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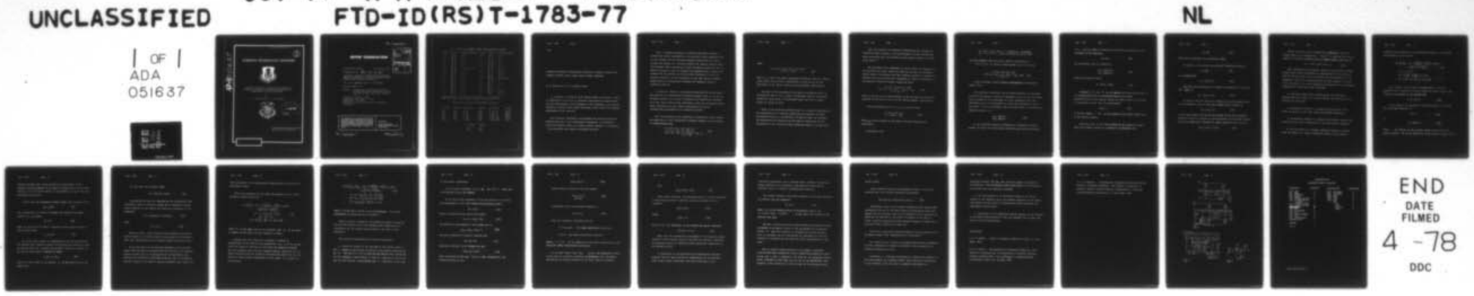

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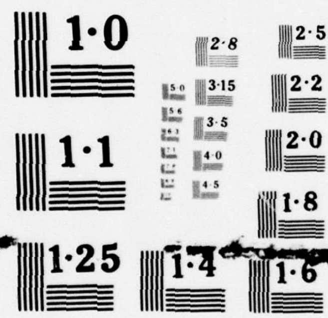

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AIR FORCE SYSTEMS COMMAND

INVARIANT AUTOMATIC STABILIZATION SYSTEM OF
A VERTICAL TAKEOFF AND LANDING AIRCRAFT (VTOL)
UNDER STEADY FLIGHT CONDITIONS

by

R. M. Maresh and V. T. Vigovskiy

FOREIGN TECHNOLOGY DIVISION

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EDITED TRANSLATION

FTD-ID(RS)T-1783-77 19 October 1977

MICROFICHE NR: FTD-77-C-001327

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By: R. M. Maresh and V. T. Vigovskiy

English pages: 21

Source: Primeneniye Invariantnykh Sistem Avtomaticheskogo Upravleniya, Izd-vo "Nauka", Moscow, 1970, pp. 168-176.

Country of origin: USSR
Translated by: Carol S. Nack
Requester: FTD/PDRS
Approved for public release; distribution unlimited.

PREPARED BY:

TRANSLATION DIVISION
FOREIGN TECHNOLOGY DIVISION
WP-AFB, OHIO.

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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*<u>ye</u> initially, after vowels, and after ъ, ь; <u>e</u> elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

1783

INVARIANT AUTOMATIC STABILIZATION SYSTEM OF A VERTICAL TAKEOFF AND LANDING AIRCRAFT (VTOL) UNDER STEADY FLIGHT CONDITIONS

R. M. Maresh and V. T. Vigovskiy (Kiev)

1. Statement of problem. Under steady flight conditions, a VTOL is subjected to the action of different disturbances connected both with the heterogeneity and turbulence of the atmosphere, and with the operations realized under these conditions, which affect the inherent performance of the aircraft.

Both external atmospheric disturbances and inherent parametric disturbances lead to the simultaneous origination of disturbing forces and moments. There is a single control assembly - the elevator - for countering this effect in ordinary aircraft.

