Ministry of Education and Science of Ukraine
National Aviation University

AEROHYDROGASDYNAMICS AND FLIGHT DYNAMICS
PART II. A: FLIGHT DYNAMICS

SELF-STUDY METHOD GUIDE

Part II. A

FLIGHT DYNAMICS
Trajectory Problems. A
for the Students of the
Field of Study 27 “Transport”,
Specialty 272 “Aviation Transport”

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Містять декілька рекомендацій для самостійної роботи, щодо виконання розрахунково-графічної роботи з дисципліни «Аерогідрогазодинаміка та динаміка польоту», в Частині ІІ. А, що стосується розділу «Динаміка польоту» при розв’язанні траєкторних задач повітряного судна.

Для студентів 3-го курсу галузі знань 27 «Транспорт», спеціальності 272 «Авіаційний транспорт».

A992 **Aerohydrogasdynamics and Flight Dynamics. Part II. A : Flight Dynamics** : Self-Study Method Guide . Part II. A . Flight Dynamics . Trajectory Problems. A / compiler: A. V. Goncharenko. – K. : NAU, 2020. – 66 p.

The **METHOD GUIDE** contains a few recommendations on the Self-Study in regards with the completion of the Calculation and Graphic Work on the academic subject of “Aerohydrogasdynamics and Flight Dynamics”, in Part II. A, concerning the section of “Flight Dynamics” at solving the aircraft trajectory problems.

Designed for the 3rd year students of the Field of Study 27 “Transport”, Specialty 272 “Aviation Transport”.

CONTENTS

INTRODUCTION

This **METHOD GUIDE ON THE SELF-STUDY** (SS) is contemplated in response to the needs of our students in more detailed elaborations concerning problems stated, set or given for the students' independent work on this subject for the specified **CALCULATION AND GRAPHIC WORK** (CGW), possibly used in their **TERM PAPERING** (TP), **COURSE PROJECTING** (CP), further **GRADUATION PAPERS** or even **PH.D. STUDIES.** The whole material is split into portions. Each portion is intended to cover a fraction of probable applications aimed at **AERO-HYDRO-GAS-DYNAMICS AND FLIGHT DYNAMICS** or their adjacent problems.

The presented in this, **Second Part. A, PART II. A** of the **METHOD GUIDE ON the SS** problems are dedicated, and a special attention is drawn here, to the scientific component of the SS work. Specifically, the objectives of the **PART II. A** are to help students cope with the challenging problems relating to the **AIRCRAFT** (A/C) **TRAJECTORY (PATH) PROBLEMS** (T(P)/P) in regards with the A/C and its elements **AERODYNAMIC CHARACTERISTIC** (AC) determined in accordance with the **First Part, PART I,** of the **METHOD GUIDE** on the SS in the framework of the **MATERIAL PARTICLE MOTION THEORY.**

The set of the considered problems is based upon the **ACADEMIC SUBJECT PROGRAM** on **"AEROHYDROGASDYNAMICS AND FLIGHT DYNAMICS"**, as well as upon the **RECOMMENDED LITERATURE SOURCES** (the list is presented, but not limited to it). The **LIST OF LITERATURE** at the end of the **METHOD GUIDE** is basic (major) and compiled partially in the alphabetic order with respect to the matter of the supposed (assumed) importance.

The **REFERENCE LIST** is selected, set in the order [1-212], does not pretend for completeness, but instead it is aimed at developing the students' abilities of thinking and to analyze, contemplate in the specified directory field rather than their abilities to know and memorize. However, these are very significant too. Actually, in the contemporary informative boom world, the needed or required data can easily be retrieved from the internet, found in multiple references, studies, guidance materials [1-17], dictionaries [10], comprehensive books [11] or monographs etc. The **METHOD GUIDE** is designed for the 3rd year students of the Field of Study: 27 "Transport", Specialty: 272

"Aviation Transport". It includes detailed solutions for several (some, a few) examples of the A/C P/P.

It is proposed to select the **VARIANTS** for the CGW, as well as for TP or CP completion in accordance with the recommendations of [12, 18, 19]:

1. If the last figure of the number of the **STUDENT'S CREDIT BOOK** is "5" and more, then it is the A/C with the **TURBOJET ENGINE** that must be taking for consideration.
2. If the last figure of the number of the **STUDENT'S CREDIT BOOK** is less than "5", then it is the A/C with the **TURBOPROP ENGINE** that must be taking for consideration.
3. The **VARIANT** itself is selected by the last figure of the number of the **STUDENT'S CREDIT BOOK.**
4. For the **WING** calculation it is also by the last figure of the number of the **STUDENT'S CREDIT BOOK.**
5. For the **WING MECHANIZATION** calculation it is by the third from the end figure of the number of the **STUDENT'S CREDIT BOOK.**

In fact, the presented **PART II. A** of the **METHOD GUIDE** on the SS is a development of the **PART I**, of which results are the initial data for the problems considered (set, formulated, stated) herewith.

I. START & ACCELERATION DOWN THE RUNWAY BEFORE TAKEOFF

The principal theoretical provisions can be found out in references [1-17].

In assumption that **AIRCRAFT** is an **ABSOLUTELY RIGID BODY**, with the **CONSTANT MASS**, the **DIFFERENTIAL EQUATIONS** of the **AIRCRAFT MOTION** in the **VECTOR FORM** will be, [2, p. 18, (1.2)]:

$$m\frac{d\vec{V}}{dt}=\vec{F}, \tag{1}$$

$$m\frac{d\vec{K}}{dt}=\vec{M}, \tag{2}$$

where m – the **MASS** of the **AIRCRAFT;** $\vec{V}$ – the **SPEED** of the **AIRCRAFT'S CENTRE OF MASS;** t – **TIME;** $\vec{F}$ – the **MAIN VECTOR OF THE EXTERNAL FORCES;** $\vec{K}$ – the **SUMMARIZED ANGULAR MOMENTUM (KINETIC MOMENT) VECTOR** with respect to the **AIRCRAFT'S CENTRE OF MASS;** $\vec{M}$ – the **MAIN MOMENT OF THE EXTERNAL FORCES** with respect to the **AIRCRAFT'S CENTRE OF MASS.**

§ 1. Parameters essential for the motion evaluation during accelerating down the runway

At the **START** and **ACCELERATION OF AIRCRAFT** for the **TAKEOFF,** the system of (1, 2) (in the idealized assumption of: the **BALANCED AIRCRAFT** motion (therefore, $\vec{K}=\vec{M}=0\big)$; and the **AIRCRAFT** runs **RECTILINEARLY** along the $\boldsymbol{(Ox)}$ **AXIS;** and in the **TRANSLATIONAL WAY;** plus neglecting the **FRICTION** or supposing it to be included into the **THRUST)** will get the view of

$$m\ddot{x}=T-D, \tag{3}$$

$$m\ddot{y} = -mg + L, \tag{4}$$

where:

$$\ddot{x} = \frac{dV_x}{dt} = \frac{d\dot{x}}{dt} = \frac{d^2x}{dt^2} \tag{5}$$

– **HORIZONTAL PROJECTION** of the **ACCELERATION** of the **AIRCRAFT'S CENTRE OF MASS;**

$$V_x = \dot{x} = \frac{dx}{dt} \tag{6}$$

– **HORIZONTAL PROJECTION** of the **SPEED** of the **AIRCRAFT'S CENTRE OF MASS** $\vec{V}$; x – displacement of (distance run by) the **AIRCRAFT'S CENTRE OF MASS** along the **RUNWAY (HORIZONTAL AXIS OF** (Ox)**);**

T – the **AIRCRAFT'S ENGINES THRUST;** D – the **AERODYNAMIC DRAG FORCE:**

$$D = C_x \frac{\rho V^2}{2} S, \tag{7}$$

where C_x – the **AERODYNAMIC DRAG FORCE COEFFICIENT** at the **AIRCRAFT'S ACCELERATION (PRE-TAKEOFF) CONFIGURATION AND CONDITIONS;** ρ – the **DENSITY OF THE AIR** at the **AIRCRAFT'S ACCELERATION CONDITIONS;** S – the **CHARACTERISTIC AREA;**

$$\ddot{y} = \frac{dV_y}{dt} = \frac{d\dot{y}}{dt} = \frac{d^2y}{dt^2} \tag{8}$$

– **VERTICAL PROJECTION** of the **ACCELERATION** of the **AIRCRAFT'S CENTRE OF MASS;**

$$V_y = \dot{y} = \frac{dy}{dt} \tag{9}$$

– **VERTICAL PROJECTION** of the **SPEED** of the **AIRCRAFT'S CENTRE OF MASS** $\vec{V}$; y – displacement of the **AIRCRAFT'S CENTRE OF MASS** perpendicularly to the **RUNWAY (VERTICAL AXIS OF** (Oy)**);**

g – acceleration of the **FORCE OF GRAVITY;** L – the **AERODYNAMIC FORCE OF LIFT:**

$$L = C_y \frac{\rho V^2}{2} S, \tag{10}$$

where C_y – the **AERODYNAMIC LIFT FORCE COEFFICIENT** at the **AIRCRAFT'S ACCELERATION CONFIGURATION AND CONDITIONS.**

§ 2. Determination of the speed when accelerating down the runway

Then, based on (1-10), supposing: the assumed above simplifications about the **HORIZONTAL AIRCRAFT'S CENTRE OF MASS MOTION ALONG THE HORIZONTAL AXIS OF** (Ox), which results in the simplifying equation of $V_x = V$; plus idealizations for the zero **LIFT** and **FRICTION,** or the **FRICTION** being included into the **THRUST;** and the constant **THRUST;** one can write down

$$m\frac{dV_x}{dt} = m\frac{dV}{dt} = T - C_x \frac{\rho V^2}{2} S. \tag{11}$$

In accordance with [7, Volume 1, Chapter X, § 2, p. 318, item # 12], the **ANALYTICAL SOLUTION** to the **DIFFERENTIAL EQUATION** of (11) will be as it follows:

$$\frac{dV}{T - C_x \frac{\rho S}{2} V^2} = \frac{dt}{m}. \qquad \frac{\dfrac{dV}{C_x \frac{\rho S}{2}}}{\dfrac{T}{C_x \frac{\rho S}{2}} - \dfrac{C_x \frac{\rho S}{2}}{C_x \frac{\rho S}{2}} V^2} = \frac{dt}{m}. \tag{12}$$

