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AERODYNAMIC BEHAVIOR AIRCRAFT CAUSED BY RESIDUAL STRAIN WINGS

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Abstract. *The influence of residual strain on the airframe aerodynamic characteristics of aircraft was considered. The possibility of estimation of changes in deformation of airframe using data of leveling was shown. The method of estimating the change of aerodynamic characteristics caused by the influence of residual strain airframe was proposed. Technique can be used in the operation and overhaul of aircraft with large operating time.*

Keywords: aerodynamic characteristics, residual strain construction asymmetric moments, the distribution of circulation, the scheme of leveling, trigonometric series.

Introduction

In the process of a long-term usage, aircraft encounter the problem of a permanent strain of the construction [1]. As a result they gain assymetric moments that change the aerodynamic characteristics of the aircraft. The changes in the aerodynamic characteristics lead to the changes in the aircraft performances and it lowers the level of safe and secure flights. Development of the methods that help in the process of the aircraft usage to correct the operating restrictions gives the opportunity to have the necessary safety level.

Research and publication analysis

Calculation of the direct impact of the permanent wing strain on the aerodynamic characteristics of the aircraft is not an easy task and it requires plenty of analytic, numeric and experimental methods.

Nowadays numeric methods prevail [2–4].

Worked out schemes and programms are based on the numeric methods of the air movement calculation streaming the whole aircraft or a part of it. These are rather complicated programms that contain equations of continuity, variation of momentum and energy and thermodynamic characteristics. Multidimensionality and nonlinearity of the received equation system make analytic calculation impossible. They integrate with approximate numeric methods which can not always be successfully implied, because while studying the streamline of the irregular forms even computerized outlays are unacceptably huge [5].

That's why simplicity is implied into the initial equations in the form of restrictions to the airstream state.

The first essential simplification investigates the steady flow.

The second one investigates the perfect gas model i.e. gas viscosity is not considered [6].

Nowadays numeric methods are the main methods to calculate the aerodynamic characteristics while designing the aircraft.

But in the aircraft usage and maintenance much more simple methods are required. It is easy to get an approximate answer taking into consideration the gas velocity model.

Work objective is to develop simple methods to evaluate the changes in the aerodynamic characteristics of the aircraft that have permanent wing strain for operational and maintenance enterprises of civil aviation.

Estimation procedure of aerodynamic characteristics

There is an assumption used in the methods being worked out which is connected with the aerodynamic characteristics of the wing and wingspan.

According to the S.A. Chaplygin (1913) and L. Prandtlya (1918) a finite wing can be substituted with a horseshoe vortex system [7].

Along each vortex the circulation will be constant, but while changing they will go end wise. In this scheme the number of vortexes can be equal to eternity and then the circulation along the wingspan will be measured permanently decreasing from the center to the wing tips.

To calculate the circulation of the wingspan the basic integra-differential equation is used:

$$\Gamma(z) = 0{,}5 a_0(z) b(z) V_\infty \times \left[\alpha(z) + \frac{1}{4\pi V_\infty} \int_{-\frac{l}{2}}^{+\frac{l}{2}} \frac{\frac{d\Gamma}{dz_1} dz_1}{z_1 - z} \right], \quad (1)$$

where $a_0(z)$ – a derivative, c_y^α in the z-airfoil section;

$b(z)$ – chord in the z-airfoil section;

V_∞ – wing ambient velocity;

$\alpha(z)$ – angle of attack (angle between the wing's chord and velocity vector) in the z-airfoil section;

z_1 – dimension of a common vortex dΓ spanwise;

z – component where the circulation calculation is made, Γ(z);

$-\frac{l}{2}$, $+\frac{l}{2}$ – dimensions of the left and right tips of the wing panel.

The are no common methods of solving this integra-differential equation.

As a rule, such aquations are solved using approximate methods.

The most common are Glauert-Treftz method, V.V. Golybev's method, A.B. Rysberg's method, S.G. Nuzhyn's method and etc [8].

Glauert-Treftz method is usually used for practical apply.

It is based on the suggestion, that circulation separation spanwise is represented in an endless trigonometric sequence

$$\Gamma(z) = 2lV_\infty \sum_{n=1}^{\infty} A_n \sin n\theta, \quad (2)$$

where l – wingspan;

$A_1 ... A_n$ – indexes, be determined.