Thus, it becomes necessary to install additional automatic systems and control assemblies on the aircraft. These assemblies can be lift engines and jet surfaces designed specifically for use in takeoff and landing on a vertical takeoff and landing aircraft with a lift assembly (PSU) consisting of many low-power engines and jet or reactive controls. Below we consider the possibilities of using lift engines and jet controls in steady flight conditions in order to provide invariance of the coordinates of the VTOL during automatic stabilization of longitudinal movement and different types of disturbing effects.

2. Invariant system of longitudinal stabilization during gusts. The equations of longitudinal disturbed movement given in [1] for an ordinary aircraft can be used to describe the longitudinal movement of a VTOL under steady flight conditions, since its performance under these conditions can only differ quantitatively from the corresponding performance of an ordinary aircraft.

With this assumption and conditions of horizontal cruise flight, the equations for the longitudinal disturbed movement are as follows, in dimensionless form:

$$\begin{gathered}(p+n_{11})V+n_{12}\alpha+n_{13}\vartheta=n_p\delta_p+f_1;\\ -n_{21}V+(p+n_{22})\alpha-(p+n_{23})\vartheta=f_2;\\ n_{31}V+(n_0p+n_{32})\alpha+(p^2+n_{33}p)\vartheta=-n_{\text{в}}\delta_{\text{в}}+f_3;\\ \alpha=\vartheta-ph,\end{gathered} \tag{2.1}$$

where

$$f_1 = p\nu_x;\ \ f_2 = p\nu_y;\ f_3 = -m_z^{\nu_y}\nu_y;\ \ \nu_x = U_x / V_0;$$
$$\nu_y = U_y / V_0;\ \ p \equiv d/dt. \qquad (2.2)$$

Here V, α, θ and h are small increases in velocity, angle of attack, pitch angle, and altitude, respectively, and n_P and n_B are the efficiency of the thrust control and the elevator, respectively.

The rest of the designations are used in accordance with [1]. Disturbances type f_1 and f_2 lead to deviations from the horizontal trajectory, while type f_3 disturbances cause the VTOL to rotate around the center of mass.

Based on the stability condition and B. N. Petrov's criterion of the realizability of invariant conditions for balancing the wind disturbances acting on the aircraft, we need at least two channels for propagating the effects from the point of application of the disturbance to the coordinate whose invariance must be provided [2].

With the condition of automatic stabilization of airspeed and relatively small changes in the ground speed, the main coordinates whose invariance must be provided are the flight altitude h and the pitch angle θ.

The horizontal gust components u_x do not affect the dynamics of the aircraft very much, especially when the aircraft has automatic thrust control. This means that when studying dynamics it suffices to consider only the vertical gust components u_y. Here the equations of longitudinal disturbed movement assume the form:

$$\begin{gathered}(p+n_{22})\alpha-(p+n_{23})\vartheta=f_2+n_c\delta_c;\\ (n_0p+n_{32})\alpha+(p^2+n_{33}p)\vartheta=-n_B\delta_B+f_3+m_c\delta_c;\\ \alpha-\vartheta+ph=0,\end{gathered}\qquad(2.3)$$

where n_c and m_c are the effectiveness of the jet surfaces during the creation of the control force and the control moment, respectively.

From relationships (2.2) at $V_0 \gg u_y$ we will find:

$$\begin{gathered}f_2=pv_y=pu_y/V_0=p\alpha_B;\\ f_3=-m_z^{v}v_{\dot{y}}=-m_z^{\alpha}\alpha_B,\end{gathered}\qquad(2.4)$$

where α_B is the increase in the angle of attack caused by the disturbance.