Deliberately ommited for the perceptional ease formulas of (13-23) lead to

$$V(t) = \dot{x}(t) = \sqrt{\frac{T}{C_x \frac{\rho S}{2}}} \left(\frac{e^{\frac{\sqrt{2C_x \rho S T}}{m} t} - 1}{e^{\frac{\sqrt{2C_x \rho S T}}{m} t} + 1} \right). \tag{24}$$

§ 3. Determination of the distance when accelerating down the runway

The **Distance Run by the Aircraft down the Runway with Respect to Time** can be found from equation (24):

$$\int dx = \sqrt{\frac{T}{C_x \frac{\rho S}{2}}} \int \left(\frac{e^{\frac{\sqrt{2C_x \rho S T}}{m} t} - 1}{e^{\frac{\sqrt{2C_x \rho S T}}{m} t} + 1} \right) dt \, . \tag{25}$$

Deliberately ommited formulas of (26-51) yield

$$x(t) = \frac{m}{C_x \rho S} \left[2 \ln \left(\frac{e^{\frac{\sqrt{2C_x \rho S T}}{m} t} + 1}{2} \right) - \ln \left| - e^{\frac{\sqrt{2C_x \rho S T}}{m} t} \right| \right] . \tag{52}$$

Both, the **Analytical** and **Numerical Solutions** for (1-52) are going to be illustrated down the **Text** in the corresponding **Sections.**

§ 4. Determination of the takeoff speed

For the conventionally **Horizontal Acceleration** before the **Takeoff** of the **Aircraft** down the **Runway**, from the differential equation of (4), one can obtain, through the evident derivation of (53, 54),

$$V = \sqrt{\frac{2mg}{C_y \rho S}} \, . \tag{55}$$

Here, at the approach of (53-55), the **Lift Force Coefficient** value of C_y ought to be taken into account from the **Polar for the Takeoff Aircraft Configuration** found and plotted in the **First Part of the CGW** completed in accordance with the **First Part of the Method Guide** [12, 18, 19]. Moreover, the **Speed** of V obtained from relation of (55) should be ensured in the **Renewed Conditions** due to the **Takeoff Aircraft Re-Configuration,** that is for the corresponding increased C_x value and because of that increased **DRAG FORCE.**

In the presented simplified consideration, since the real **TAKEOFF FROM THE GROUND PERIOD** takes not much time, it is acceptable for the **EDUCATIONAL EASE** to apply the **AIRCRAFT SPEED** just **GRATER** than the **SPEED** of V yielded by the expression of (55).

§ 5. Plotting the diagrams of the aircraft start and acceleration down the runway

Equation (11) can be integrated either numerically or analytically (12-24).

In the case when the accepted data are:

$$T = 500 \cdot 10^3 \text{ N}; \qquad m = 100 \cdot 10^3 \text{ kg}; \qquad \rho = 1.225 \text{ kg/m}^3;$$

$$C_x = 0.02; \qquad S = 200 \text{ m}^2; \tag{56}$$

both results (analytical and numerical) are shown in Fig. 1.

The numerical integration result diagram is designated as $y(t)$: solid red bold curve. The analytical solution by (24) plot is depicted as $V(t)$: dashed cyan curve (see Fig. 1).

The **TAKEOFF SPEED** (see Fig. 1) is represented as $Vtof$: portrayed with the green dashed line; and it equals to 151.24 m/s calculated by formula (55) on the conditions of (56) and

$$C_y = 0.35; \qquad g = 9.807 \text{ m/s}^2; \tag{57}$$

at the **AIRCRAFT'S TAKEOFF CONFIGURATION AND CONDITIONS.**

Integration of the differential equation (4) solution (24), or double integration of the differential equation (4), yields the result represented with the diagram of the run distance illustrated in Fig. 2.

In the demonstrated case, the **TAKEOFF FROM THE GROUND** occurs after the **SPEED** of approximately 160 m/s, which equals 576 km/h, achieved at the **DISTANCE RUN** of 2,500 … 3,000 m, and at the timing of 32 … 35 s (see Fig. 1 and 2).

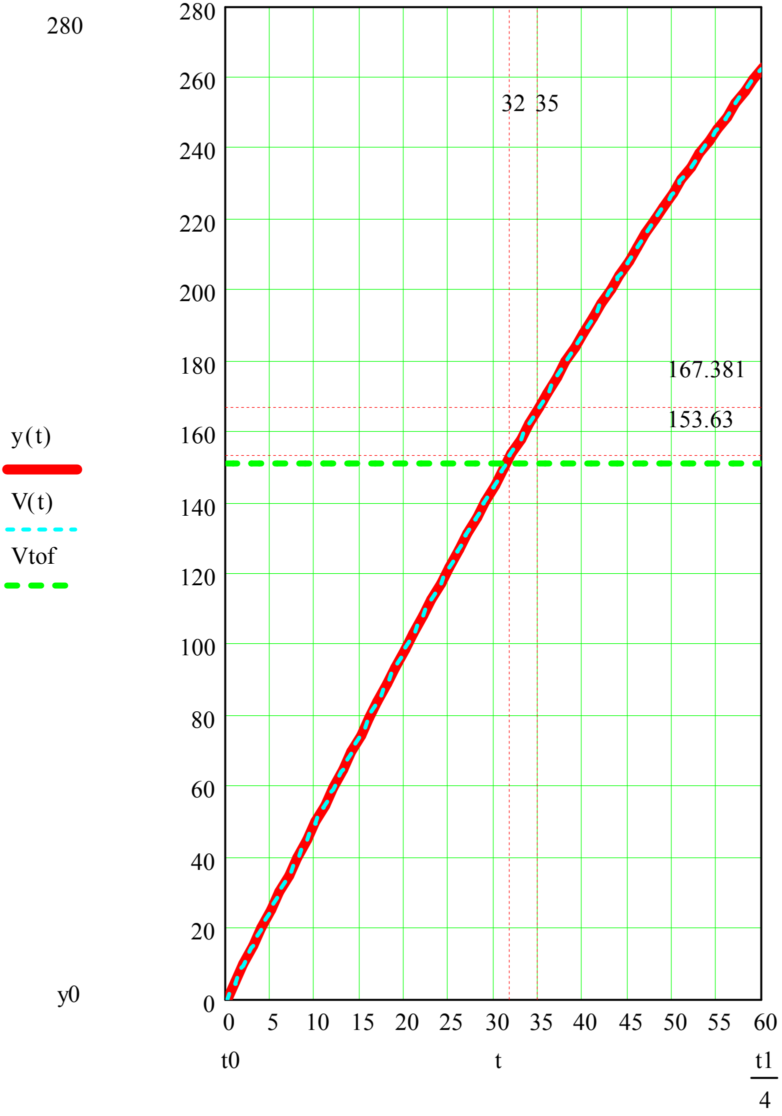

Fig. 1 – The diagram of the **Aircraft’s Speed** at the **Acceleration** down the **Runway** after the **Aircraft’s Start**

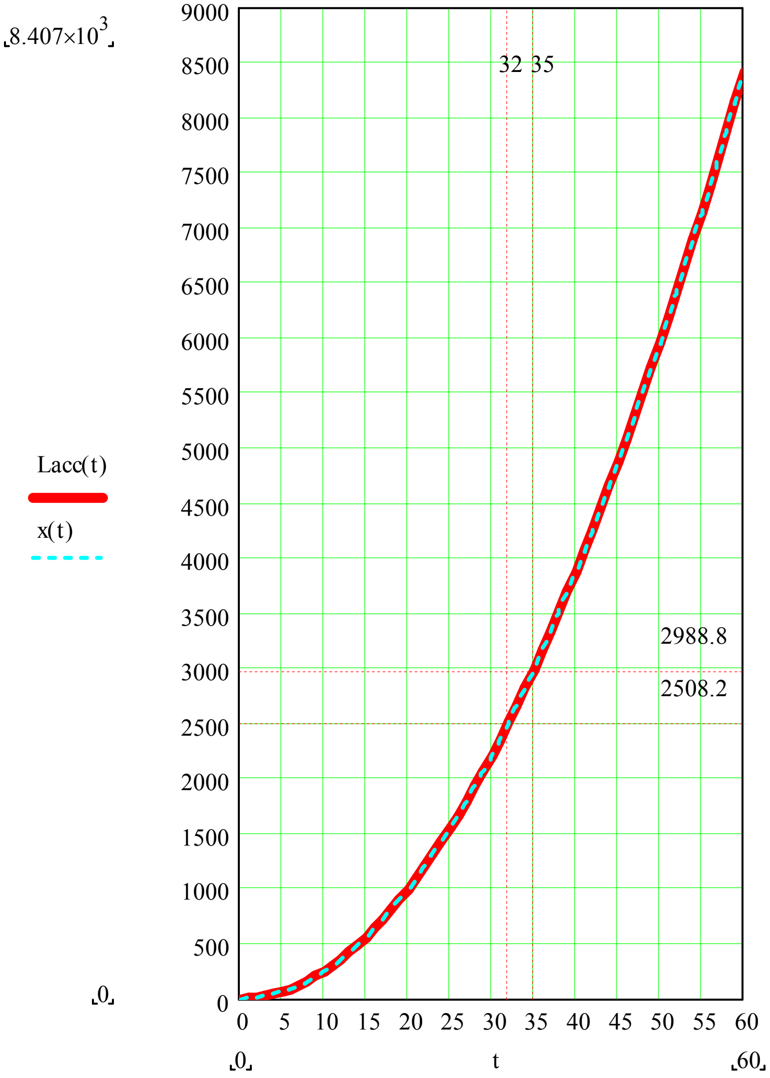

Fig. 2 – The diagram of the **AIRCRAFT'S SPEED** at the **ACCELERATION** down the **RUNWAY** after the **AIRCRAFT'S START**

In Fig. 2, the numerical integration result diagram for the equation of (24) is designated as $\mathrm{Lacc}(t)$: solid red bold curve. The analytical solution plot obtained by the formula of (52) is depicted as $x(t)$: dashed cyan curve (see Fig. 2).

