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ABOUT STABILITY OF THE MOVEMENT OF THE REFUELING VEHICLE EQUIPED WITH DIGITAL SYSTEM OF BRAKE FORCES DISTRIBUTION DURING THE EMERGENCY BRAKING

Abstract: The impact of enforced oscillations of the free surface of fuel in the car tank on the stability area of a closed digital brake force distribution system is considered. **The object of the study** is the process of stabilized movement of the tanker during the emergency braking. **The subject of the study** is a large tanker with a gross weight (3-3.5) $*10^4$ kg, equipped with a tank with a volume of (17-20) m^3 and a system of direction stability. **The goal of the work** is investigation of the impact of transported fuel fluctuations on the stability of the refueling vehicle during the emergency braking and introducing of methods for selecting values of variable parameters of the electronic brake force distribution system to minimize it. **Conclusion.** Considering the oscillations of the free surface of the liquid in the mathematical model of disturbed movement of a closed system of stability significantly reduces the stability area of the system in the low frequency range due to the loop, the size and position of which depend on the filling level of the tank. Need to choose an envelope loop that according to different levels of tank filling.

Keywords: refueling vehicle; system of brake forces distribution; stability area; variable parameters of system.

Introduction

Problem statement. The world's best models of refueling vehicles (RV) are equipped with automatic brake control systems, which consist of at least two parallel operating systems: anti-lock braking system (ABS), which prevents the wheels from locking when the brake pedal is pressed abruptly, and anti-slip system (TRC) that prevents the wheels from slipping caused by excessive pressure on the accelerator pedal.

Both ABS and TRC systems always control stability of vehicle direction, but the accuracy of traction control can be limited if using only these two systems. The VSC system (vehicle stability control) has become activated. This system can control the necessary indicators of vehicle stability during the braking process. However, the experience of RV usage indicates about valuable impact the transported fuel on the RV direction stability during the emergency braking. Based on this, the goal of this article is research of impact of variable parameters of electronic system for brake distribution and introduce the methodology of choosing them to minimize its impact.

Analysis of publications. Since the beginning of the XXI century, there has been widespread use of vehicle stability control systems (VSC) by automotive corporations in the United States, Japan, South Korea and the European Union. In parallel with practical development, these corporations conduct in-depth research of these systems to improve them [1-3]. The international scientific and technical conferences, which discuss the results of research on the development of electronic brake force distribution systems (EBD) [4 -8], are held on regular basis.

The EBD system works in combination with the ABS system and allows to distribute brake forces on wheels more effectively and to increase controllability and stability of vehicle during braking process. The above publications discuss VSC and EBD systems used in luxury passenger cars. Problems of increasing the heavily loaded refueling vehicle stability are studied by scientists of Ukraine, Belarus and Russia for such RVs: KrAZ [11-15], KAMAZ, URAL and MAZ [9, 10], which are equipped with tanks with a volume of 20 m^3. Belarusian researchers are developing ways to reduce the impact of fuel fluctuations in the RV tank by introducing special fuel tank construction, on the contrary Ukrainian and Russian scientists are developing ways to improve the VSC and EBD systems. Thus, in the article [11] the application of a block of command devices and algorithms of a platformless inertial system is proposed, and in [12] the structural and functional scheme of the electromagnetic system VSC is proposed. In [13, 14] the problem of parametric synthesis of the digital EBD system for KrAZ-63221 is solved. In [15], a mathematical model of the perturbed motion of the RV considering the oscillations of the free surface of the fuel in the tank presented. This model can be used to solve the problem of parametric synthesis of VSC and EBD systems.

Main part

In [15] it was proved that the longitudinal oscillations of the liquid in the tank have almost no effect on the RV stability. The vehicle stability in the process of emergency braking is significantly affected only by the first tone of transverse oscillations of the liquid in the tank. The mathematical model of perturbed motion of the vehicle in the jerking channel has the form:

$$\ddot{\psi}(t) = -\frac{BK_r}{I}\Delta p(t) - \frac{2H_m M f_c}{I}\upsilon(t)\dot{\psi}(t) + \\ +\left(f_c m_1^y \big/ I \right)\cdot (H_n + h_1)\ddot{y}_1(t) + \left(f_c m_1^y \big/ I \right)\cdot g y_1(t); \quad (1)$$

$$\ddot{y}_1(t)+\varepsilon_1\dot{y}_1(t)+\omega_1^2 y_1(t)=-\upsilon(t)\dot{\psi}(t)-\Delta L\ddot{\psi}(t); \quad (2)$$

$$\Delta\ddot{p}(t)+\frac{f_k}{I_k}\Delta\dot{p}(t)+\frac{C_k}{I_k}\Delta p(t)=\bar{K}_u U(t). \quad (3)$$

The equation (1) describes the change of the angular deviation $\psi(t)$ of the vehicle longitudinal own inertia axis from an original movement direction in the process of emergency braking. The equation (2) describes the first tone of transverse oscillations of the liquid in the tank, and the variable $y_1(t)$ is a generalized coordinate of the partial layer of liquid in the tank, which corresponds to the first tone of transverse oscillations of the liquid. The equation (3) describes the dynamics of the electromagnetic amplifier (EMA) in the stability system VSC, where the variable $\Delta p(t)$ is the difference in working pressure in the brake lines of the right and left sides of the RV, and the variable $U(t)$ is the control signal generated by EBD system.

