control unit compares the actual speed of the drive with the speed specified by the gunner and regulates the valve setting accordingly to compensate for any discrepancy between the two (the advantage of such a servo control lies in the precision that it affords, its disadvantage is the loss of power at the servo valve, which becomes considerable when the drive is operating at low speed).

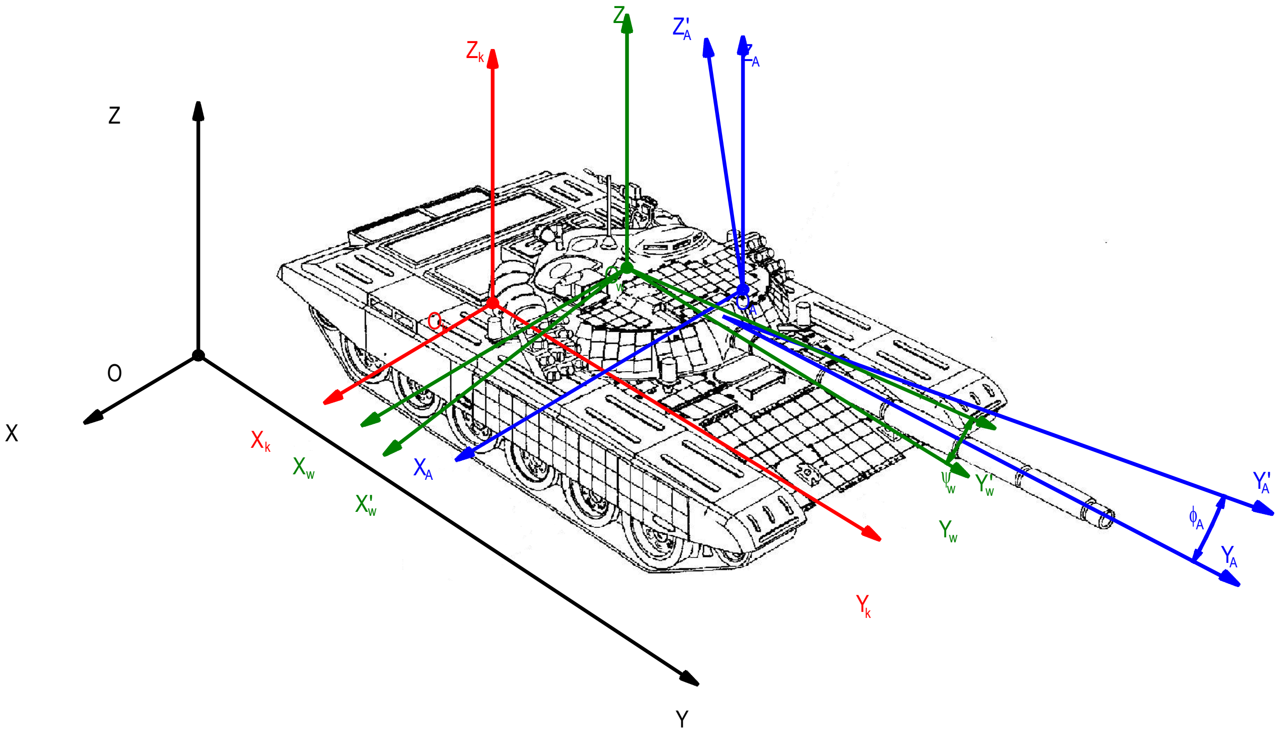

Fig. 1. Cartesian coordinates related to the PT 91 battle tank (ground, hull, turret and gun)

In the early 70s such powered mounting were used in production tanks of the intermediate generation T-72. Turret mass as percentage of battle mass was under 25%. Over the past thirty years the turret mass risen to over 30% of battle mass. It was in consequence of assembly additional explosive reactive armour and smoke grenade launchers. Additionally, the requirements for maximum laying acceleration and speeds have stiffened considerably over the same period.