A few seconds later the **TAKEOFF FROM THE GROUND,** the **AIRCRAFT** should have the **RE-CONFIGURATION** for the **CLIMBING MODE.**

II. TAKEOFF

The principal theoretical provisions can be found out in references [1-17].

The results of the previous **CHAPTER** symbolize that at the **SPEED** of approximately 160 m/s, which equals 576 km/h, achieved at the **DISTANCE RUN** of 2,500 … 3,000 m, and at the timing of 32 … 35 s (see Fig. 1 and 2), the **AIRCRAFT** should take the **TAKEOFF CONFIGURATION** and **TAKEOFF FROM THE GROUND.**

This short **STAGE** of the **AIRCRAFT'S FLIGHT** is characterized with a several second **TRANSITION PROCESS** from the **TAKEOFF FROM THE GROUND** to the **CLIMBING AIRCRAFT CONFIGURATION.**

§ 6. Determination of the takeoff equations of motion

After acquiring the **TAKEOFF CONFIGURATION** the **AIRCRAFT'S CENTER OF MASS** motion is not considered to be a **HORIZONTAL** any more (up to the **HORIZONTAL FRAGMENT OF THE FLIGHT).**

Supposedly, the controlling influence is organized in such way that the projections of the main vector of the external forces $\vec{F}$ upon the reference (coordinate) system (xOy) axes: F_x and F_y, depend proportionally upon the corresponding coordinates of the **AIRCRAFT'S CENTER OF MASS:** x and y; and the main vector's of the external forces $\vec{F}$ projections are given with the following equations of

$$F_x = -a(x - X_c), \tag{58}$$

$$F_y = -a(y - Y_c), \tag{59}$$

where a – the proportionality coefficient; X_c and Y_c – the coordinates of the center of the main vector $\vec{F}$ attraction.

A prototypic problem can be found in reference [5, pp. 201, 202, Problem # 26.34].

Then, the differential equations of motion in projections upon the axes of the reference (coordinate) system:

$$m\frac{d^2x}{dt^2} = F_x = -a(x - X_c), \tag{60}$$

$$m\frac{d^2y}{dt^2} = F_y = -a(y - Y_c). \tag{61}$$

Equations of (60, 61), dropping out their detailes of solution (62-90), will result, in accordance with [8, Volume 2, Chapter XIII, §§ 21-24, pp. 74-90], the **ANALYTICAL SOLUTION** to the **DIFFERENTIAL EQUATIONS:**

$$x(t) = V_{tof}\sqrt{\frac{m}{a}}\sin\left(\sqrt{\frac{a}{m}}t\right) + X_c\left[1 - \cos\left(\sqrt{\frac{a}{m}}t\right)\right], \tag{91}$$

$$y(t) = Y_c\left[1 - \cos\left(\sqrt{\frac{a}{m}}t\right)\right]. \tag{92}$$

§ 7. Plotting the diagrams of the takeoff

Implementing the provisions of (1-92) it is possible to visualize the acquired dependencies. The data for the computer simulation are obtained from the previous modeling and calculations (including in the **FIRST PART OF THE CGW** completed in accordance with the **FIRST PART OF THE METHOD GUIDE** [12, 18, 19]) as follows:

$$V_{tof} = 160 \text{ m/s}; \qquad m = 100\cdot 10^3 \text{ kg}; \qquad a = 100 \text{ N/m or } \left(\frac{kg}{s^2}\right);$$

$$X_c = 4000 \text{ m}; \qquad Y_c = 4000 \text{ m}. \tag{93}$$

The results for coordinates are shown in Fig. 3-5.

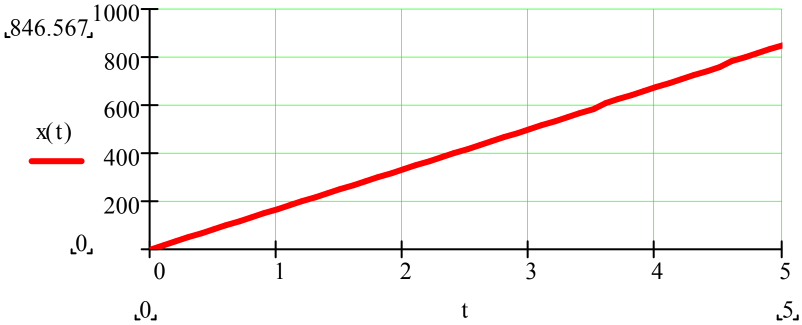

Fig. 3 – The horizontal coordinate diagram of the **AIRCRAFT'S TAKEOFF FROM THE GROUND**

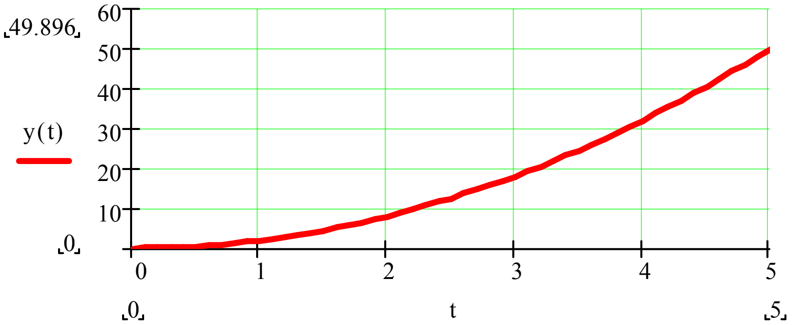

Fig. 4 – The vertical coordinate diagram of the **AIRCRAFT'S TAKEOFF FROM THE GROUND**

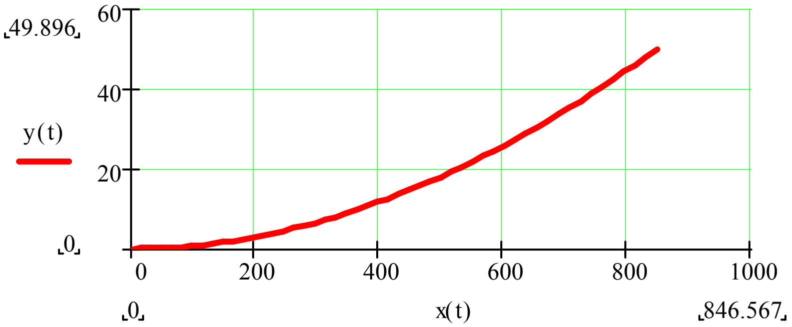

Fig. 5 – The vertical plane trajectory (path) diagram of the **AIRCRAFT'S TAKEOFF FROM THE GROUND**

The **Speed** diagrams are shown in Fig. 6-9.

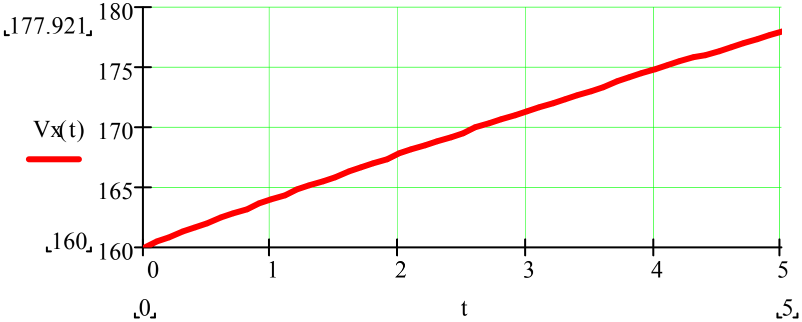

Fig. 6 – The horizontal **Speed** diagram of the **Aircraft's Takeoff from the Ground**

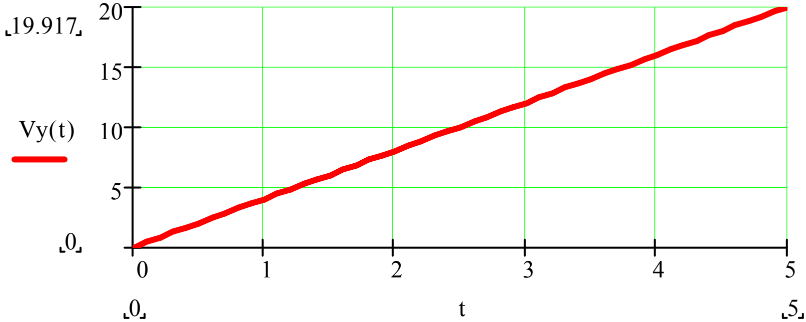

Fig. 7 – The vertical **Speed** diagram of the **Aircraft's Takeoff from the Ground**