The coefficients of the differential equations (1) - (3) system contain the following values of the design parameters of the RV with the VSC system: M - mass of the RV; I - moment of inertia of the RV relative to its own vertical axis of inertia; B - track width of the RV; H_m - distance from the driving surface of the RV to its center of mass; H_n - distance from the driving surface to the bottom of the tank; ΔL is the distance from the center of mass of the RV to the center of the tank; f_c - coefficient of resistance to movement, which depends on the properties of the soil; I_k - moment of inertia of the rocker; I_k is the coefficient of fluid friction in the EMA axis; C_k - coefficient of rigidity of the spring that fixes the EMA rocker in the neutral state; h_1 is the distance from the bottom of the tank to the center of mass of the partial layer of liquid in the absence of its oscillations; ε_1 - damping coefficient (?) of transverse oscillations of the partial layer of the liquid corresponding to the first tone; ω_1 - own frequency of the first tone of transverse oscillations of the liquid in the tank; $K_r, \bar{K}_u$ - proportion coefficients.

Calculation formulas for the values of $m_1^y, h_1, \varepsilon_1$ and ω_1 are given in [15]. The system of differential equations (1) - (3) is nonlinear because the right-hand side of equations (1) and (2) includes nonlinear members which are containing the product $\upsilon(t)\dot{\psi}(t)$, where $\upsilon(t)$ is the current speed of the RV during braking. To simplify the construction of the stability area of VSC in the plane of the variable parameters of EBD, which forms a control algorithm:

$$U[nT]=K_{\psi}\psi[nT]+K_{\dot{\psi}}\omega_{\psi}[nT], \quad (4)$$

Let us use the method of "frozen" coefficients [16]. According to this method, at any given time

$$t_i\in[0,T_r],(i=\overline{1,s}), \quad (5)$$

where T_r is the deceleration time.

There is the value of $\upsilon(t)$ that is considered as constant and equal to $\upsilon(t_i),(i=\overline{1,s})$ in the mathematical model (1) - (3). It is assumed that if the system (1) - (3) at any time (5) is stable, then the system (1) - (3) is stable over the entire interval $[0,T_r]$. The method of "frozen" coefficients does not have a clear mathematical justification, but this method solves many practical problems of dynamic design of non-stationary objects.

Therefore, in the system (1) - (3) the RV speed will be considered constant $\upsilon(t)=\upsilon$. In this case, the system (1) - (3) is considered linear. To simplify next transformations, we introduce the following notations:

$$\frac{BK_r}{I}=a_{\psi p};\frac{2H_m Mf_c}{I}=a'_{\psi\psi};$$

$$\frac{f_c m_1^y}{I}(H_n+h_1)=a''_{\psi y};$$

$$\frac{f_c m_1^y}{I}g=a_{\psi y};\frac{f_k}{I_k}=a'_{pp};\frac{C_k}{I_k}=a_{pp}$$

Then the continuous part of the closed RV stability system takes the form:

$$\begin{aligned}&\ddot{\psi}(t)+a_{\psi p}\Delta p(t)+a'_{\psi\psi}\upsilon(????)\dot{\psi}(t)-\\&-a''_{\psi y}\ddot{y}_1(t)-a_{\psi y}y_1(t)=0;\\&\ddot{y}_1(t)+\varepsilon_1\dot{y}_1(t)+\omega_1^2 y_1(t)+\upsilon\dot{\psi}(t)\\&\quad+\Delta L\ddot{\psi}(t)=0;\\&\Delta\ddot{p}(t)+a'_{pp}\Delta\dot{p}(t)+a_{pp}\Delta p(t)=\bar{K}_u U(t).\end{aligned} \quad (6)$$