Considering that

$$n_{22} = 0{,}5\,(c_y^{\alpha} - c_x'); \; n_{23} = 0{,}5c_x'; \; n_0 = -Vb_A m_z^{\dot{\alpha}}/2r_z^2; \; n_{32} = -b_A m m_z^{\alpha}/2r_z^2\rho S;$$
$$n_{33} = -Vb_A m_z^{\omega_z}/2r_z^2; \; n_{\text{в}} = -\mu m_z^{\delta_{\text{в}}}; \; \mu = b_A m/2r_z^2\rho S; \; n_{\text{стр}} = C_y^{\delta_{\text{c}}}; \; m_{\text{c}} = m_z^{\delta_{\text{c}}};$$

and also assuming that the ground speed is stabilized and $m_z^{\dot{\alpha}} = C_x' = C_x = 0$, we will reduce system (2.3) to the form

$$\begin{aligned} &(p + C_y^{\alpha})\,\theta - C_y^{\alpha}\vartheta = C_y^{\alpha}\alpha_{\text{в}} - C_y^{\delta_{\text{c}}}\delta_{\text{c}}; \\ &-m_z^{\alpha}\theta + (p^2 + m_z^{\omega_z}p + m_z^{\alpha})\,\vartheta - m_z^{\delta_{\text{в}}}\delta_{\text{в}} = -m_z^{\alpha}\alpha_{\text{в}} + m_z^{\delta_{\text{c}}}\delta_{\text{c}}; \\ &\theta - ph = 0. \end{aligned} \qquad (2.5)$$

Figure 1a shows a block diagram corresponding to the control system (2.5).

The invariance conditions can be written directly on the basis of the block diagram or system of equations (2.5). In the first case, they are based on the requirement of total compensation for the disturbance α_B by the deflection δ_C of the jet distributor, and in the second - on the requirement that the right sides of the first two equations vanish, i.e.,

$$\begin{aligned} &m_z^{\alpha}\alpha_{\text{в}} - m_z^{\delta_{\text{c}}}\delta_{\text{c}} \equiv 0; \\ &C_y^{\alpha}\alpha_{\text{в}} - C_y^{\delta_{\text{c}}}\delta_{\text{c}} \equiv 0. \end{aligned} \qquad (2.6)$$

If the invariant system is designed as a combination control system, the angle of attack sensor must have high enough precision.

i.e., $\alpha_B^1 \approx \alpha_{\text{nom}}$. Then the deflection of the jet distributor can be expressed by the dependence

$$\delta_c = K_\alpha \alpha_B, \tag{2.7}$$

and conditions (2.6) are written as

$$\begin{aligned} m_z^\alpha \alpha_B - m_z^{\delta_c} K_\alpha \alpha_B \equiv 0; \\ C_y^\alpha \alpha_B - C_y^{\delta_c} K_\alpha \alpha_B \equiv 0, \end{aligned} \tag{2.8}$$

whence the transfer number

$$K_\alpha = m_z^\alpha / m_z^{\delta_c} = C_y^\alpha / C_y^{\delta_c}. \tag{2.9}$$

Parameters $m_z^{\delta_c}$ and $C_y^{\delta_c}$ do not depend on the characteristics of the incoming flow and are determined only by the energy characteristics of the exhaust nozzles and their thrust arm relative to the center of mass. Here the relationship

$$m_z^{\delta_c} / C_y^{\delta_c} = \bar{l}, \tag{2.10}$$

is obvious, where $\bar{l} = l/b_A$ is the relative total thrust vector arm of the exhaust nozzles.

Condition (2.9) of the realizability of the invariant system using only exhaust nozzles at constant K_α is satisfied when

$$m_z^\alpha = \bar{l}C_y^\alpha, \qquad (2.11)$$

which can be achieved only in specific cases.

In general, if we select the value of K_α from the condition

$$K_\alpha = C_y^\alpha / C_y^{\delta_c}, \qquad (2.12)$$

it is obvious that

$$K_{\alpha_1} = m_z^\alpha / m_z^{\delta_c} \neq K_\alpha. \qquad (2.13)$$

Here the undercompensation of moment is determined by the value Δm_z^α, equal to

$$\Delta m_z^\alpha = m_z^{\delta_c}(K_{\alpha_1} - K_\alpha). \qquad (2.14)$$

In order to use the elevon to eliminate this undercompensation, it is necessary to add an additional signal which is equal to