Inevitably, the effect of higher turret masses and the consequent increase in moment of inertia of the traversing mass, combined with the higher performance called for, was an increase in the power of the turret drives. This in turn caused these systems to grow in weight, installed volume and heat losses – and to their markedly higher power consumption imposing a considerable load on the vehicle's power supply. This explains the search for new power sources for stabilised powered mountings as well as methods of improvement existing systems.

2. Traverse stabiliser

Traverse tank gun stabiliser is an electro-hydraulic control system and makes possible aiming at a target, tracking of a target and stabilisation of a given gun turret angular position.

The functional scheme of the system is shown in Fig. 2. Stabiliser has been divided into appropriate functional parts [5]:

- **C** – gunner hand controller;
- **F** – free gyroscope (contain: F_S – synchro-control-transformer);
- **R** – rate gyroscope (contain: R_S – synchro-control-transformer);
- **A** – electronic amplifier (contain: A_1 – voltage amplifier, A_2 – phase sensor, A_3 – power amplifier;
- **P** – hydraulic pump (contain: P_1 – electromagnet, P_2, P_3 – two-stage hydraulic amplifier);
- **E** – hydraulic engine;
- **S** – linear acceleration sensor (contain: S_S – synchro-control-transformer);

- **H** – hydraulic pressure pick-up;
- **T** – turret (as a controlled system).

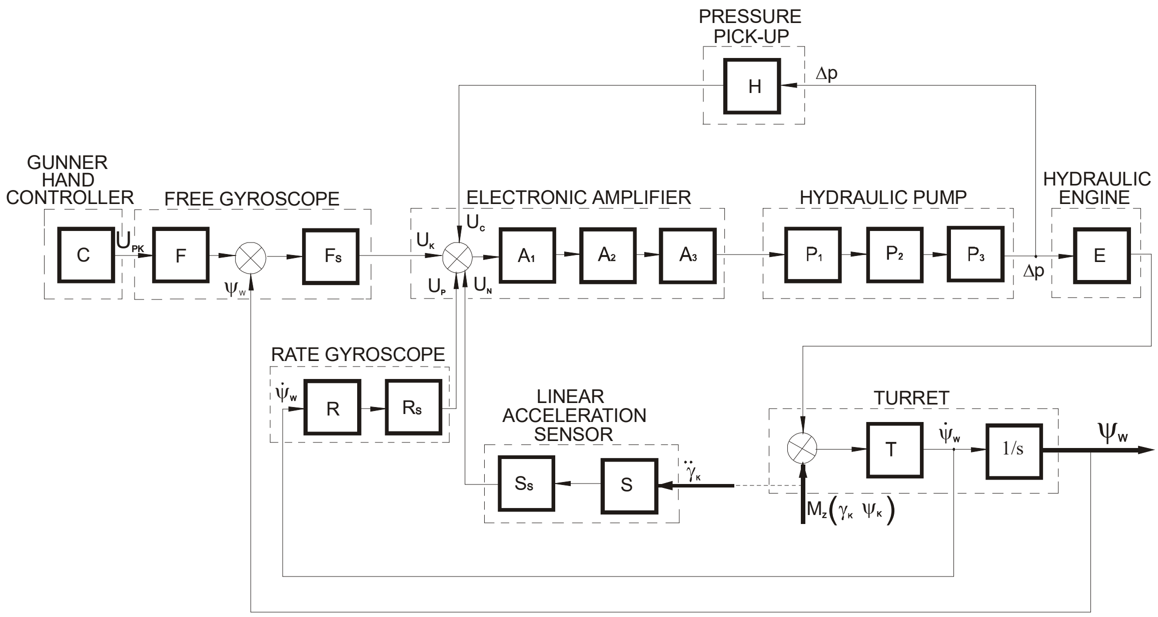

Fig. 2. Functional scheme of the tank gun turret stabiliser

The stabiliser realises the following two basic functions:
- alteration of the gun turret angular position with respect to the hull with the aid of a gunner hand controller **C** during aiming at a target and tracking of a target;
- stabilisation of a given gun turret angular position ψ_w in the turret thrust bearing plane in the presence of the disturbing torque $M_z(\gamma_K, \psi_K)$ caused by the tank movement.