Let us write the system of differential equations (6) in vector and matrix form

$$A_1 p^2 Y(t)+B_1 pY(t)+C_1 Y(t)=DU(t), \quad (7)$$

where $Y(t)$ – a vector of system's (7) state:

$$Y(t)=\begin{bmatrix}\psi(t)\\ y_1(t)\\ \Delta p(t)\end{bmatrix},$$

and corresponding matrixes have the following form:

$$A_1=\begin{bmatrix}1 & -a''_{\psi y} & 0\\ \Delta L & 1 & 0\\ 0 & 0 & 1\end{bmatrix}; \quad B_1=\begin{bmatrix}a'_{\psi\psi} & 0 & 0\\ \upsilon & \varepsilon_1 & 0\\ 0 & 0 & a'_{pp}\end{bmatrix};$$

$$C_1=\begin{bmatrix}0 & -a_{\psi y} & a_{\psi p}\\ 0 & \omega_1^2 & 0\\ 0 & 0 & a_{pp}\end{bmatrix}; \quad D=\begin{bmatrix}0\\ 0\\ \bar{K}_u\end{bmatrix}.$$

The equation (7) can be written as:

$$\begin{aligned}&p^2 Y(t)=-A_1^{-1}B_1 pY(t)-\\&-A_1^{-1}C_1 Y(t)+A_1^{-1}DU(t),\end{aligned} \quad (8)$$

moreover:

$$A_1^{-1}B_1 = \begin{bmatrix} \dfrac{a'_{\psi\psi}}{1+a''_{\psi y}\Delta L} + \dfrac{a''_{\psi y}\upsilon}{1+a''_{\psi y}\Delta L} & \dfrac{a''_{\psi y}\varepsilon_1}{1+a''_{\psi y}\Delta L} & 0 \\ -\dfrac{a'_{\psi\psi}\Delta L}{1+a''_{\psi y}\Delta L} + \dfrac{\upsilon}{1+a''_{\psi y}\Delta L} & \dfrac{\varepsilon_1}{1+a''_{\psi y}\Delta L} & 0 \\ 0 & 0 & a'_{pp} \end{bmatrix};$$

$$A_1^{-1}C_1 = \begin{bmatrix} 0 & -\dfrac{a_{\psi y}}{1+a''_{\psi y}\Delta L} + \dfrac{\omega_1^2}{1+a''_{\psi y}\Delta L} & \dfrac{a_{\psi p}}{1+a''_{\psi y}\Delta L} \\ 0 & \dfrac{a_{\psi y}\Delta L}{1+a''_{\psi y}\Delta L} + \dfrac{\omega_1^2}{1+a''_{\psi y}\Delta L} & -\dfrac{a_{\psi p}\Delta L}{1+a''_{\psi y}\Delta L} \\ 0 & 0 & a_{pp} \end{bmatrix};$$

$$A_1^{-1}D = \begin{bmatrix} 0 \\ 0 \\ \bar{K}_u \end{bmatrix}$$

Differential equation (8) can be transformed to the system of differential equations of 6[th] order:

$$\begin{aligned} &\ddot{\psi} = -b'_{\psi\psi}\dot{\psi}(t) - b'_{\psi y}\dot{y}_1(t) - b_{\psi y}y_1(t) - b_{\psi p}\Delta p(t); \\ &\ddot{y}_1(t) = -b'_{y\psi}\dot{\psi}(t) - b'_{yy}\dot{y}_1(t) - b_{yy}y_1(t) + b_{yp}\Delta p(t); \quad (9) \\ &\Delta\ddot{p}(t) = -a'_{pp}\Delta\dot{p}(t) - a_{pp}\Delta p(t) + \bar{K}_u U(t), \end{aligned}$$

The coefficients from the equation (9) are described below:

$$b'_{\psi\psi} = \frac{a'_{\psi\psi} + a''_{\psi y}\upsilon}{1+a''_{\psi y}\Delta L};$$

$$b'_{\psi y} = \frac{a''_{\psi y}\varepsilon_1}{1+a''_{\psi y}\Delta L}; b_{\psi y} = \frac{-a_{\psi y} + \omega_1^2}{1+a''_{\psi y}\Delta L};$$

$$b_{\psi p} = \frac{a_{\psi p}}{1+a''_{\psi y}\Delta L};$$

$$b'_{y\psi} = \frac{-a'_{\psi\psi}\Delta L + \upsilon}{1+a''_{\psi y}\Delta L}; b'_{yy} = \frac{\varepsilon_1}{1+a''_{\psi y}\Delta L};$$

$$b_{yy} = \frac{a_{\psi y}\Delta L + \omega_1^2}{1+a''_{\psi y}\Delta L}; b_{yp} = (-)\frac{a_{\psi p}\Delta L}{1+a''_{\psi y}\Delta L}.$$