$$K_{\delta_k}\alpha = \Delta m_z^\alpha \alpha \ / \ m_z^{\delta_B}, \qquad (2.15)$$

in the ideal case to the law of the control of the main automatic pilot, and with the addition of the derivative, the transfer function of the the additional compensation signal generation unit will be:

$$W_{\delta_k}(p) = \Delta m_z^\alpha (1 + Tp) / m_z^{\delta_B}. \qquad (2.16)$$

Figure 1b shows a block diagram of a combination invariant system, where it is assumed that $W_{изм}(p) = 1$, and where the law of control of the main automatic pilot in steady flight conditions is

$$\delta_{в} = -(K_{\vartheta}\vartheta + K_{\dot{\vartheta}}p\vartheta) + K_h(h_з - h). \quad (2.17)$$

When constructing an invariant system in the deviation control system class, direct measurement of the deviation of the angle of attack from the stable value is replaced by the measurement of its components θ and ph in accordance with the last equation in system (2.3). The rest of the block diagram of the system and the invariance realizability conditions remain unchanged.

3. Invariant stabilization system during load discharge. Disturbances which affect the aircraft during load discharge can be divided into two types:

1. Disturbances related to a change in the position of the center of gravity of the load inside the freight compartment.

2. Disturbances related to a change in the flight weight of the aircraft at the time of separation of the load from the aircraft.

If the load moves at a constant velocity inside the aircraft under the effect of a certain mechanical drive, at zero initial conditions the equations of the disturbed movement of an aircraft with automatic pilot will be:

$$
\begin{aligned}
& p^2\alpha + \left[C_y^\alpha \frac{qS}{m_0 V} - (m_z^{\omega_z} + m_z^{\bar{\alpha}}) \frac{qSb_A^2}{J_{z_0} V} \right] p\alpha + C_y^\alpha \frac{qSb_A}{J_{z_0}} [\sigma_H - \Delta\bar{x}_T]\, \alpha = \\
& \qquad = C_{y_0} \frac{qSb_A}{J_{z_0}} \Delta\bar{x}_T + m_z^{\delta_B} \frac{qSb_A}{J_{z_0}} \delta_B; \qquad (3.1) \\
& p\vartheta = p\alpha + \frac{g}{V} \frac{C_y^\alpha}{C_{y_0}} \alpha; \\
& \Delta\bar{x}_T = \frac{V_{\text{гр}}}{p} \frac{C_{\text{гр}}}{G_0 b_A} + \frac{g}{p^2} \frac{G_{\text{гр}}}{G_0 b_A} \left(\alpha - \varphi_0 - \frac{k}{R} i \right), \\
& \Delta n_y = \frac{V}{g} (p\vartheta - p\alpha) = \frac{C_y^\alpha}{C_{y_0}} \alpha, \; \delta_B = K_\vartheta \vartheta + K_{\dot\vartheta} p\vartheta.
\end{aligned}
$$

Fig. 2 shows a block diagram corresponding to system of equations (3.1) (excluding the part inside the dotted lines). When composing the diagram it was assumed that

$$\alpha - \varphi_0 - ki/R \approx 0. \qquad (3.2)$$

In the stage of the movement of the load inside the aircraft, the invariance condition is

$$\Delta\bar{x}_T = 0 \qquad (3.3)$$

or

$$G_{\text{гр}} - K_x M_T^{\delta_{\text{ст}}} = 0, \qquad (3.4)$$

where $K_x = \Delta\delta_{\text{ст}}/\Delta x_{\text{гр}}$ is the transfer number in the load shift sensor circuit, $\Delta\delta_{\text{ст}}$ is the deflection of the throttle control of the opposing engines, $M_{T}^{\delta_{CT}}$ is the derivative of the moment of the opposing angles according to the angle of deflection of the throttle control, G_0 is the flight weight of the aircraft, and b_A is the mean aerodynamic wing chord.