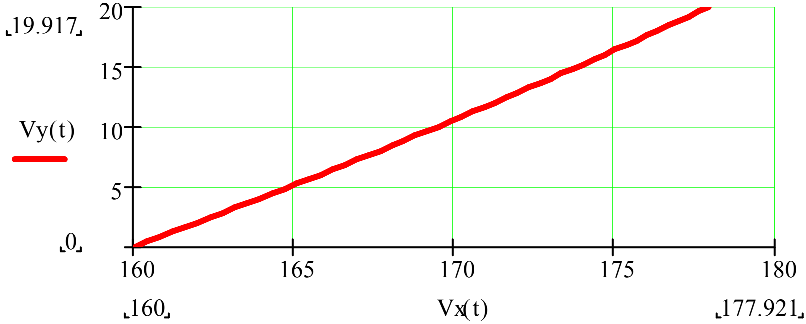

Fig. 8 – The vertical versus horizontal **Speed** diagram of the **Aircraft's Takeoff from the Ground**

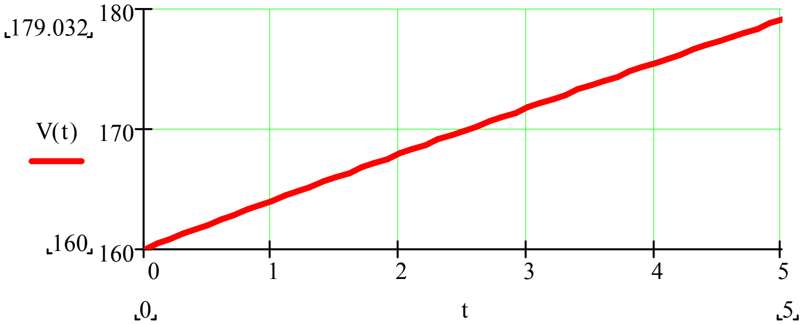

Fig. 9 – The **Speed** diagram of the **Aircraft's Takeoff from the Ground**

The **Acceleration** diagrams are shown in Fig. 10-13.

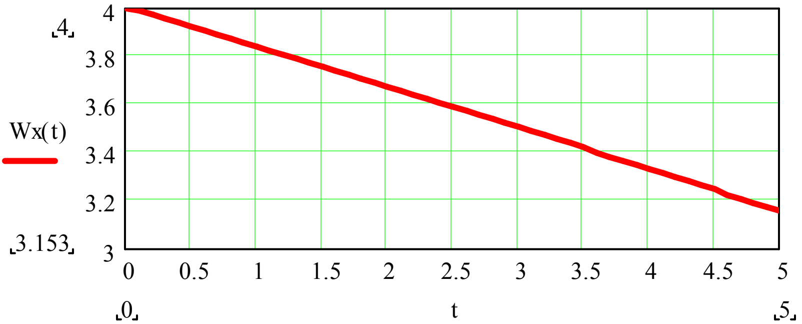

Fig. 10 – The horizontal **Acceleration** diagram of the **Aircraft's Takeoff from the Ground**

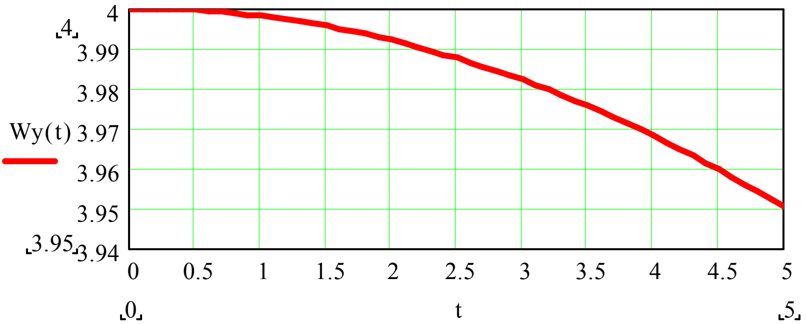

Fig. 11 – The vertical **Acceleration** diagram of the **Aircraft's Takeoff from the Ground**

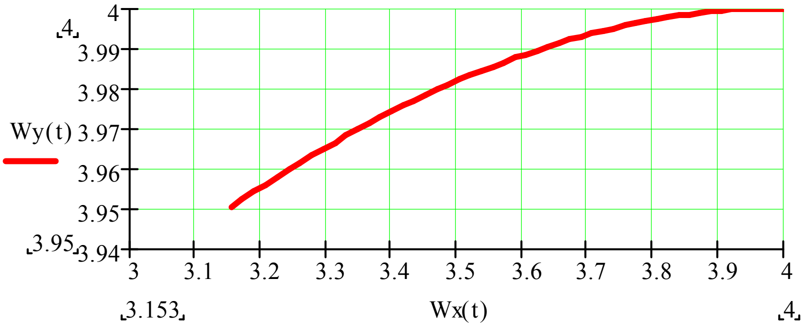

Fig. 12 – The vertical versus horizontal **ACCELERATION** diagram of the **AIRCRAFT'S TAKEOFF FROM THE GROUND**

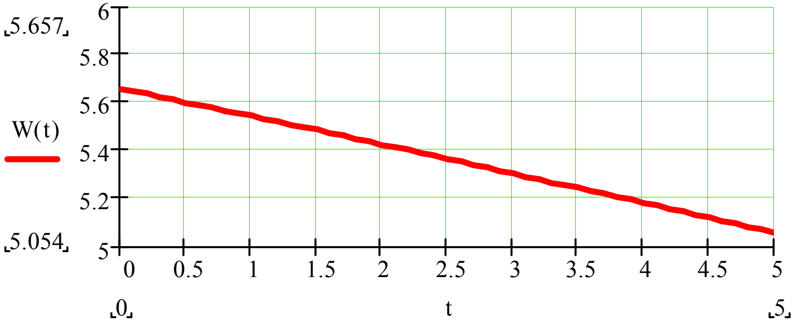

Fig. 13 – The **ACCELERATION** diagram of the **AIRCRAFT'S TAKEOFF FROM THE GROUND**

Determination of the equations expressions for the **AIRCRAFT'S TAKEOFF FROM THE GROUND PATH (TRAJECTORY),** as well as **SPEEDS** and **ACCELERATIONS,** is the task for the students. That is, it is the students' concern, as a portion of the independent extra work. Surely, they will not put too much effort in that. Moreover, we do not anticipate much trouble for them in the computerized calculations and diagrams plotting either.

The total **AIRCRAFT'S TAKEOFF FROM THE GROUND SPEED** (see Fig. 9) and **ACCELERATION** (see Fig. 13) are determined by the obvious formulas following the **PYTHAGOREAN THEOREM.**

The **FORCE** diagrams are simply mass times the **ACCELERATION** ones shown in Fig. 10-13.

Next to the **TAKEOFF** is the **CLIMBING MODE.**

III. CLIMBING

The principal theoretical provisions can be found out in references [1-17].

§ 8. Determination of the climbing equations of motion

The supposed equations of the **AIRCRAFT'S CENTER OF MASS MOTION** in a **VERTICAL PLANE** are as follows:

$$x(t) = k_1 t + at^2 \qquad \text{and} \qquad y(t) = k_2 t + k_3 at^2 , \tag{94}$$

where k_1, k_2, k_3, and a – parameters of the motion, their identification and interpretation (including dimensions and measurement units) are ordered and ought to (should) be performed by the students independently.

To find the **AIRCRAFT'S CENTER OF MASS MOTION PATH EQUATION,** one should exclude the parameter of time from the motion equations like (94). For the case when

$$\frac{y(t)}{k_3} = \frac{k_2}{k_3} t + at^2 \qquad \text{and} \qquad \frac{k_2}{k_3} = k_1 , \tag{95}$$

then,

$$\frac{y(t)}{k_3} = k_1 t + at^2 = x(t) \qquad \text{and} \qquad y(t) = k_3 x(t) . \tag{96}$$

If the parameter of

$$k_3 = \text{const} , \tag{97}$$

then, the **AIRCRAFT'S CENTER OF MASS MOTION PATH (TRAJECTORY)** is the straight line having the inclination of

$$\text{tg}\theta = \frac{dy}{dx} = k_3 . \tag{98}$$

The **AIRCRAFT'S CENTER OF MASS MOTION SPEED EQUATIONS** in projections to the axes of the reference system will be:

$$V_x = \frac{dx(t)}{dt} = k_1 + 2at \qquad \text{and} \qquad V_y = \frac{dy(t)}{dt} = k_2 + 2k_3 at \tag{99}$$

if

$$k_1 = \text{const}, \qquad a = \text{const}, \qquad \text{and} \qquad k_2 = \text{const}. \qquad (100)$$

The **AIRCRAFT'S CENTER OF MASS MOTION ACCELERATION EQUATIONS** in projections to the axes of the reference system will be:

$$W_x = \frac{d^2 x(t)}{dt^2} = 2a \qquad \text{and} \qquad W_y = \frac{d^2 y(t)}{dt^2} = 2k_3 a. \qquad (101)$$

The total **AIRCRAFT'S CENTER OF MASS MOTION ACCELERATION EQUATION** will be:

$$W = \sqrt{W_x^2 + W_y^2} = \sqrt{(2a)^2 + (2k_3 a)^2} = 2a\sqrt{1 + k_3^2}. \qquad (102)$$

In projections upon the attached to the **SPEED OF THE AIRCRAFT'S CENTER OF MASS** reference system (speedy, natural reference system), the differential equations of motion (in the case of (94-102) described above) will get the view of:

$$mW_V = T - D - mg\sin\theta, \qquad (103)$$

$$mW_L = L - mg\cos\theta, \qquad (104)$$

where W_V and W_L – projections of the **AIRCRAFT'S CENTER OF MASS ACCELERATION** in the speedy (natural) reference system, i.e. W_V : upon the **SPEED** axis, W_L: upon the **FORCE OF LIFT** axis (perpendicular to the **SPEED** axis).