Angle θ is connected with component z in the following way:

$$z = \frac{1}{2}\cos\theta.$$

Inserting into the basic equation (1) the circulation whicha has been calculated by formula (2) and making the necessary transformations we will get the following

$$\sum_{n=1}^{\infty} A_n \sin n\theta(n\mu + \sin\theta) = \mu\alpha \sin\theta, \quad (3)$$

$$\mu = \frac{a_0(\theta) b(\theta)}{4l},$$

where n – number of expansion terms in the trigonometric sequence;

α – angle of attack in the discussed airfoil section.

Angle of attack α can be represented in the following way

$$\alpha(\theta) = \alpha_0(90^\circ) + \alpha(90^\circ) + \varphi_3(\theta),$$

where $\alpha_0(90^\circ)$ – zero-lift angle of the airfoil section θ=90°;

$\alpha(90^\circ)$ – angle of attack of the airfoil section θ=90°, determined at the speed of remote velocity определяемый;

$\varphi_3(\theta)$ – swirl angle, that usually consists of aerodynamic, geometric (subjected with a permanent strain) swirl.

The received equation (3) suits for any airfoil section that gives us the opportunity to use this characteristic to determine components $A_1 \ldots A_n$.

Call-off quantity of expansion terms in the n sequence measures error with which the circulation calculation has been performed. To find out the n expansion terms $A_1 \ldots A_n$ we should give the n airfoil section.

Design wing sections are chosen in the most distinguished points of the wing: in the places of airfoil discontinuity, in the places of noticable chord changes (for example, in the place where square centre wing verges into a tapered console), in the places of aerodynamic or geometric wing warping discontinuity, etc.

Equations (3) are made to calculate the airfoils and are united into a system of algebraic equations, the solving of which will help us to find out the components $A_1 \ldots A_n$.

Under the target holding speed V_∞ and the angle of attack α(z) circulation separation on the wing is calculated with the help of formula (2) where components $A_1 \ldots A_n$ are found from the equation system solution (3).

Knowing the circulation separation spanwise we can determine the forces and momemta that effect the wing and also expansion of the aerodynamic components caused by permanent strains.

The winglift is calculated with the help of the formula:

$$Y = \int_{-\frac{l}{2}}^{+\frac{l}{2}} \rho V_\infty \Gamma(z)\mathrm{d}z =$$

$$\rho V_\infty^2 l^2 \int_0^\pi \left(\sum_{n=1}^{\infty} A_n \cdot \sin n\theta \right) \sin\theta d\theta. \quad (4)$$

Because

$$\int_0^\pi \sin n\theta \sin\theta d\theta = \begin{cases} \pi/2 \text{ when } n=1; \\ 0 \quad \text{when } n \neq 1, \end{cases}$$

then

$$Y = \rho V_\infty^2 l^2 \frac{\pi}{2} A_1.$$

The winglift index can be found from

$$c_y = \frac{Y}{\frac{\rho V_\infty^2}{2} S} = \pi \frac{l^2}{S} A_1 = \pi\lambda A_1.$$

Index expansion caused by residual strain wings is determined as residulation of lift indexes of warped and symmetric wing

$$\Delta c_{y_{warp\ wing}} = \pi\lambda(A_1^* + A_1), \quad (5)$$

where A_1^* – indexes of trigonometric sequence, calculated for the warped wing, A_1 are expansion indexes for symmetric wing.

One of the constituents of the drag force of the aircraft is the induced drag force can be found from

$$X_i = \int_{-\frac{l}{2}}^{+\frac{l}{2}} \rho V_\infty \Gamma(z) \Delta\alpha(z) \mathrm{d}z. \quad (6)$$

In case $m = n$

$$\int_0^\pi A_n^2 \sin^2 n\theta d\theta = A_n^2 \int_0^\pi \sin^2 n\theta d(n\theta) = nA_n^2 \frac{\pi}{2},$$

and when $m \neq n$,

$$\int_0^\pi mA_n \sin n\theta A_m \sin m\theta d\theta =$$

$$= mA_n A_m \int_0^\pi \sin n\theta \sin m\theta d\theta = 0,$$

then

$$X_i = \pi l^2 \frac{\rho V_\infty^2}{2} \sum_{n=1}^{\infty} nA_n^2.. \quad (7)$$