The vector of system's state is used to transform the equation (9) to the normal form:

$$X(t) = \begin{bmatrix} \psi(t) \\ \dot{\psi}(t) \\ y(t) \\ \dot{y}(t) \\ \Delta p(t) \\ \Delta\dot{p}(t) \end{bmatrix} = \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ x_4(t) \\ x_5(t) \\ x_6(t) \end{bmatrix};$$

$$\begin{aligned} &\dot{x}_1(t) = x_2(t); \\ &\dot{x}_2(t) = -b'_{\psi\psi}x_2(t) - b_{\psi y}x_3(t) - b'_{\psi y}x_4(t) - \\ &\qquad - b_{\psi p}x_5(t); \\ &\dot{x}_3(t) = x_4(t); \qquad (10) \\ &\dot{x}_4(t) = -b'_{y\psi}x_2(t) - b_{yy}x_3(t) - b'_{yy}x_4(t) + b_{yp}x_5(t); \\ &\dot{x}_5(t) = x_6(t); \\ &\dot{x}_6(t) = -a'_{pp}x_5(t) - a_{pp}x_6(t) + \bar{K}_u U(t), \end{aligned}$$

or it can be presented as the equation in matrix form:

$$\dot{X}(t) = AX(t) + BU(t), \qquad (10)$$

matrixes A and B are described below:

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & -b'_{\psi\psi} & -b_{\psi y} & -b'_{\psi y} & -b_{\psi y} & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & -b'_{y\psi} & -b_{yy} & -b'_{yy} & b_{yp} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & -a'_{pp} & -a_{pp} \end{bmatrix}; B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \bar{K}_u \end{bmatrix}; \quad (11)$$

Formula (4) can be written as follows:

$$U[nT] = KX[nT], \qquad (12)$$

where the vector K is:

$$K = \begin{bmatrix} K_\psi & K_{\dot{\psi}} & 0 & 0 & 0 & 0 \end{bmatrix}. \qquad (13)$$

According to [16] the transition from a continuously discrete closed system (11), (13) to a discrete closed system can be made:

$$X[(n+1)T] = [\Phi + HK]X[nT]. \qquad (14)$$

With a characteristic equation

$$\det = [\Phi + HK - EZ] = 0, \qquad (15)$$

where matrixes Φ and H can be described using the following formulas:

$$\Phi = \sum_{i=0}^{\infty}\frac{1}{i!}A^iT^i; H = \sum_{i=0}^{\infty}\left[\frac{1}{(i+1)!}A^iT^{i+1}\right]B.$$

Of course, when using modern on-board digital computers with a small value of the quantization period the following is assumed:

$$\Phi = E + AT; H = BT,$$

then the characteristic equation (16) takes the form:

$$\det\left[AT + BKT + E(1-Z)\right] = 0 \qquad (16)$$

Matrixes (12) and (14) can be inserted into characteristic equation (17). As the result:

$$(1-Z)^6 - (1-Z)^5\left(a'_{pp} + b'_{yy} + b'_{\psi\psi}\right)T + \\ +(1-Z)^4\begin{pmatrix} b'_{\psi\psi}b'_{yy} - b'_{y\psi}b'_{\psi y} + a'_{pp}b'_{yy} + \\ +a'_{pp}b'_{\psi\psi} + a_{pp} + b_{yy} \end{pmatrix}T^2 -$$

$$
\begin{aligned}
&-(1-Z)^3\begin{bmatrix} a'_{pp}\left(b'_{\psi\psi}b'_{yy}-b'_{y\psi}b'_{\psi y}\right)+ \\ +a_{pp}\left(b'_{\psi\psi}+b'_{yy}\right)+b_{yy}a'_{pp}+ \\ +b_{yy}b'_{\psi\psi}-b_{y\psi}b_{\psi y}\end{bmatrix}T^3- \\
&-(1-Z)^3 b_{\psi p}T^3\overline{K}_u K_{\dot\psi}+ \\
&+(1-Z)^2\begin{bmatrix} a_{pp}\left(b'_{\psi\psi}b'_{yy}-b'_{y\psi}b'_{\psi y}\right)+b_{yy}+ \\ +a'_{pp}\left(b_{yy}b'_{\psi\psi}-b'_{y\psi}b_{\psi y}\right)\end{bmatrix}T^4+ \\
&+(1-Z)^2\left(b'_{\psi y}b_{yp}+b'_{yy}b_{\psi p}+b_{\psi p}\right)T^4\overline{K}_u K_{\dot\psi}- \\
&-(1-Z)\left(b_{yy}b'_{\psi\psi}-b'_{y\psi}b_{\psi y}\right)T^5- \\
&=(1-Z)\left(b_{\psi y}b_{\psi p}+b_{yy}b_{\psi p}\right)T^5\overline{K}_u K_{\dot\psi}- \\
&-(1-Z)\left(b'_{\psi y}b_{yp}+b'_{yy}b_{\psi p}\right)T^5\overline{K}_u K_{\dot\psi}+ \\
&+\left(b_{\psi y}b_{\psi p}+b_{yy}b_{\psi p}\right)T^6\overline{K}_u K_{\dot\psi}=0
\end{aligned}
\qquad (17)
$$