Since the **AIRCRAFT'S CENTER OF MASS PATH (TRAJECTORY)** is a rectilinear one, see the assumptions of (94-98),

$$0 = L - mg\cos\theta \qquad \text{and} \qquad L = mg\cos\theta. \qquad (105)$$

Knowing the **AIRCRAFT'S THRUST-TO-WEIGHT RATIO:**

$$\mu = \frac{T}{mg} \qquad (106)$$

and **FINENESS:**

$$K = \frac{L}{D}, \qquad (107)$$

one can find

$$D = \mu mg - mW_V - mg\sin\theta, \qquad (108)$$

$$K = \frac{g\cos\theta}{\mu g - W_V - g\sin\theta}. \qquad (109)$$

From (109):

$$W_V = g\left(\mu - \frac{\cos\theta}{K} - \sin\theta\right). \tag{110}$$

Finaly, from (102, 110):

$$W_V = g\left(\mu - \frac{\cos\theta}{K} - \sin\theta\right) = W = 2a\sqrt{1+k_3^2}\ . \tag{111}$$

$$a = \frac{W_V}{2\sqrt{1+k_3^2}} = \frac{g\left(\mu - \frac{\cos\theta}{K} - \sin\theta\right)}{2\sqrt{1+k_3^2}}. \tag{112}$$

§ 9. Plotting the diagrams of climbing

For the data of:

$$k_1 = 120 \qquad \text{and} \qquad k_2 = 6, \tag{113}$$

the inclination of the **AIRCRAFT'S CENTER OF MASS MOTION PATH (TRAJECTORY)** straight line is measured with (98):

$$\mathrm{tg}\theta = \frac{dy}{dx} = k_3; \tag{114}$$

and from the second formula of (95)

$$k_3 = \frac{k_2}{k_1}. \tag{115}$$

Thus,

$$k_3 = \frac{6}{120} = 0.05\ . \tag{116}$$

Also, at

$$\mu = 0.25 \qquad \text{and} \qquad K = 8, \tag{117}$$

it is possible to find from (111, 112)

$$a = \frac{9.807\left(0.25 - \frac{\cos[\mathrm{arctg}(0.05)]}{8} - \sin[\mathrm{arctg}(0.05)]\right)}{2\sqrt{1+0.05^2}} = 0.368. \tag{118}$$

$$W_V = 9.807\left(0.25 - \frac{\cos[\mathrm{arctg}(0.05)]}{8} - \sin[\mathrm{arctg}(0.05)]\right) = 0.738\,. \quad (119)$$

The diagrams of **CLIMBING** for (94-119) are shown in Fig. 14-20.

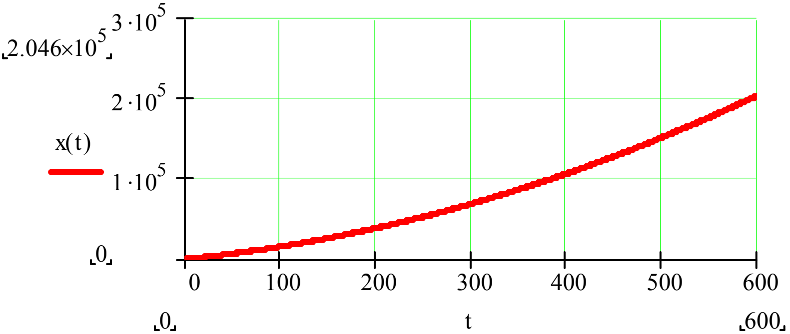

Fig. 14 – The **RANGE** diagram of the **AIRCRAFT'S CLIMBING**

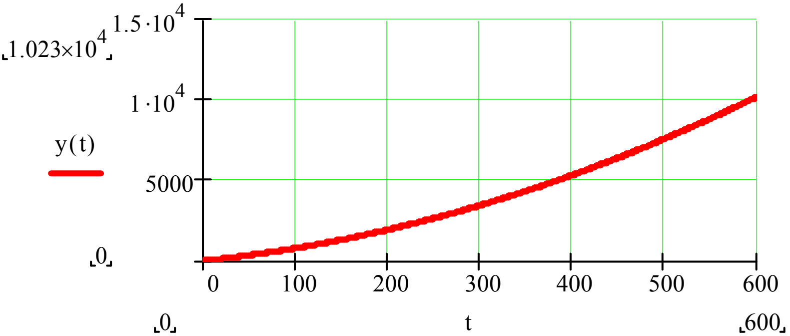

Fig. 15 – The **ALTITUDE** diagram of the **AIRCRAFT'S CLIMBING**

For the **ALTITUDE,** the initial coordinate acquired by the **AIRCRAFT AFTER THE TAKEOFF** is negligible in the presented modeling acceptable suppositions (see Fig. 15).

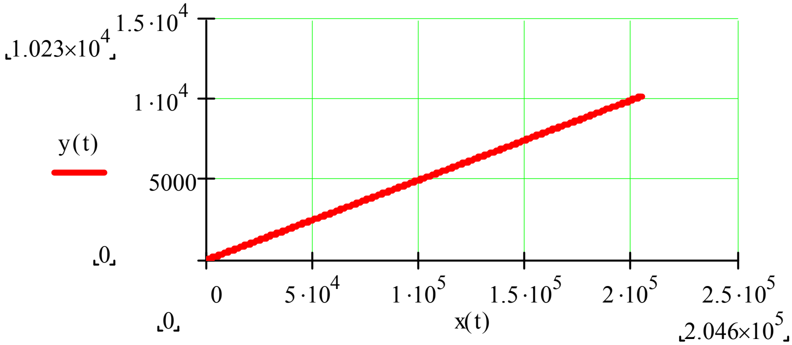

Fig. 16 – The **ALTITUDE** versus **RANGE** diagram of the **AIRCRAFT'S CLIMBING**

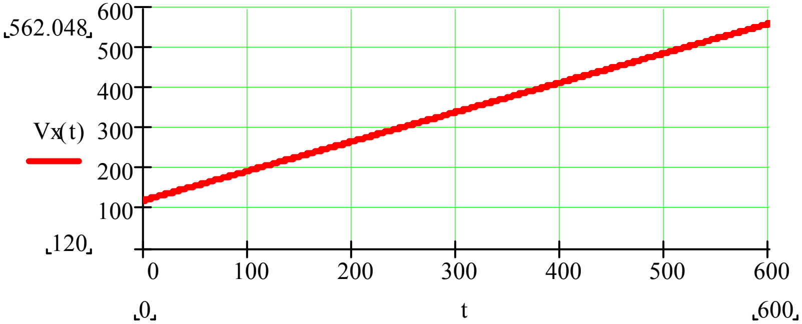

Fig. 17 – The horizontal **SPEED** diagram of the **AIRCRAFT'S CLIMBING**

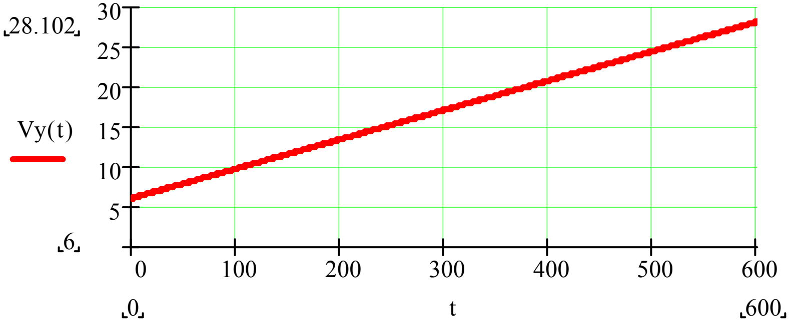

Fig. 18 – The vertical **SPEED** diagram of the **AIRCRAFT'S CLIMBING**

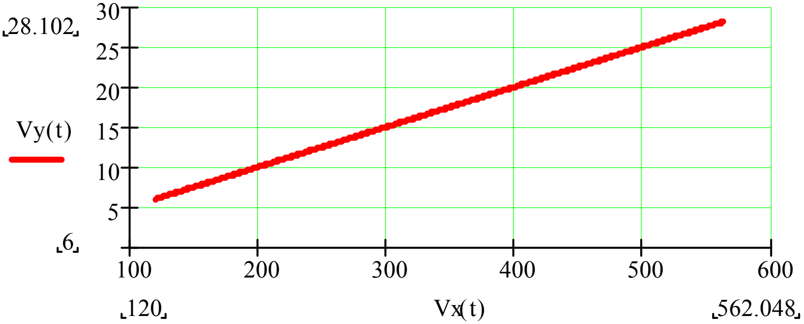

Fig. 19 – The vertical versus horizontal **SPEED** diagram of the **AIRCRAFT'S CLIMBING**

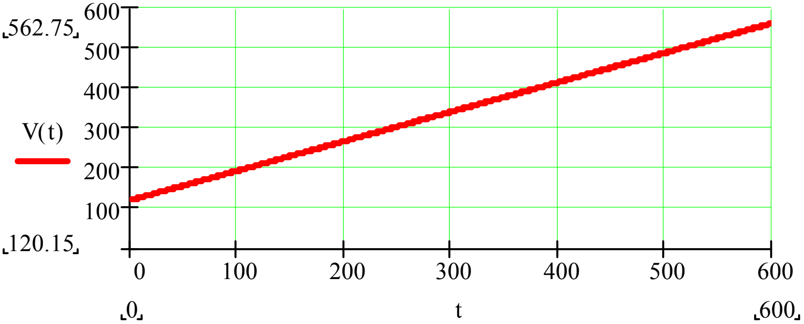

Fig. 20 – The **SPEED** diagram of the **AIRCRAFT'S CLIMBING**

The approach of (94-119) ignores the **AIRCRAFT'S MASS VARIATION WHEN CLIMBING,** therefore, in the framework of such assumption, the supposed **FORCES** are just **MASS** times the **ACCELERATIONS.**

IV. HORIZONTAL FLIGHT

The principal theoretical provisions can be found out in references [1-17, 51, 82, 121, 122, 161].