We will find the necessary transfer number from condition (3.4)

$$K_x = G_{\text{rp}}/M_{T}^{\delta_{CT}} \tag{3.5}$$

and, considering the connection between the value of the thrust vector T and its moment

$$M_T = Tl_{x_T}, \tag{3.6}$$

where l_{x_T} is the arm of vector T relative to the initial center of mass, we will have:

$$K_x = G_{\text{rp}}/l_{x_T}T^{\delta_{CT}}. \tag{3.7}$$

We can use four engines to compensate for the disturbances for the selected lift assembly diagram, two of which are located in front of, and the other two - behind the aircraft's center of gravity. If the arms of both pairs of engines are equal,

$$T = 2T_1, \quad l_{x_T} = 2l_{x_{T_1}}, \tag{3.8}$$

where T_1 is the thrust of one engine; $l_{x_{T_1}}$ is the thrust arm of one engine pair.

In this case, the transfer number

$$K_x = G_{rp}/4l_{x_{T_1}}T_1^{\delta_{cr}} = K_T/T_1^{\delta_{cr}}. \qquad (3.9)$$

Considering the need for compensating for disturbances when discharging loads of different weight and at different aircraft flight weights, we can control the value of K_x according to the expression

$$K_{\bar{x}} = G_{rp}/4G_0b_A l_{x_{T_1}}T_1^{\delta_{cr}} = K_{T_1}/4b_A l_{x_{T_1}}T_1^{\delta_{cr}}, \qquad (3.10)$$

where

$$K_{T_1} = G_{rp}/G_0. \qquad (3.11)$$

Figure 2 shows a block diagram of the invariant combination control system in the first stage of the process of discharging a load, with consideration of the portion inside the dotted lines.

The second stage of the disturbed movement of the aircraft begins when the load is separated from the aircraft. The automatic control system's job is to compensate for the disturbance and maintain the aircraft's flight mode while the load is discharged. Here the values of the angle of attack, overload, pitch angle, and other parameters in the transitional process should not exceed the permissible limits.

After the separation of the load, the equations of the "VTOL - automatic pilot" system are:

$$\begin{gathered}
p^2\alpha + \left[C_y^\alpha \frac{qS}{m_{б.г}V} - (m_z^{\bar{\omega}_z} + m_z^{\bar{\dot{\alpha}}}) \frac{qSb_A^2}{J_{zб.г}V}\right] p\alpha + C_y^\alpha \frac{qSb_A}{J_{zб.г}} [\sigma_н - \Delta\overline{X}_т]\alpha = \\
= C_{y_0} \frac{qSb_A}{J_{zб.г}} \Delta\overline{X}_т + m_z^{\delta_в} \frac{qSb_A}{J_{zб.г}} \delta_в; \\
p\vartheta - p\alpha + \frac{g}{V}\left(\frac{G_0}{G_{б.г}} \frac{C_y^\alpha}{C_{y_0}}\alpha + \frac{G_{гр}}{G_{б.г}}\right); \qquad (3.12) \\
\Delta\overline{X}_т = \overline{X}_{т\,б.г} - \overline{X}_{т0}; \\
\Delta n_y = \frac{G_0}{G_{б.г}} \frac{C_y^\alpha}{C_{y_0}}\alpha + \frac{G_{гр}}{G_{б.г}}, \quad \delta_в = K_\vartheta \vartheta + K_{\dot{\vartheta}} p\vartheta
\end{gathered}$$

where $m_{б.г}$ is the empty mass of the aircraft; and $J_{zб.г}$ is the moment of inertia of the empty aircraft relative to axis z.