In the operating conditions tracking and aiming at a target processes occur simultaneously.

Then, via laboratory tests, dynamic and static characteristics of those parts have been obtained as well as numerical values of coefficients of suitable mathematical models have been determined [9, 20].

On the basis of obtained static characteristics and transfer functions of individual parts of the system and of the knowledge about the system feed-backs, the structural scheme of the overall system has been found (with three inputs and one output) [6, 7, 8, 11, 36] – see Fig. 3.

The input signals are:

U_{PK} – the reference signal given by the operator,

ψ_K – disturbing signal caused by the hull "snake-like" movements,

γ_K – disturbing signal caused by the transversal angular displacement of the hull around the longitudinal axis.

The gun turret angular displacement ψ_w represents the output signal.

Most of static characteristics are linear or almost linear. Strong nonlinearities that should be included in the mathematical model of the system resulted from:
- coulomb friction forces between the turret and the hull,
- electronic amplifier saturation,
- saturation of the hydraulic pump,
- saturation of the hydraulic servo-motor.

The system has four main feedbacks:
- negative angular position feed-back realised by free gyroscope and caused by the gun turret „snake-like" angular displacements;

- negative rate feed-back realised by rate gyroscope and caused by the gun turret „snake-like" movements angular speed;
- negative acceleration feed-back realised by linear acceleration sensor and caused by the gun turret transversal linear accelerations;
- negative feed-back realised by pressure pick-up and caused by working liquid pressures;

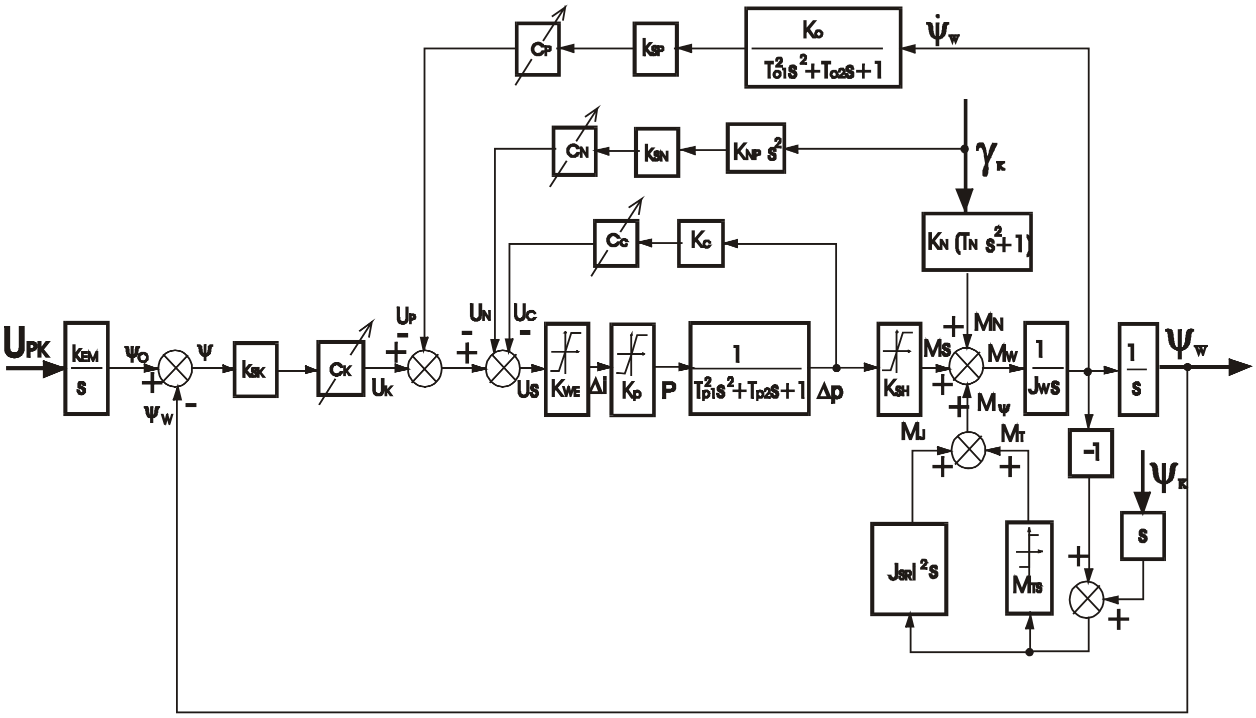

Fig. 3. Structural scheme of the tank gun turret stabiliser

The mathematical model has been formulated at the following assumptions:

- the free gyroscope has been treated as a proportional element (due to small viscous friction in bearings and small inertia moments of frames);
- the aiming electromagnet of the free gyroscope has been presented as an ideal integrator (due to small inertia moments of frames);
- the synchro-control-transformer has been treated as a proportional element (due to large difference between frequency of control and supply voltage);
- the linear acceleration sensor has been treated as a proportional element (due to small viscous friction in bearings and linear characteristic of rod spring);
- the pressure pick-up has been treated as a proportional element (due to small time constants);
- the electronic amplifier has been treated as a proportional element (due to small time constants);
- the hydraulic pump has been treated as a inertial second-order element (due to small viscous friction and small inertia moments in control gear);
- the hydraulic engine has been treated as a proportional element (due to reduction of the inertia moment of the rotor to the turret rotation axis);
- the turret reduction gear has been treated as rigid and its backlashes have been omitted;
- the inertia moment of the turret reduction gear has been reduced to the axis of turret rotation.

The system of equations constitutes a mathematical model of the stabilizer. The differential equations constitute mathematical description of the turret stabilizer modules and the turret. These are ODE's of first or second order with constant coefficients. The algebraic equations describe non-linear characteristics and summing nodes.

The system of differential and algebraic equations, formulated on the basis of the structural scheme (Fig. 3), has the form:

$$T^2{}_{01}\ddot{U}_P + T_{02}\dot{U}_P + U_P - \dot{\psi}_W K_0 k_{SP} C_P = 0, \quad (1)$$

$$K_{NP} k_{SN} C_N \ddot{\gamma}_K - U_N = 0, \quad (2)$$

$$\Delta p K_C C_C - U_C = 0, \quad (3)$$

$$\dot{\psi}_0 = U_{PK} k_{EM}, \quad (4)$$

$$(\psi_0 - \psi_W) k_{SK} c_K - U_K = 0, \quad (5)$$

$$U_K + U_P + U_N + U_C + U_S = 0, \quad (6)$$

$$U_S K_{WE} - \Delta i = 0 \; for \; -U_{S\max} \le U_S \le U_{S\max}, \quad (7)$$

$$U_S K_{WE} - i_{\max} = 0 \; for \; U_S > U_{S\max}, \quad (8)$$

$$U_S K_{WE} + i_{\max} = 0 \; for \; U_S < -U_{S\max}, \quad (9)$$

$$\Delta i K_P - p = 0 \; for \; -i_{Ma} \le \Delta i \le i_{Ma}, \quad (10)$$

$$\Delta i K_P - p_{\max} = 0 \; for \; \Delta i > i_{Ma}, \quad (11)$$

$$\Delta i K_P + p_{\max} = 0 \; for \; \Delta i < -i_{Ma}, \quad (12)$$

$$T^2{}_{P1}\Delta\ddot{p} + T_{P2}\Delta\dot{p} + \Delta p - p = 0, \quad (13)$$

$$\Delta p K_{SH} - M_S = 0 \; for \; -p_{Ma} \le \Delta p \le p_{Ma}, \quad (14)$$

$$\Delta p K_{SH} - M_{S\max} = 0 \; for \; \Delta p > p_{Ma}, \quad (15)$$

$$\Delta p K_{SH} + M_{S\max} = 0 \; for \; \Delta p < -p_{Ma}, \quad (16)$$

$$\ddot{\gamma}_K K_N T_N + \gamma_K K_N - M_N = 0, \quad (17)$$

$$\psi_W i^2 J_{SR} + M_J = \psi_K i^2 J_{SR}, \quad (18)$$

$$M_T = 0 \quad for \quad -\delta \le (\dot{\psi}_K - \dot{\psi}_W) \le \delta, \quad (19)$$