For this **STAGE** the differential equations of the **AIRCRAFT'S CENTRE OF MASS MOTION** will be:

$$m\frac{dV_x}{dt} = m\frac{dV}{dt} = T - C_x\frac{\rho V^2}{2}S\,, \tag{120}$$

$$m\frac{dV_y}{dt} = 0 = -mg + C_y\frac{\rho V^2}{2}S\,. \tag{121}$$

§ 10. Impact of the angle between the thrust and speed

Taking into account the angle between the engine **THRUST** and the **SPEED** of flight, likewise in reference [5, p. 199, Problem # 26.23]:

$$\beta, \tag{122}$$

the system of equations of (120, 121) will get the form of:

$$m\frac{dV}{dt} = T\cos\beta - C_x\frac{\rho V^2}{2}S\,, \tag{123}$$

$$0 = T\sin\beta - mg + C_y\frac{\rho V^2}{2}S\,. \tag{124}$$

This means that from (123) through the simplest transformations of (125, 126)

$$\mathrm{tg}\beta = \frac{mg - C_y\dfrac{\rho V^2}{2}S}{m\dfrac{dV}{dt} + C_x\dfrac{\rho V^2}{2}S}\,. \tag{127}$$

For a steady horizontal flight

$$V = \text{const} \qquad \text{and} \qquad \frac{dV}{dt} = 0\,. \tag{128}$$

Thus,

$$\operatorname{tg}\beta = \frac{mg - C_y \dfrac{\rho V^2}{2} S}{C_x \dfrac{\rho V^2}{2} S} = \frac{mg}{D} - K \,. \tag{129}$$

§ 11. The maximum speed

The maximum **SPEED** will be found from (123), prototypic problem is of the reference [5, p. 204, Problem # 27.13], after (130,131):

$$V_{\max} = \sqrt{\frac{2T\cos\beta}{C_x \rho S}} \,. \tag{132}$$

§ 12. Required thrust

Consider the constant **THRUST** required for changing the **SPEED** of the **HORIZONTAL FLIGHT.** It is proposed to study [5, p. 205, Problem # 27.20]

$$m\frac{d^2x}{dt^2} = m\frac{dV}{dt} = m\frac{dV}{dx}\frac{dx}{dt} = T - C_x \frac{\rho V^2}{2} S \,. \tag{133}$$

Then, after the derivations and solutions of (134-147)

$$T = C_x \frac{\rho S}{2}\left(\frac{V_1^2 - V_0^2 e^{-\frac{C_x \rho S}{m}x}}{1 - e^{-\frac{C_x \rho S}{m}x}} \right). \tag{148}$$

§ 13. Numerical simulation

The results of the numerical simulation for the influence of the angle between the engine **THRUST** and the **SPEED** of flight (122-129) are as follows:

The accepted data for the calculations are, [5, p. 199, Problem # 26.23]:

$$C_x = 0.03, \qquad \rho = 1.1 \text{ kg/m}^3, \qquad S = 30.3 \text{ m}^2, \qquad m = 2000 \text{ kg},$$

$$\frac{dV}{dt} = 5 \text{ m/s}^2, \quad V = 200 \text{ m/s}, \quad \beta = 10\ ^\circ, \quad g = 9.8 \text{ m/s}^2. \quad (149)$$

The parameters of (149) are instantaneous, therefore the immediate necessary **THRUST** and **LIFT** will constitute:

$$T = 30463 \text{ N} \qquad \text{and} \qquad L = 14310 \text{ N}. \qquad (150)$$

The maximum **SPEED,** for example, if the **THRUST** is

$$T = 30760 \text{ N}, \qquad (151)$$

and other values are as above, will be obtained by (130-132), [5, p. 204, Problem # 27.13]:

$$V_{\max} = 246.1 \text{ m/s}. \qquad (152)$$

The required **THRUST** by (133-148) can be considered, for example, as a function of the five independent variables, [5, p. 205, Problem # 27.20]:

$$a = C_x \frac{\rho S}{2}, \qquad V_0, \qquad V_1, \qquad m, \qquad s = x. \qquad (153)$$

We leave it for the students to determine the corresponding dimensions and measurement units for the values of (153).

The results of the numerical simulation for (133-148) in the suppositions of (153) are represented in Fig. 21.

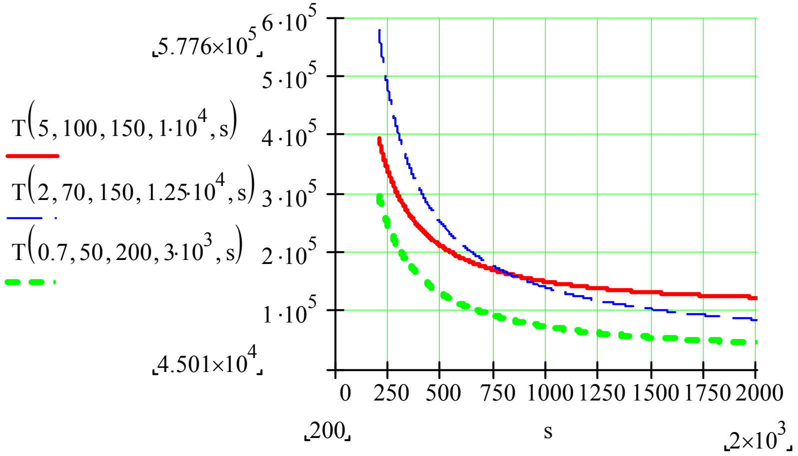

Fig. 21 – The required **Thrust** for the specified **Speed** variation depending upon the **Aerodynamic Characteristic, Speed Range, Aircraft's Mass, and Flown Distance**

§ 14. The variable mass maximum endurance and range horizontal flights

In fact, during the flight, the **Aircraft's Mass** changes because, first of all, the mass of the fuel on board decreases [6, pp. 198-215], [51, 82, 121, 122, 161]. In order to maintain the **Horizontal Rectilinear Flight** the **Variation** of the **Flight Speed** is needed in accordance with the amount of the **Fuel Consumption.**

Maximum Endurance and **Range** of the **Horizontal Rectilinear Flight** is one of the very important characteristics of the **Aircraft's Structure** perfection as well as the **Aircraft's Operational** excellence. Hence, **Maximum Endurance** and **Range** problem is an eternal (everlasting) one; and it continuously instigates the search of the optimality: [6, pp. 198-215], [51, 82, 121, 122, 161].

In the simplest setting, such problem is formulated in the framework of calculus of variations: [6, pp. 198-215], [51, 82, 121, 122, 161].

In principle, conditions of the **HORIZONTAL FLIGHT** are as above, for example, likewise (120, 121):

$$m\frac{dV_x}{dt} = m\frac{dV}{dt} = T - C_x\frac{\rho V^2}{2}S\,, \tag{154}$$

$$m\frac{dV_y}{dt} = 0 = -mg + C_y\frac{\rho V^2}{2}S\,. \tag{155}$$

Considering the **SPEED** variation negligibly small for the **ACCELERATION**, the system of the initial equations of (154, 155) can be reduced to, [51, 82, 121, 122, 161]:

$$0 = T - C_x\frac{\rho V^2}{2}S\,, \tag{156}$$

$$0 = -mg + C_y\frac{\rho V^2}{2}S\,. \tag{157}$$

Then

$$T = C_x\frac{\rho V^2}{2}S\,, \tag{158}$$

where

$$T = -\eta_T\frac{dm}{dt}\,, \tag{159}$$

where η_T – coefficient of the proportionality between the developed by the **AIRCRAFT'S ENGINES THRUST** and the **RATE OF THE BURNT FUEL:**

$$\frac{dm}{dt}\,. \tag{160}$$

The coefficient of the proportionality between the **THRUST** and the **FUEL CONSUMPTION RATE**

$$\eta_T = \eta\frac{Q}{V}\,, \tag{161}$$

where η – **EFFICIENCY** (coefficient of the useful action) of the **AIRCRAFT'S PROPULSION COMPLEX,** Q – **CALORIFIC VALUE OF THE AVIATION FUEL BY ITS WORKING MASS.**

Therefore

$$-\eta \frac{Q}{V} \frac{dm}{dt} = C_x \frac{\rho V^2}{2} S . \qquad (162)$$

Now,

$$C_x = C_{x_0} + b C_y^2 , \qquad (163)$$

where C_x, C_{x_0}, b, and C_y – aerodynamic coefficients determined at a specified diapasons of the air speeds, for instance, in the wind tunnels blowing (could be implemented from the **FIRST PART OF THE CGW** completed in accordance with the **FIRST PART OF THE METHOD GUIDE** [12, 18, 19]).