Assuming that the change in the moment of inertia is insignificant at the time of load separation, i.e., $J_{zб.г} \approx J_{z0}$, we can write the system of equations of the invariant system as follows, with the condition that the lift assembly engines compensate for the moment resulting from the change in the centering moment and that the thrust of these engines compensates for the change in the weight of the aircraft:

$$p^2\alpha + \left[C_y^{\alpha} \frac{qS}{(m_{б.\,г} + T_{\Sigma}/g)V} - (m_z^{\bar{\omega}_z} + m_z^{\bar{\alpha}}) \frac{qSb_{\text{A}}^2}{J_{z_0} V} \right] p\alpha + C_y^{\alpha} \frac{qSb_{\text{A}}}{J_{z_0}} (\sigma_{\text{н}} - \Delta \overline{X}_{\text{т}})\alpha =$$

$$= C_{y_0} \frac{qSb_{\text{A}}}{J_{z_0}} \Delta \overline{X}_{\text{т}} + m_z^{\delta_{\text{в}}} \frac{qSb_{\text{A}}}{J_{z_0}} \delta_{\text{в}}; \tag{3.13}$$

$$p\vartheta = p\alpha + \frac{g}{V} \left(\frac{G_0}{G_{б.\,г} + T_{\Sigma}} \cdot \frac{C_y^{\alpha}}{C_{y_0}} \alpha + \frac{G_{г.\,р} - T_{\Sigma}}{G_{б.\,г} + T_{\Sigma}} \right);$$

$$\Delta \overline{X}_{\text{т}} = \overline{X}_{\text{т}б.\,г} - \overline{X}_{\text{т}_0} + \overline{X}_{\text{т}_{T_\Sigma}}, \quad \delta_{\text{в}} = K_{\vartheta}\vartheta + K_{\dot{\vartheta}} p\vartheta;$$

$$\Delta n_y = \frac{G_0}{G_{б.\,г} + T_{\Sigma}} \frac{C_y^{\alpha}}{C_{y_0}} \alpha + \frac{G_{гр} - T_{\Sigma}}{G_{б.\,г}}, \quad T_{\Sigma} = G_{гр},$$

where T_{Σ} is the total thrust of the lift engines; $\overline{X}_{\text{т}_{T_\Sigma}}$ is the displacement of centering due to vector T_{Σ}.

Figure 3 shows a diagram of the forces and moments created by the load and engines of the lift assembly when compensating for disturbances by the reverse thrust method at the time of load separation.

The following designations are used in the diagram:

a - center of gravity of the aircraft in the initial state, c and d - points of application of thrust of the opposing engines; $2T_{\text{н}}$ and $2T_{\text{х}}$ - the thrust of the two nose and and the two feed engines of the lift assembly, respectively; $lx_{\text{н}}$ and $lx_{\text{х}}$ - the thrust arm of the nose and feed engines, respectively; and $x_{\text{гр}}$ - the shift in the load in the freight compartment.

In the initial position, $x_{\text{гр}} = 0$ and $2T_{\text{н}} = 2T_{\text{х}} = 0$. There are no disturbing forces and moments.

In the first stage (movement of the load inside the aircraft), the displacement of the load creates the disturbing moment

$$M_{\text{в}_1} = x_{\text{гр}} G_{\text{гр}}, \quad (3.14)$$

which is balanced by the sum of the moments

$$M_{\text{н}} + M_{\text{х}} = 2T_{\text{н}} l_{x_{\text{н}}} + 2T_{\text{х}} l_{x_{\text{х}}}. \quad (3.15)$$

The equation of the moments of the system will be

$$2T_{\text{н}} l_{x_{\text{н}}} + 2T_{\text{х}} l_{x_{\text{х}}} - G_{\text{гр}} x_{\text{гр}} = 0. \quad (3.16)$$

The force equilibrium condition requires that

$$2T_{\text{н}} = 2T_{\text{х}} = 2T, \quad (3.17)$$

whereupon condition (3.16) assumes the form

$$2T (l_{x_{\text{н}}} + l_{x_{\text{х}}}) = G_{\text{гр}} x_{\text{гр}}. \quad (3.18)$$