To found out the induced drag force of the wing we use the formula

$$c_{xi} = \frac{X_i}{\frac{\rho V_\infty^2}{2} S} = \pi\lambda \sum_{n=1}^{\infty} nA_n^2. \quad (8)$$

Index expansion of the drag force caused by residual strain wings is calculated analogically to the lift index expansion

$$\Delta c_{x_{warp\ wing}} = \pi\lambda \sum_{n=1}^{\infty} n(A_n^{*2} - A_n^2).$$

Differential torque caused by the residual strain wings and respectively lateral axis *Ox*, e.i. roll moment ($\Delta M_{x_{warpwing}}$)

Determined by the integral

$$\Delta M_{x_{warp\ wing}} = \rho V_\infty \int_{-\frac{l}{2}}^{+\frac{l}{2}} z\Gamma(z)dz =$$

$$= \frac{\rho}{2} V_\infty^2 l^3 \int_0^\pi \left(\sum_{n=1}^{\infty} A_n \sin n\theta \right) \sin\theta \cos\theta d\theta =$$

$$= \frac{\rho}{2} V_\infty^2 l^3 \frac{\pi}{4} A_2. \quad (9)$$

Index expansion of the roll moment is calculated from

$$\Delta m_{x_{warp\ wing}} = \frac{\Delta M_{x_{warp\ wing}}}{\frac{\rho V_\infty^2}{2} Sl} = \frac{\pi}{4} \lambda A_2. \quad (10)$$

Moment expansion relatively to the vertical axis *Oy*, i.e. yawing moment $(\Delta M_{y_{warp\ wing}})$ is calculated analogically

$$\Delta M_{y\ warp\ wing} = \rho \int_{-\frac{l}{2}}^{+\frac{l}{2}} V_y(z)\Gamma(z) z dz = -\frac{\rho}{2} V_\infty^2 l^3 \times$$

$$\times \int_0^\pi \left(\sum_{n=1}^{\infty} nA_n \sin n\theta \right) \left(\sum_{n=1}^{\infty} A_n \sin n\theta \right) \cos\theta d\theta =$$

$$= -\frac{\rho}{2} V_\infty^2 l^3 \frac{\pi}{4} \sum_{p=1}^{m-1} (2p+1) A_p A_{p+1}. \quad (11)$$

Yaw expansion index is calculated with the help of the formula

$$\Delta m_{y_{warp\ wing}} = \frac{\Delta M_{y_{warp\ wing}}}{\frac{\rho V_\infty^2}{2} Sl} =$$

$$= -\frac{\pi}{4}\lambda\sum_{p=1}^{m-1}(2p+1)A_p A_{p+1}. \quad (12)$$

Using the formulae (1)…(12) in the MATLAB system a software system to calculate aerodynamic behavior aircraft caused by residual strain wings has been worked out.

To use the worked out methods practically we should test its workability.

Nowadays the above mentioned problem is solved with the help of discrete vortex method that is clearly analysed in S.M. Belocerkovskiy's works [2; 9].

To evaluate the proposed methods the circulation calculations along rigid wings span were used (λ=2,5÷10- the aspect ratio, η=1÷5 – the taper ratio, χ_0=0÷30^0 - sweepback angle) [10].

Calculations were made to determine the nondimensional spanwise circulation of the given wings using the proposed methods. During calculations 11 items of trigonometric sequence were used.

The results of the calculations performed are shown in the fig. 1.

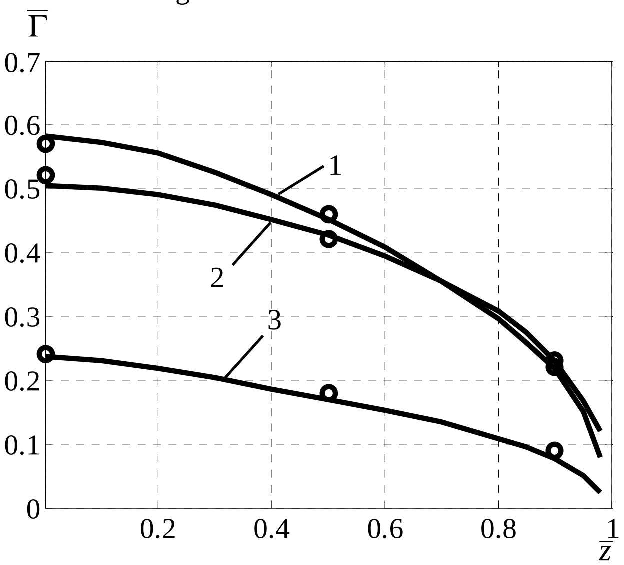

Fig. 1. Nondimensional spanwise circulation distribution:
1 – $\chi_0 = 30^\circ, \eta = 5, \lambda = 5$;
2 – $\chi_0 = 0^\circ, \eta = 2, \lambda = 2{,}5$;
3 – $\chi_0 = 0^\circ, \eta = 5, \lambda = 10$;
o – results from given works [9];
— – results under present technique