The transformations of (162), with the use of (163) and via (164-169) will lead to

$$dt = -\frac{2\eta Q \rho V S}{C_{x_0} \left(\rho V^2 S\right)^2 + 4b(mg)^2} dm . \qquad (170)$$

The **OBJECTIVE INTEGRAL (FUNCTIONAL)** of the **FLIGHT ENDURANCE (DURATION)** will get the view of [51, 82, 121, 122, 161]:

$$T = -\int_{M_0}^{M_E} \frac{2\eta Q \rho V S}{C_{x_0} \left(S \rho V^2\right)^2 + b(2mg)^2} dm , \qquad (171)$$

where M_0 – mass of the **AIRCRAFT** at the **INITIAL MOMENT OF TIME** (at the point of the **AIRCRAFT** “horizontal” flight trajectory/path beginning), M_E – mass of the **AIRCRAFT** at the end of the active “horizontal” flight fragment.

For the **HORIZONTAL FLIGHT RANGE** covered by the **AIRCRAFT,** the **OBJECTIVE INTEGRAL (FUNCTIONAL)** will be obtained based upon the condition of the differential ratio connecting the necessary values for the purposed parameters of the **FLIGHT DISTANCE, SPEED,** and **TIME:**

$$dr = V dt , \qquad (172)$$

where dr – **RANGE** differential.

Hence, [51, 82, 121, 122, 161]:

$$dr = -\frac{2\eta Q \rho V^2 S}{C_{x_0} \left(\rho V^2 S\right)^2 + 4b(mg)^2} dm . \qquad (173)$$

$$R = -\int_{M_0}^{M_E} \frac{2\eta Q\rho V^2 S}{C_{x_0}\left(S\rho V^2\right)^2 + b(2mg)^2}\,dm\,. \tag{174}$$

The **OBJECTIVE FUNCTIONALS** of (171, 174) **OPTIMAL SOLUTIONS** are the **EXTREMALS** (solutions) to the **SIMPLEST VARIATIONAL PROBLEM** from the **CALCULUS OF VARIATIONS.**

The **EXTREMALS** for (171, 174) are to be found in the view of a function:

$$V_{\text{opt}}(m) \tag{175}$$

delivering a maximum (extremum, optimum) value to the **OBJECTIVE FUNCTIONALS** of (171, 174).

The necessary conditions for the **EXTREMALS** of (171, 174) existence are the **EULER-LAGRANGE EQUATIONS:**

$$\frac{\partial F_T^*}{\partial V} - \frac{d}{dm}\left(\frac{\partial F_T^*}{\partial V'_m}\right) = 0\,, \qquad \frac{\partial F_R^*}{\partial V} - \frac{d}{dm}\left(\frac{\partial F_R^*}{\partial V'_m}\right) = 0\,, \tag{176}$$

where F_T^* and F_R^* – the underintegral functions (integrands) of the **OBJECTIVE FUNCTIONALS** of (171, 174) correspondingly;

$$V'_m = \frac{dV}{dm}\,; \tag{177}$$

satisfaction.

Those solutions of the **EULER-LAGRANGE EQUATIONS** (176), for instance, for (171), therefore the first of the (176) equations is applied, will be:

$$\frac{\partial F_T^*}{\partial V'_m} \equiv 0\,, \qquad \frac{d}{dm}\left(\frac{\partial F_T^*}{\partial V'_m}\right) \equiv 0\,, \qquad \frac{\partial F_T^*}{\partial V} = 0\,, \tag{178}$$

and through (179-181) for the **ENDURANCE EXTREMAL,** [51, 82, 121, 122, 161]:

$$V_{\text{opt}}^{(T)}(m) = \sqrt[4]{\frac{4}{3}\frac{b(mg)^2}{C_{x_0}(\rho S)^2}}\,. \tag{182}$$

For the **RANGE OPTIMAL SOLUTION,** [51, 82, 121, 122, 161], bypassing (183-186):

$$V_{\text{opt}}^{(R)}(m)=\sqrt[4]{4\frac{b(mg)^2}{C_{x_0}(\rho S)^2}}\,. \tag{187}$$

Solving differential equations of (170, 173) with the **EXTREMALS (OPTIMAL SOLUTIONS)** of (182, 187), in respect, will yield optimal functions of:

$$m_{\text{opt}}^{(T)}(t) \qquad \text{and} \qquad m_{\text{opt}}^{(R)}(r)\,. \tag{188}$$

For obtaining

$$m_{\text{opt}}^{(T)}(r) \qquad \text{and} \qquad m_{\text{opt}}^{(R)}(t)\,, \tag{189}$$

the differential equations of (173, 170) ought to (should, must) be solved with the **EXTREMALS (OPTIMAL SOLUTIONS)** of (182, 187), in their respect.

Substituting the **OPTIMAL FUNCTIONS** of (188, 189), for their corresponding values, for the **EXTREMALS** of (182, 187), one can get **OPTIMAL SPEED FUNCTIONS** as of either time or distance. But, careful, pay attention that for the **EXTREMALS** of (182, 187) to yield the correct (plausible, reasonable, sensible, rational) result, the superscript (upper index, top indication) of the (182, 187) and (188, 189) should coincide (be the same, match) in respect.

In order to get the **ENDURANCE** and **RANGE VALUES** the **OBJECTIVE FUNCTIONALS (INTEGRALS)** of (171, 174) are to be solved with the **SPEED FUNCTIONS** investigated. For having the integral values of (171, 174) as functions of some independent variable, it can be proposed to implement that variable as the upper (top) end of the integration, the mass possibly being correctly replaced (substituted) throughout the integral with the variable under the investigation.

Thus, [51, 82, 121, 122, 161], after substitution of (182) for (171), the latter yields for the **ENDURANCE**

$$T(m)=\left(\frac{3}{4}\right)^{\frac{3}{4}}\frac{\eta Q\sqrt{\rho S}}{\sqrt[4]{C_{x_0}}\left[bg^2\right]^{\frac{3}{4}}}\left(\frac{1}{\sqrt{m}}-\frac{1}{\sqrt{M_0}}\right). \tag{190}$$

For the **RANGE**, using (187) in (174), one can have, [51, 82, 121, 122, 161]:

$$R(m)=\frac{\eta Q}{2g\sqrt{bC_{x_0}}}\ln\left(\frac{M_0}{m}\right). \tag{191}$$

§ 15. Visualization of the variable mass maximum endurance and range horizontal flight simulations

The accepted data for conducting the **HORIZONTAL FLIGHT MAXIMUM RANGE** and **ENDURANCE COMPUTER SIMULATIONS** are as follows:

$$b=0.045\,,\quad \eta=0.25\,,\quad Q=32\cdot10^6\,,\quad M_0=45\cdot10^3\,,\quad M_E=30\cdot10^3\,,$$
$$g=9.8\,,\qquad C_{x_0}=0.036\,,\qquad S=34\,,\qquad \rho=1.1\,. \tag{192}$$

The dimensions and measurement units in (192) are left for the students' concern. **EXTREMALS (OPTIMAL SOLUTIONS)** obtained by (182, 187) are shown in Fig. 22.

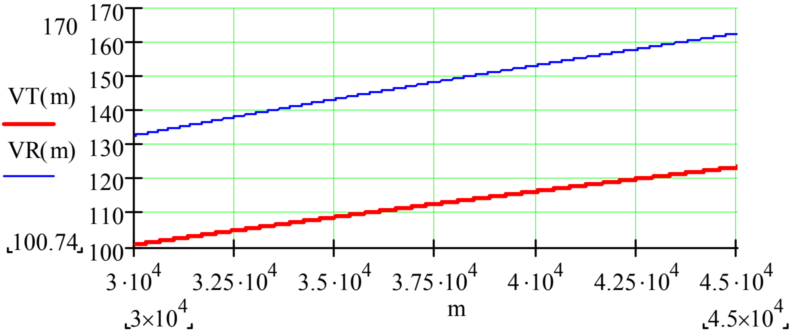

Fig. 22 – The **EXTREMALS** for the **AIRCRAFT'S SPEED** at **HORIZONTAL FLIGHT** for **MAXIMUM ENDURANCE** and **RANGE**

The conditions of (176) are just the necessary ones. To ensure (be sure) that the **EXTREMALS** of (182, 187) really deliver **MAXIMUM** values to the **OBJECTIVE FUNCTIONALS** of **ENDURANCE** and **RANGE** of (171, 174), it is possible to variate the **EXTREMALS.**

Let us say, the variations are made in the type of

$$V(m) = am^2 + dm + c\,, \tag{193}$$

where a, d, and c – the unknown so far coefficients that have to be determined on condition of the **SPEED** variation with the fixed terminal values.

Matrix-vector method gives:

$$\mathbf{V}_{-\boldsymbol{\delta}} = \begin{Vmatrix} V(M_0) \\ V\left(\dfrac{M_0 + M_E}{2}\right) - \delta \\ V(M_E) \end{Vmatrix}, \tag{194}$$

where $\mathbf{V}_{-\boldsymbol{\delta}}$ – the vector-column of **SPEEDS,** variated with δ – the value of the **SPEED** variation;

$$\mathbf{M} = \begin{Vmatrix} M_0^2 & M_0^1 & M_0^0 \\ \left(\dfrac{M_0 + M_E}{2}\right)^2 & \left(\dfrac{M_0 + M_E}{2}\right)^1 & \left(\dfrac{M_0 + M_E}{2}\right)^0 \\ M_E^2 & M_E^1 & M_E^0 \end{Vmatrix}, \tag{195}$$

where $\mathbf{M}$ – the matrix of **MASSES.**

In the vector-matrix notation, the system of the equations for the unknown coefficients of: a, d, and c determination has the view of

$$\mathbf{V}_{-\boldsymbol{\delta}} = \mathbf{M} \cdot \mathbf{C}_{-\boldsymbol{\delta}}\,, \tag{196}$$

where $\mathbf{C}_{-\boldsymbol{\delta}}$ – the vector-column of the unknown coefficients of: a, d, and c for the **SPEEDS** values lower than optimal, i.e.

$$\mathbf{C}_{-\boldsymbol{\delta}} = \begin{Vmatrix} a \\ d \\ c \end{Vmatrix}. \tag{197}$$

Then, from (196)

$$\mathbf{C}_{-\boldsymbol{\delta}} = \mathbf{M}^{-1} \cdot \mathbf{V}_{-\boldsymbol{\delta}}\,. \tag{198}$$

The accepted variation is

$$\delta = 5\,. \tag{199}$$

The dimensions and measurement units in (199) are to be determined by the students independently.