$$M_T - M_{TS} = 0 \quad for \quad (\dot{\psi}_K - \dot{\psi}_W) > \delta, \quad (20)$$

$$M_T + M_{TS} = 0 \quad for \quad (\dot{\psi}_K - \dot{\psi}_W) < \delta, \quad (21)$$

$$M_J + M_T - M_\psi = 0, \quad (22)$$

$$M_S + M_N + M_\psi - M_W = 0, \quad (23)$$

$$\ddot{\psi}_W J_W - M_W = 0. \quad (24)$$

For the differential equations, one assumed the zero initial conditions:

$$\psi_W = \dot{\psi}_W = \dot{\psi}_W = \dot{\psi}_0 = U_P = U_K = U_S = U_C = U_N = U_{PK} = \Delta i = p = \Delta p =$$
$$= M_S = M_J = M_T = M_N = M_\psi = M_W = 0.$$

In the above equations, the following notation is used:

$T_{01}, T_{02}, T_{P1}, T_{P2}$ – denote time constants of rate gyroscope and hydraulic pump, respectively;

$k_{SP}, K_O, k_{SK}, k_{EM}, k_{SN}, K_{WE}, K_P, K_{SH}, K_C, c_K, c_P, c_N, c_C$ – denote gain coefficients of synchro-control-transformers of gyroscopes, aiming electromagnet of gyroscope, acceleration sensor, electronic amplifier, hydraulic pump, hydraulic engine, pressure pick-up and four regulation potentiometers respectively;

$J_W, K_N, T_N, J_{SR}, M_{TS}$ – construction parameters of turret and turret reduction gear coulomb friction respectively;

$U_{S\max}, i_{\max}, i_{Ma}, p_{\max}, p_{Ma}, \delta, M_{S\max}$ – characteristic points on non-linear characteristics of electronic amplifier, hydraulic pump, hydraulic engine and coulomb friction, respectively;

$U_{PK}, \gamma_K, \ddot{\gamma}_K, \dot{\psi}_K, \ddot{\psi}_K$ – inputs.

The system of equation (1 24) constitutes a mathematical model of the turret gun stabiliser.

3. Elevation stabiliser

Elevation tank gun stabiliser is an electro-hydraulic control system and makes possible aiming at a target, tracking of a target and stabilisation of a given gun angular position.
The functional scheme of the system is shown in Fig. 4. Stabiliser has been divided into appropriate functional parts [13, 14]:

- gun-sight (contain: GC-gunner controller, SS-sight servo, FG- free gyroscope, SCT-synchro-control-transformer);
- gyro-box (contain: RG- rate gyroscope, , SCT- synchro-control-transformer);
- electronic amplifier (contain: VA-voltage amplifier, PS-phase sensor, PA- power amplifier);
- servo-valve (contain: E – electromagnet, P – hydraulic pump);
- elevation drive (ED – hydraulic servo-motor);
- tanks gun (G – gun as a controlled system).

The stabiliser realises the following two basic functions:

- alteration of the gun angular position with respect to the hull with the aid of a gunner hand controller GC during aiming at a target and tracking of a target;
- stabilisation of a given gun angular position φ_A in the presence of the disturbing torque $M(\varphi_K)$ caused by the tank movement.

In the operating conditions tracking and aiming at a target processes occur simultaneously.

Then, via laboratory tests, dynamic and static characteristics of those parts have been obtained as well as numerical values of coefficients of suitable mathematical models have been determined [16, 18, 22].