The following notations are introduced for simplifying of characteristic equation (18):

$$A_1(T)=\left(a'_{pp}+b'_{yy}+b'_{\psi\psi}\right)T;$$

$$A_2(T)=\begin{pmatrix} b'_{\psi\psi}b'_{yy}-b'_{y\psi}b'_{\psi y}+a'_{pp}b'_{yy}+ \\ +a'_{pp}b'_{\psi\psi}+a_{pp}+b_{yy}\end{pmatrix}T^2;$$

$$A_3(T)=\begin{bmatrix} a'_{pp}\left(b'_{\psi\psi}b'_{yy}-b'_{y\psi}b'_{\psi y}\right)+a_{pp}\times \\ \times\left(b'_{\psi\psi}+b'_{yy}\right)+b_{yy}a'_{pp}+b_{yy}b'_{\psi\psi}-b_{y\psi}b_{\psi y}\end{bmatrix}T^3;$$

$$A_{31}(T)=b_{\psi p}T^3\overline{K}_u$$

$$A_4(T)=\begin{bmatrix} a_{pp}\left(b'_{\psi\psi}b'_{yy}-b'_{y\psi}b'_{\psi y}\right)+b_{yy}+ \\ +a'_{pp}\left(b_{yy}b'_{\psi\psi}+b'_{y\psi}b_{\psi y}\right)\end{bmatrix}T^4;$$

$$A_{41}(T)=(b'_{\psi y}b_{yp}+b'_{yy}b_{\psi p})T^4\overline{K}_u;$$

$$A_{42}(T)=b_{\psi p}T^4\overline{K}_u;$$

$$A_5(T)=(b_{yy}b'_{\psi\psi}-b'_{y\psi}b_{\psi y})T^5;$$

$$A_{51}(T)=(b_{\psi y}b_{\psi p}+b_{yy}b_{\psi p})T^5\overline{K}_u;$$

$$A_{52}(T)=(b'_{\psi y}b_{yp}+b'_{yy}b_{\psi p})T^5\overline{K}_u;$$

$$A_6(T)=(b_{\psi y}b_{\psi p}+b_{yy}b_{\psi p})T^6\overline{K}_u.$$

Then the characteristic equation of closed digital VSC system takes the form:

$$
\begin{aligned}
&(1-Z)^6-(1-Z)^5A_1(T)+(1-Z)^4A_2(T)- \\
&-(1-Z)^3A_3(T)-(1-Z)^3A_{31}(T)K_{\dot\psi}+ \\
&+(1-Z)^2A_4(T)+(1-Z)^2A_{41}(T)K_{\dot\psi}+ \\
&+(1-Z)^2A_{42}(T)K_{\psi}-(1-Z)A_5(T)-(1-Z)\times \\
&\times A_{51}(T)K_{\dot\psi}-(1-Z)A_{52}(T)K_{\psi}+A_6(T)K_{\psi}=0.
\end{aligned}
\qquad (18)
$$

The following replacement in characteristic (19) is possible using the W -transformation method:

$$Z=(1+W)/(1-W).$$

As a result, we obtain the new characteristic equation regarding complex variable W :

$$
\begin{aligned}
&\begin{bmatrix} -32A_1(T)+16A_2(T)-8A_3(T)+ \\ +6A_4(T)-2A_5(T)\end{bmatrix}W^6+ \\
&+\begin{bmatrix} 32A_1(T)-32A_2(T)+24A_3(T)- \\ -16A_4(T)+10A_5(T)\end{bmatrix}W^5+ \\
&+[16A_2(T)-24A_3(T)+24A_4(T)-20A_5(T)]W^4+ \\
&=[8A_3(T)-16A_4(T)+20A_5(T)]W^3+ \\
&[4A_4(T)-10A_5(T)]W^2+2A_5(T)W+64+ \\
&+K_{\dot\psi}\{[-8A_{31}(T)+4A_{41}(T)-2A_{51}(T)]W^6+ \\
&+[24A_{31}(T)-16A_{41}(T)+10A_{51}(T)]W^5+ \\
&+[-24A_{31}(T)+24A_{41}(T)-20A_{51}(T)]W^4+ \\
&+[8A_{31}(T)-16A_{41}(T)+20A_{51}(T)]W^3+ \\
&+[4A_{41}(T)-10A_{51}(T)]W^2+2A_{51}(T)W\}+ \\
&+K_{\psi}\{[4A_{42}(T)-2A_{52}(T)+A_6(T)]W^6+ \\
&+[-16A_{42}(T)+10A_{52}(T)-6A_6(T)]W^5+ \\
&+[24A_{42}(T)-20A_{52}(T)+15A_6(T)]W^4+ \\
&+[-16A_{42}(T)+20A_{52}(T)-20A_6(T)]W^3+ \\
&+[4A_{42}(T)-10A_{52}(T)+15A_6(T)]W^2+ \\
&+[2A_{52}(T)-6A_6(T)]W+A_6(T)\}=0.
\end{aligned}
\qquad (19)
$$