The obtained by the procedures likewise (193-199) parameters for the **SPEEDS** values are as follows:

$$\mathbf{M}^{-1} = \begin{Vmatrix} 8.889\cdot10^{-9} & -1.778\cdot10^{-8} & 8.889\cdot10^{-9} \\ -6\cdot10^{-4} & 1.333\cdot10^{-3} & -7.333\cdot10^{-4} \\ 10 & -24 & 15 \end{Vmatrix}, \qquad (200)$$

$$\mathbf{C}_{-\delta} = \begin{Vmatrix} 7.875\cdot10^{-8} \\ -4.397\cdot10^{-3} \\ 161.77 \end{Vmatrix}. \qquad (201)$$

Continuing with the variations for the **SPEED** values for both **ENDURANCE** and **RANGE,** both lower and greater than the **OPTIMAL** ones (for that purpose the obvious replacements for the variation (199) sign in formulas like (194) should be made), it is obtained the curves illustrated in Fig. 23.

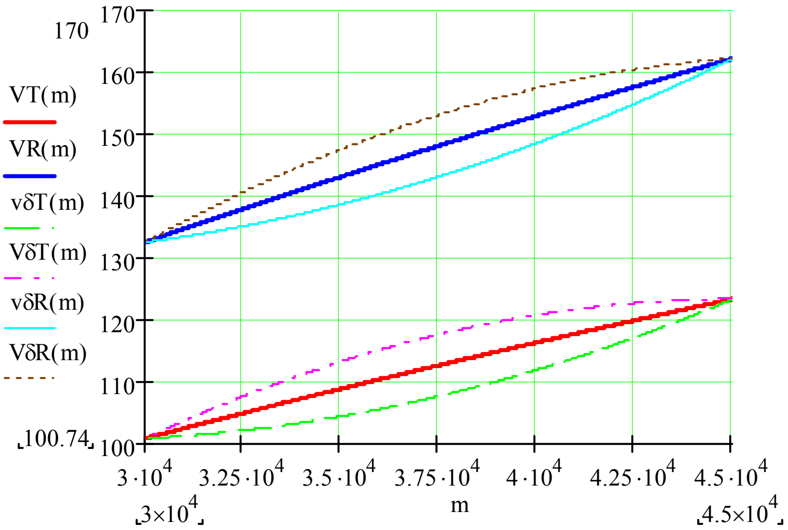

Fig. 23 – The **AIRCRAFT'S OPTIMAL SPEEDS** at **HORIZONTAL FLIGHT** for **MAXIMUM ENDURANCE** and **RANGE** with their variations

The **EXTREMALITY CHECK** is portraited in Fig. 24 and 25.

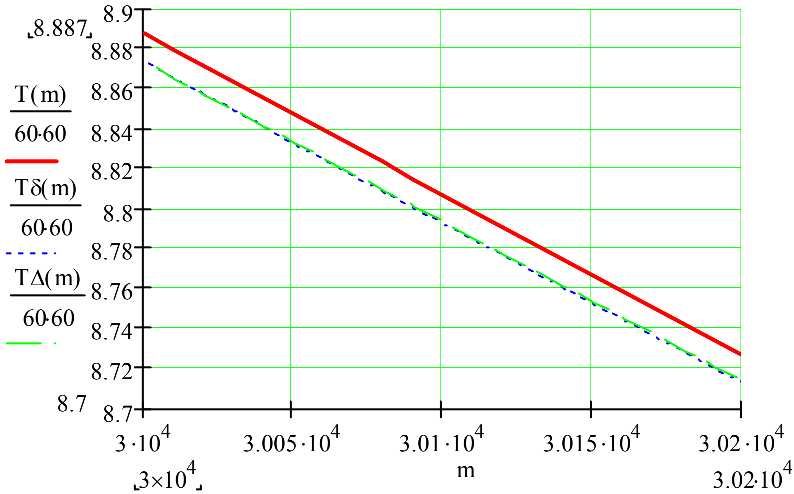

Fig. 24 – The **Maximality** of the **Aircraft's Optimal Speed** at the **Horizontal Flight** for **Maximum Endurance** compared with the variated **Speed Endurances**

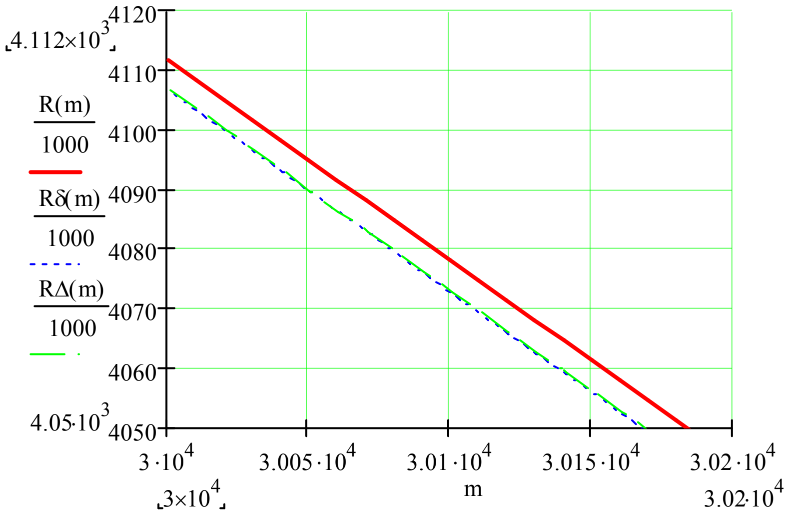

Fig. 25 – The **Maximality** of the **Aircraft's Optimal Speed** at the **Horizontal Flight** for **Maximum Range** compared with the variated **Speed Range**

The **EXTREMALS** (182, 187) **OPTIMALITY** (delivering **MAXIMUM** values to the **OBJECTIVE FUNCTIONALS** of (171, 174), that is (190, 191), in comparison with the **ENDURANCE** and **RANGE** values for the variated **SPEEDS** (see Fig. 23) above) can be noticed and traced with the curves represented in Fig. 24 for the **ENDURANCE** and Fig. 25 for the **RANGE.**

It is clear from the curves in Fig. 24 and 25, that the larger variation that can be made, the greater effect of the optimization that could be obtained.

V. PROSPECTIVE DEVELOPMENTS OF TRAJECTORY PROBLEMS

The principal theoretical provisions can be found out in references [1-17].

As that was described above, the problems of a **MATERIAL PARTICLE MOTION** is applicable to the **AIRCRAFT'S PATH (TRAJECTORY) PROBLEMS.** However, a more complex **MOTION OF AIRCRAFT** also needs (requires, demands) some attention.

Another kind of the considered herewith problems development would be some problem settings (statements, formulations, solutions) for other **STAGES OF THE AIRCRAFT'S FLIGHT,** as well as for the **AIRCRAFT'S FLIGHT CONFIGURATIONS, Maneuvers, Flight Situations,** with respect to their **EXTERNAL** and **INTERNAL CONDITIONS, CONFLICTS** between them etc.

Those **OBJECTIVE SUBJECTS** are going to be covered in the **FOLLOWING EDITIONS AND ISSUES** of the presented **SECOND PART** of the **METHOD GUIDE** on the **ACADEMIC SUBJECT** of **AEROHYDROGASDYNAMICS AND FLIGHT DYNAMICS**, which in turn follows the **FIRST PART** [12, 18, 19].

Nonetheless, a few **PARAGRAPHS** dedicated to such problems are presented herein downwards.

§ 16. Aircraft descent motions

In some respect the **AIRCRAFT'S DESCENT** could be considered as a reverse **FLIGHT STAGE** to the **CLIMBING MODE.** The students are suggested to develop the problems of the **AIRCRAFT'S DESCENT** independently making necessary modifications to the differential equations of motion.

§ 17. Touchdown

Similarly to the simplified considerations of the **AIRCRAFT'S DESCENT** as an antagonistic **MODE** to **CLIMBING** (which have been instructed in the **PARAGRAPH** above), the **TOUCHDOWN STAGE OF THE FLIGHT** could be, with the surely necessary modifications, treated as the antagonistic **MODE** to the **AIRCRAFT'S TAKEOFF FROM THE GROUND.**

It is going to be covered in further issues of the **METHOD GUIDE.** For the moment, it is for the students' self work considerations, which are highly and truly welcome, by the way.

§ 18. Deceleration to stop

The run of the **AIRCRAFT** along the **RUNWAY** after the **TOUCHDOWN** occurs in a **DECELERATING MANNER.** It is suggested for the students' self consideration either, in regards to the required models development of course.

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АЕРОГІДРОГАЗОДИНАМІКА ТА ДИНАМІКА ПОЛЬОТУ

Частина II. А

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Методичні рекомендації
до виконання самостійної роботи
для студентів 3-го курсу галузі знань 27 «Транспорт»,
спеціальності 272 «Авіаційний транспорт»

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