After separation of the load $G_{\text{гр}} x_{\text{гр}} = 0$, and, consequently, the following should be true

$$2T(l_{x_н} + l_{x_х}) = 0. \quad (3.19)$$

During thrust reversal of the tail engines

$$\begin{gathered} 2T(l_{x_н} + l_{x_х}) = 0, \\ 4T = G_{гр}. \end{gathered} \quad (3.20)$$

Conditions (3.20) are satisfied jointly, if

$$l_{x_н} = l_{x_х} = l_x. \quad (3.21)$$

Then the invariance conditions will be

$T = G_{гр} x_{гр.\,макс} / 4 l_x$ - the moment equilibrium condition,

$T = G_{гр}/4$ - the force equilibrium condition.

Whence $l_x = x_{гр.макс}$ is the condition of the joint satisfaction of the force and moment equilibrium requirements

In the more common case, when $l_{x_н} \neq l_{x_х}$, the inequality $T_н \neq T_х$ occurs when the balancing condition is satisfied, i.e., the force equilibrium is already disturbed in the first stage of movement.

Here

$$2T_{\text{н}}l_{x_{\text{н}}} + 2T_{\text{х}}l_{x_{\text{х}}} = G_{\text{гр}}x_{\text{гр}}. \qquad (3.22)$$

After thrust reversal, the equivalent force T_{Σ} should be applied in the original center of gravity, which is possible with the condition

$$2l_{x_{\text{н}}}T_{\text{н}} = 2l_{x_{\text{х}}}T_{\text{х}}, \qquad (3.23)$$

whence

$$l_{x_{\text{н}}}T_{\text{н}}/l_{x_{\text{х}}} = T_{\text{х}}. \qquad (3.24)$$

But $2T_{\text{х}} + 2T_{\text{н}} = G_{\text{гр}}$; therefore, we will obtain the second condition:

$$2T_{\text{н}}(l_{x_{\text{н}}}/l_{x_{\text{х}}} + 1) = G_{\text{гр}}. \qquad (3.25)$$

Thus, with the asymmetrical arrangement of the opposing engines relative to the original center of gravity, the absolute invariance of the system cannot be achieved without additional connections in the automatic pilot.

4. Limitations on the possibility of constructing invariant systems. With the above methods of compensating for disturbances under stable flight conditions, the total invariance of the

controlled coordinates can be achieved when a number of design and energy conditions are satisfied, along with the conditions of stability and B. N. Petrov's realizability criterion.

The system's absolute invariance relative to wind gusts can only be provided with the condition

$$4R_{\text{с.м}} \geqslant \Delta Y, \tag{4.1}$$

where $R_{\text{с.м}}$ is the maximum thrust of the exhaust nozzle, and $\Delta Y = C_y S\rho(\overline{V}_0 + \overline{U}_y)^2/2 \quad - C_{y_0} S\rho V]_0^2/2$ - is the added lift created by the vertical wind gust.

The main contradiction which arises during the selection of the parameters of an exhaust nozzle is the requirement for decreasing thrust $R_{\text{с.м}}$ with the condition of reducing the working gas flow rate, on one hand, and the requirement for increasing it with the condition of compensating for high-level wind disturbances, on the other.

When an exhaust nozzle operates in the angular coordinate stabilization mode, sufficient control moments are provided by large thrust arms l_x and l_z; therefore, the value of $R_{\text{с.м}}$ determined during normal operation in this mode can turn out to be insufficient when operating under conditions of compensating for disturbances during steady flight.

Total invariance during the discharge of loads is also only achieved when the following condition is satisfied

$$4T_{\text{макс}} \geqslant G_{\text{гр. макс}}, \quad 4T_{\text{макс}} l_x \geqslant G_{\text{гр. макс}} X_{\text{гр. макс}}. \qquad (4.2)$$

Furthermore, there is one general limitation which appears when compensating for any of the above types of disturbances using lift engines and jet surfaces. This is the limitation of the precision of measuring the position of the center of gravity of the VTOL in flight. Centering determined before takeoff changes in flight due to burn-up of fuel, shifting of loads, etc.