The replacement $w=j\omega$ can be done within the characteristic equation (20). If real and imaginary parts are equal to 0, then the following system of 2 algebraic equations with two unknown parameters K_{ψ} and $K_{\dot\psi}$ will be obtained.

$$
\begin{aligned}
&A(\omega,T)K_{\psi}+B(\omega,T)K_{\dot\psi}=C(\omega,T); \\
&D(\omega,T)K_{\psi}+E(\omega,T)K_{\dot\psi}=F(\omega,T),
\end{aligned}
\qquad (20)
$$

Within the system the following notation are accepted:

$$
\begin{aligned}
&A(\omega,T)=-[4A_{42}(T)-2A_{52}(T)+A_6(T)]\omega^6+ \\
&+[24A_{42}(T)-20A_{52}(T)+15A_6(T)]\omega^4- \\
&-[4A_{42}(T)-10A_{52}(T)+15A_6(T)]\omega^2+A_6(T);
\end{aligned}
$$

$$
\begin{aligned}
&B(\omega,T)=-[-8A_{31}(T)+4A_{41}(T)-2A_{51}(T)]\omega^6+ \\
&+[-24A_{31}(T)+24A_{41}(T)-20A_{51}(T)]\omega^4- \\
&-[4A_{41}(T)-10A_{51}(T)]\omega^2;
\end{aligned}
$$

$$C(\omega,T)=\begin{bmatrix} -32A_1(T)+16A_2(T)-8A_3(T)+ \\ +6A_4(T)-2A_5(T)\end{bmatrix}\omega^6-$$

$$-\begin{bmatrix} 16A_2(T) - 24A_3(T) + 24A_4(T) - \\ -20A_5(T)]\omega^4 + [4A_4(T) - 10A_5(T) \end{bmatrix}\omega^2 - 64;$$

$$D(\omega,T) = [-16A_{42}(T) + 10A_{52}(T) - 6A_6(T)]\omega^4 -$$
$$-[-16A_{42}(T) + 20A_{52}(T) - 20A_6(T)]\omega^2 +$$
$$+2A_{52}(T) - 6A_6(T);$$

$$E(\omega,T) = [24A_{31}(T) - 16A_{41}(T) + 10A_{51}(T)]\omega^4 -$$
$$-[8A_{31}(T) - 16A_{41}(T) + 20A_{51}(T)]\omega^2 + 2A_{51}(T);$$

$$F(\omega,T) = -\begin{bmatrix} 32A_1(T) - 32A_2(T) + 24A_3(T) - \\ -16A_4(T) + 10A_5(T) \end{bmatrix}\omega^4 +$$
$$+[8A_3(T) - 16A_4(T) + 20A_5(T)]\omega^2 - 2A_{51}(T).$$

The system (21) is solved using the Cramer rule, where the corresponding determinants are written in the following form:

$$\Delta = \begin{vmatrix} A(\omega,T) & B(\omega,T) \\ D(\omega,T) & E(\omega,T) \end{vmatrix} =$$
$$= A(\omega,T)E(\omega,T) - D(\omega,T)B(\omega,T);$$

$$\Delta_\psi = \begin{vmatrix} C(\omega,T) & B(\omega,T) \\ F(\omega,T) & E(\omega,T) \end{vmatrix} =$$
$$= C(\omega,T)E(\omega,T) - F(\omega,T)B(\omega,T);$$

$$\Delta_{\dot\psi} = \begin{vmatrix} A(\omega,T) & C(\omega,T) \\ D(\omega,T) & F(\omega,T) \end{vmatrix} =$$
$$= A(\omega,T)F(\omega,T) - D(\omega,T)C(\omega,T).$$

Then we get the following relationships for building the stability areas:

$$K_\psi = \frac{\Delta_\psi}{\Delta}; K_{\dot\psi} = \frac{\Delta_{\dot\psi}}{\Delta}. \quad (21)$$

By changing the value of $.\omega.$ from zero to infinity, the boundary of the stability area in plane $\left(K_\psi, K_{\dot\psi}\right)$ is built. The determinant Δ is positive, so when the value of ω increases, the boundary of the stability area should be hatched on the left.