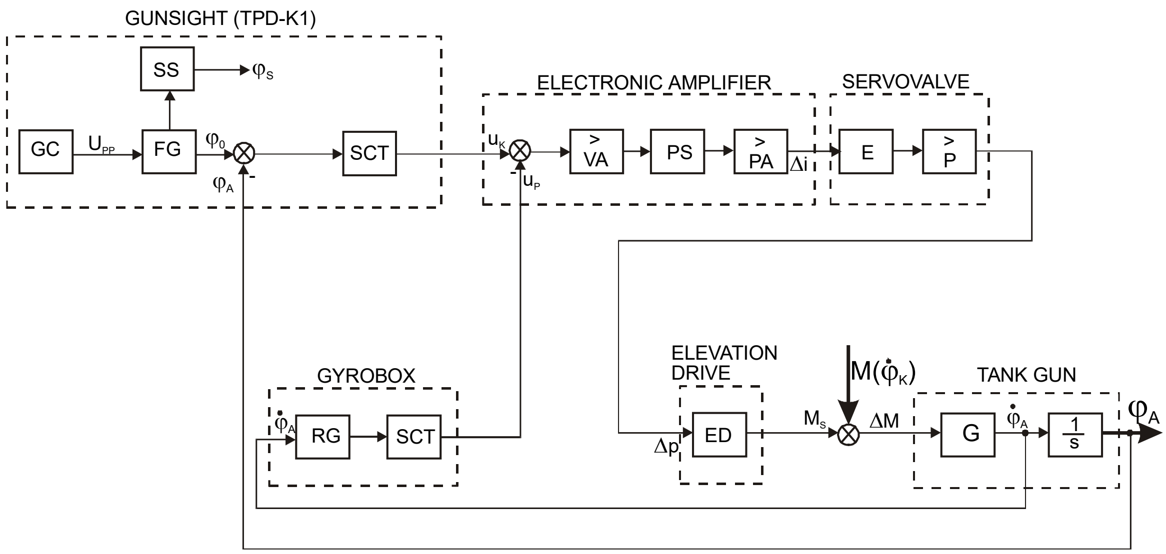

Fig. 4. Functional scheme of the tank gun stabiliser

On the basis of obtained static characteristics and transfer functions of individual parts of the system and of the knowledge about the system feed-backs, the structural scheme of the overall system has been found (with two inputs and one output) [17, 24, 36, 37] – see Fig. 5.

The input signals are:

U_{PP} – reference signal given by the operator;

φ_K – disturbing signal caused by the hall longitudinal vibration.

The gun angular displacement φ_A represents the output signal.

Most of static characteristics are linear or almost linear. Strong nonlinearities that should be included in the mathematical model of the system resulted from:

- coulomb friction forces between the gun and the turret;
- electronic amplifier saturation;
- saturation of the hydraulic pump;
- saturation of the hydraulic servomotor.

The system has two main feedbacks:

- negative angular position feed-back realised by free gyroscope and caused by the gun longitudinal angular displacements;
- negative rate feedback realised by rate gyroscope and caused by the gun longitudinal movements angular speed.

The mathematical model has been formulated at the following assumptions:

- the free gyroscope has been treated as a proportional element (due to small viscous friction in bearings and small inertia moments of frames);
- the aiming electromagnet of the free gyroscope has been presented as an ideal integrator (due to small inertia moments of frames);
- the synchro-control-transformer has been treated as a proportional element (due to large difference between frequency of control and supply voltage);
- the electronic amplifier has been treated as a proportional element (due to small time constants);
- the hydraulic pump has been treated as a inertial second-order element (due to small viscous friction);
- the hydraulic servomotor has been treated as a proportional element (due to reduction of the inertia moment of the piston to the gun rotation axis).