The error in measuring centering leads to the origination of an off-balance moment when compensating for disturbances.

As a result of all of this, the theoretically proven possibility of total invariance is reduced in practice to the possibility of achieving invariance up to ε.

Conclusion. 1. Providing invariance of a system with respect to wind disturbances can achieved without using additional connections in the automatic pilot only when a constant relationship is maintained between $C_y^{\delta_{\text{стр}}}$ and $m_z^{\delta_{\text{стр}}}$, and with respect to parametric disturbances - when satisfying strict requirements on the design of the aircraft and its operating conditions.

2. The introduction of an additional signal in the law of control of the automatic pilot can provide invariance of the system with respect to both types of disturbances without observing the requirements stated above.

3. Invariance in the combination system category can be achieved if the power characteristics of the lift assembly do not limit the level of active disturbances.

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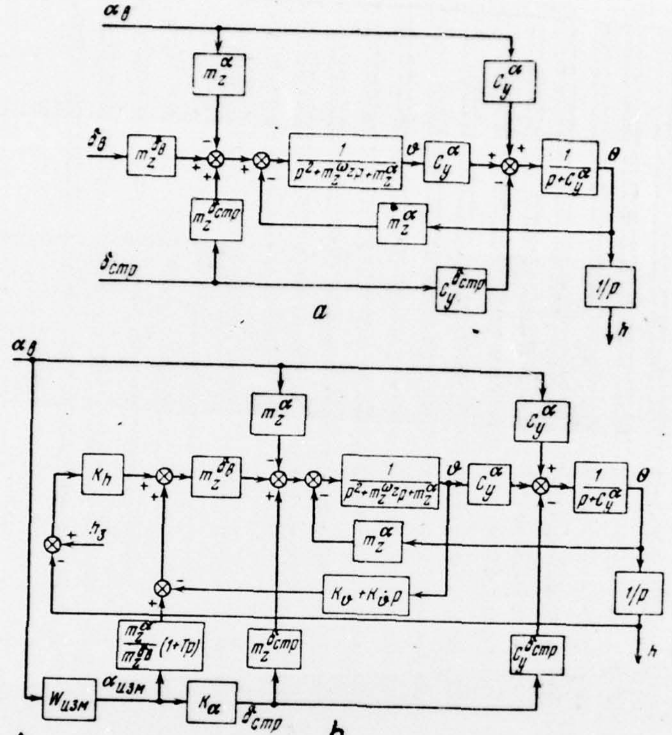

Fig. 1.

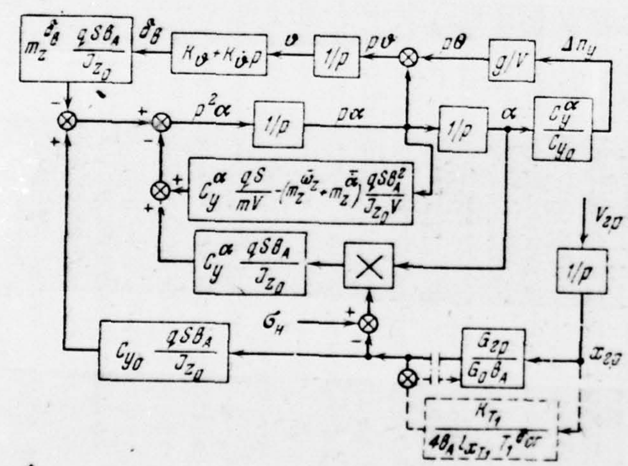

Fig. 2.

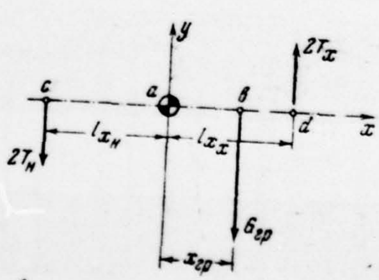

Fig. 3.

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