Calculation results

The boundaries of stability areas of closed digital single-circuit VSC were calculated for the RV KrAZ-63221 with the following parameters: tank volume 20 m^3, length 6 m, width 2,4 m and height 1,4 m. The values of mathematical model parameters are:

$$a_{\psi p} = 0,27 \times 10^{-6} m^2 N^{-1} s^{-2}; a'_{\psi\psi} = 0,01 m^{-1};$$
$$a_{pp} = 1,03 \times 10^4 s^{-2}; a'_{pp} = 0,56 \times 10^2 s^{-1};$$
$$\overline{K}_u = 1,03 \times 10^8 V^{-1} Psc \times s^{-2}; \Delta L = 1m; \upsilon = 18 m \times s^{-1};$$

Stability areas are calculated for three cases with different values of fuel level in the tank.

The first case corresponds to the $h = 0,15m$ $h = 0,15\ m$fuel level, the second case - $h = 0,5m$ $h = 0,5\ m$fuel level, and the third case - $h = 0,75m$.

The values of mathematical model (B) parameters that depend on fuel level for these three cases are listed in the table 1.

Table 1 – **Dependence of mathematical model (B) coefficients on the fuel level in tank**

Coefficient / Fuel level	$a_{\psi y}, m^{-1}s^{-2}$	$a''_{\psi y}, m^{-1}$	ω_1, Hz	ε_1, s^{-1}
0,15 m	0,021	0,0024	0,2	0,00318
0,5 m	0,045	0,0069	0,42	0,0067
0,75 m	0,056	0,0100	0,5	0,0080

The stability areas of closed digital single-circuit VSC of vehicle for specified values of mathematical model (6) parameters for the 3 considered cases are shown in Fig. 1 with the following designations:

1 – the lower boundary of the stability area part for the case with “solidified” fuel;

2 – the lower boundary of the stability area part for the case with the height of the free surface of fuel $h = 0,15m$ and speed $\upsilon = 18 m \times s^{-1}$;

3 – the lower boundary of the stability area part for the case with $h = 0,15m$ and $\upsilon = 12 m \times s^{-1}$;

4 – the lower boundary of the stability area part for the case with $h = 0,15m$ and $\upsilon = 6 m \times s^{-1}$;

5 – the lower boundary of the stability area part for the case with $h = 0,5m$ and $\upsilon = 18 m \times s^{-1}$;

6 – the lower boundary of the stability area part for the case with $h = 0,75m$ and $\upsilon = 18 m \times s^{-1}$;

7 – the line is enveloping the lower boundary of the stability area parts of the single-circuit VSC;

8 – the enveloping line of the lower boundary of the stability area parts of the double-circuit VSC;

A, B and C – specific points of the closed VSC stability area:

the closed system is not stable in A point;

the closed system is right on the border of the system stability area in B point;

both single- and double-circuit systems are stable in C point.

Conclusions

The VSC stability area in the low frequency range is significantly decreased by considering oscillations of the liquid free surface in the tank in the mathematical model of perturbed motion.

Decreasing the speed of RV during the breaking process causes increasing RV stability.