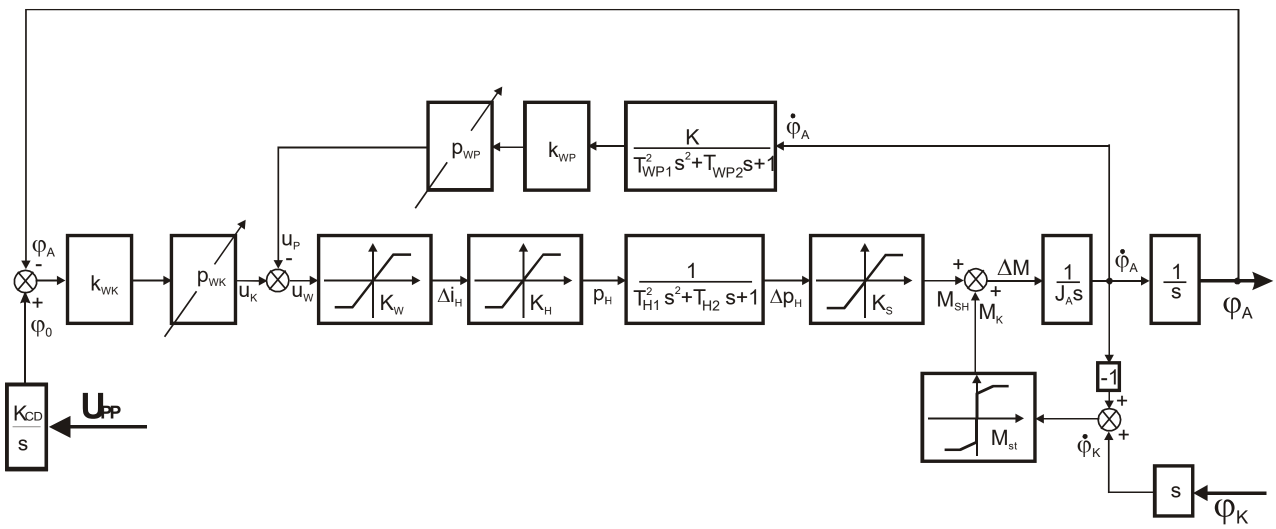

Fig. 5. Structural scheme of the tank gun stabiliser

The system of equations constitutes a mathematical model of the stabilizer. The differential equations constitute mathematical description of the gun stabilizer modules and the gun. These are ODE's of first or second order with constant coefficients. The algebraic equations describe non-linear characteristics and summing nodes.

The system of differential and algebraic equations that has been formulated on the basis of the structural scheme (Fig. 5) has the form:

$$\dot{\varphi}_0 = U_{PP} K_{CD}\,, \tag{25}$$

$$T_{WP1}^2 \ddot{u}_P + T_{WP2}\dot{u}_P + u_P - \dot{\varphi}_A K k_{WP} p_{WP} = 0\,, \tag{26}$$

$$(\varphi_0 - \varphi_A)\cdot k_{WK} p_{WK} - u_K = 0\,, \tag{27}$$

$$u_K - u_P - u_W = 0\,, \tag{28}$$

$$u_W K_W - \Delta i_H = 0 \quad for \quad -u_{WKr} \le u_W \le u_{WKr}\,, \tag{29}$$

$$u_W K_W - i_{Max} = 0 \quad for \quad u_W > u_{WK_r}\,, \tag{30}$$

$$u_W K_W + i_{Max} = 0 \quad for \quad u_W < -u_{WK_r}\,, \tag{31}$$

$$\Delta i_H K_H - p_H = 0 \quad for \quad -i_{K_r} \le \Delta i \le i_{K_r}\,, \tag{32}$$

$$\Delta i_H K_H - p_{Max} = 0 \quad for \quad \Delta i_H > i_{K_r}\,, \tag{33}$$

$$\Delta i_H K_H + p_{Max} = 0 \quad for \quad \Delta i_H < -i_{K_r}\,, \tag{34}$$

$$T_{H1}^2 \Delta\ddot{p}_H + T_{H2}\Delta\dot{p}_H + \Delta p_H - p_H = 0\,, \tag{35}$$

$$\Delta p_H K_S - M_{SH} = 0 \quad for \quad -p_{K_r} \le \Delta p_H \le p_{K_r}\,, \tag{36}$$

$$\Delta p_H K_S - M_{SMax} = 0 \quad for \quad \Delta p_H > p_{K_r}\,, \tag{37}$$

$$\Delta p_H K_S + M_{SMax} = 0 \quad for \quad \Delta p_H < -p_{K_r}\,, \tag{38}$$