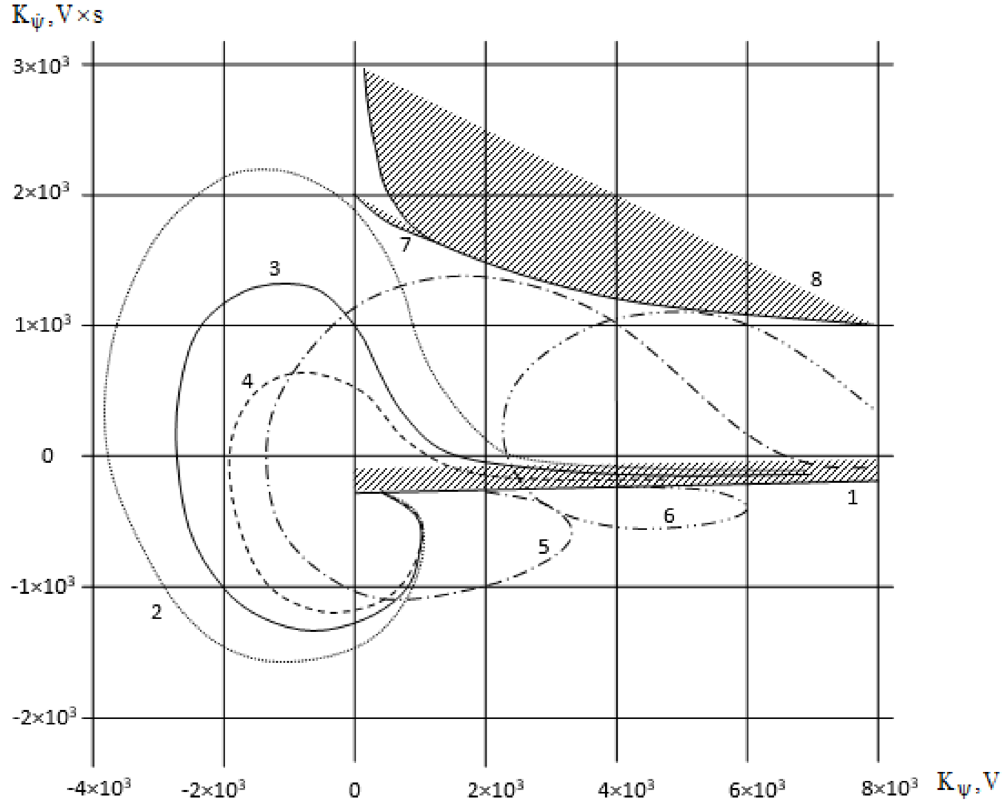

Fig.1. The VSC's stability area boundaries within low frequencies zone 0-1 Hz

Increasing level of loading the tank by fuel causes increasing of natural frequency of the fuel free surface oscillations and decreasing their amplitude.

The envelop loop, that corresponds to different height of fuel free surfaces, asymptotically approaches to the lowest part of the stability area when fuel is "hardened". The envelop loop, that corresponds to different tank loading levels, should be chosen as the lowest boundary of the varied parameters permissible values area of the RV digital VSC controller.

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Про стійкість руху автомобіля – паливозаправника з цифровою системою розподілу гальмівних зусиль в режимі екстреного гальмування

Є. Є. Александров, Т. Є. Александрова, Я. Ю. Моргун

Анотація. Розглядається вплив вимушених коливань вільної поверхні палива в цистерні автомобіля-паливозаправника на область стійкості замкненої цифрової системи розподілу гальмівних зусиль. Об'єктом дослідження являється процес стабілізованого руху автомобіля-паливозаправника в режимі термінового (екстреного) гальмування. Предметом дослідження являється великогабаритний автомобіль-паливозаправник повною масою (3-3,5)*10^4 кг, оснащений цистерною об'ємом (17-20) м^3 та системою курсової стійкості. Метою роботи є дослідження впливу коливань транспортуємого палива на стійкість руху автомобіля-паливозаправника в режимі термінового(екстреного) гальмування і запровадження методики вибору значень варійованих параметрів електронної системи розподілу гальмівних зусиль для його мінімізації. Висновки. Урахування коливань вільної поверхні рідини в математичній моделі збуреного руху замкненої системи курсової стійкості значно зменшує область стійкості системи в діапазоні низьких частот за рахунок петлі, розмір і положення якої залежать від рівня заповнення цистерни у якості нижньої межі області стійкості замкненої системи курсової стійкості автомобіля-паливозаправника слід обирати огинаючу петлю, що відповідає різним рівням заповнення цистерн.

Ключові слова: автомобіль-паливозаправник; система розподілу гальмівних зусиль; область стійкості; варійовані параметри системи.

Об устойчивости движения автомобиля – топливозаправщика с цифровой системой распределения тормозных усилий в режиме экстренного торможения

Е. Е. Александров, Т. Е. Александрова, Я. Ю. Моргун

Аннотация. Рассматривается влияние вынужденных колебаний свободной поверхности топлива в цистерне автомобиля-топливозаправщика на область устойчивости замкнутой цифровой системы распределения тормозных усилий. **Объектом исследования** является процесс стабилизированного движения автомобиля-топливозаправщика в режиме срочного (экстренного) торможение. **Предметом исследования** является крупногабаритный автомобиль-топливозаправщик массой (3-3,5) * 10^4 кг, оснащен цистерной объемом (17-20) м^3 и системой курсовой устойчивости. **Целью работы** является исследование влияния колебаний транспортируемой топлива на устойчивость движения автомобиля-топливозаправщика в режиме срочного (экстренного) торможение и внедрение методики выбора значений варьируемых параметров электронной системы распределения тормозных усилий для его минимизации. **Выводы.** Учет колебаний свободной поверхности жидкости в математической модели возмущенного движения замкнутой системы курсовой устойчивости значительно уменьшает область устойчивости системы в диапазоне низких частот за счет петли, размер и положение которой зависит от уровня заполнения цистерны в качестве нижней границы области устойчивости замкнутой системы курсовой устойчивости автомобиля-топливозаправщика следует выбирать огибающую петлю, соответствующую различным уровням заполнения цистерн.

Ключевые слова: автомобиль-топливозаправщик; система распределения тормозных усилий; область устойчивости; варьируемые параметры системы.