$$sign(\dot{\varphi}_K - \dot{\varphi}_A) M_{st} + (\dot{\varphi}_K - \dot{\varphi}_A)\cdot f - M_K = 0 \quad for \quad -\Delta\dot{\varphi}_{K_r} \le (\dot{\varphi}_K - \dot{\varphi}_A) \le \Delta\dot{\varphi}_{K_r} \\ and \quad |\dot{\varphi}_K - \dot{\varphi}_A| > \delta_S \tag{39}$$

$$M_K = 0 \quad for \quad -\delta_S \le (\dot{\varphi}_K - \dot{\varphi}_A) \le \delta_S\,, \tag{40}$$

$$M_K - M_{Stm} = 0 \quad for \quad (\dot{\varphi}_K - \dot{\varphi}_A) > \Delta\dot{\varphi}_{K_r}\,, \tag{41}$$

$$M_K + M_{Stm} = 0 \quad for \quad (\dot{\varphi}_K - \dot{\varphi}_A) < -\Delta\dot{\varphi}_{K_r}\,, \tag{42}$$

$$M_K + M_{SH} - \Delta M = 0\,, \tag{43}$$

$$\ddot{\varphi}_A J_A - \Delta M = 0\,. \tag{44}$$

For the differential equations, one assumed the zero initial conditions:
$\varphi_A = \dot{\varphi}_A = \ddot{\varphi}_A = \varphi_O = u_K = u_P = u_W = U_{PP} = \Delta i_H = p_H = \Delta p_H = M_{SH} = M_K = \Delta M = 0.$

In the above equations, the following notation is used:

$T_{WP1}, T_{WP2}, T_{H1}, T_{H2}$ – denote time constants of rate gyroscope and hydraulic servo-valve respectively;

$K, k_{WP}, k_{WK}, K_{CD}, K_W, K_H, K_S, p_{WP}, p_{WK}$ – denote gain coefficients of synchro-control-transformers of free and rate gyroscopes, aiming electromagnet of gyroscope in CD, electronic amplifier, hydraulic pump, hydraulic servo-motor, and two regulation potentiometers respectively;

J_A, M_{st}, f – inertia moment of the gun, coulomb friction and viscous friction coefficient respectively;

$u_{WKr}, i_{Max}, i_{Kr}, p_{Max}, p_{Kr}, \delta_S, M_{SMax}, M_{Stm}, \Delta\dot{\varphi}_{Kr}$ – characteristic points on non-linear characteristics of electronic amplifier, hydraulic pump, hydraulic servo-motor and coulomb friction, respectively;

$U_{PP}, \varphi_W, \dot{\varphi}_W$ – inputs.

The system of equation (25-44) constitutes a mathematical model of the gun stabiliser.

4. Concluding remarks

On the basis of the mathematical model, the algorithm and the computer program were worked–out. Making use of the Matlab-Simulink program, one worked-up the scheme for numerical computation [28, 29, 30, 35]. The mathematical model and its numerical implementation have been experimentally verified. To this aim, the results of numerical computations were compared with the existing results of experimental tests carried-out on a real plant [9, 10, 21, 23, 26, 32, 33, 34]. The results of experimental and model simulation investigations showed that the mathematical model and its numerical implementation were correctly developed.

In the next stage of the investigations, the following work should be done:

- the mathematical description of the dynamic of military tank, to determine how vibration and shocks, as vertical motion of the tracks, are transferred from the ground to the hull and stabilised armament;
- the mathematical description of the stabilised gunner's sight system in order to investigate the possibilities of improving performance characteristics of the stabilised sight system;
- to carry out (using the described above mathematical model of the system) simulation investigations of the influence of regulation potentiometers settings and changing of internal feed – backs gain coefficients on the exactness of stabilisation and transient processes quality;
- analysis of influence of disturbing input signals (propagated from the ground on the gun and turret) on the exactness of stabilisation at a given position;
- analysis of possibilities of introducing additional feed – backs in the investigated system in order to improve performance characteristics of the stabiliser.

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