Analysing the figures given in the illustrations the following examples should be made:

– $\overline{\Gamma}$ calculation results coincide with the data given in the work [10] for wings with the indicated characteristics.

– the eccepted number of the 11th sequence gives a good calculation result;

– the proposed methods can be used to calculate spanwise circulation with the following characteristics $\chi \le 30^\circ, \quad \eta = 2 \div 5, \quad \lambda \ge 2{,}5.$

To evaluate the effect of the permanent strains on the aerodynamic characteristics of the aircraft we should estimate the size of these strains.

Permanent wing strains were calculated by the way of recounting the leveling data in the control sections (i.e. leveling passports of the aircraft were used).

For the estimation of the permanent wing strain leveling measurement data and three control wing sections were used.

Investigation of the mutual location of the control section points of right and left wings gave us the opportunity to estimate the wing's bending spanwise and lateral dihedral.

On every control section in the lower sufrace of the wing near load-carrying spars two control points are located with the help of which you can estimate the geometric twist angle while twisting the wing along the elastic axis.

The horizon sufrace is taken as basis, the exceedence of the results of the control points will depend on how fuselage fit in the flight (parallel horizontal sufrace of the fuselage (GFS) horizontal line and parallel location of the center wing section relatively to the horizon line).

Using the leveling scheme of An-26 [11], algorithms were worked out:

– squint angle (clf) from the horizon line

$$\varphi_{\text{clf}} = \arctan\frac{\Delta h_{1-36} - \Delta h_{1-36}^{э}}{L_{1-36}},$$

where Δh_{1-36} – real difference level between points 1 over 36;

$\Delta h_{1-36}^{э}$ – nominal point;

L_{1-36} – horizontal distance between points 1 and 36;

– squaint angle of the fuselage from the vertical surface of aircraft

$$\varphi_{\text{f.vps.}} = \arctan\frac{\Delta h_{5\ left-5\ \text{right}}}{L_{5\ lef-5\ \text{right}}},$$

where $\Delta h_{5\ left-5\ \text{right}}$ – real difference level between point 5 on the left board and point 5 on the right board;

$L_{5\ left-5\ \text{right}}$ – horizontal distance between 5 on the left board and point 5 on the right board;

– angle of incidence of the center wing section relatively to the horizon line

$$\varphi_{wing.c.l.} = \arctan \frac{\Delta h_{9\ left-9\ \text{right}}}{L_{9\ lef-9\ \text{right}}} - \varphi_{f.vps},$$

where $\Delta h_{9\ left-9\ \text{right}}$ – real difference level between point 9 on the left wing and point 9 on the right wing;

$L_{9\ lef-9\ \text{right}}$ – horizontal distance between point 9 on the left wing and point 9 on the right wing;

– angle of incidence of the mid-wing relatively to the horizon line

$$\varphi_{mid-wing} = \arctan \frac{\Delta h_{13\ left-13\ \text{right}}}{L_{13\ lef-13\ \text{right}}} - \varphi_{f.vps},$$

where $\Delta h_{13\ left-13\ \text{right}}$ – real difference level between point 13 on the left wing and point 13 on the right wing;

$L_{13\ lef-13\ \text{right}}$ – horizontal distance between point 13 on the left wing and point 13 on the right wing;

– lateral dihedral (right and left surfaces separately)

$$\varphi_{v} = \arctan \frac{\Delta h_{13-17} - \Delta h^{э}_{13-17}}{L_{13-17}} \pm \varphi_{f.vps},$$

where Δh_{13-17} – real difference level between point 13 on the left wing and point 17 on the right wing;

$\Delta h^{э}_{13-17}$ – nominal point;

L_{13-17} – horizontal distance between 13 and 13;

$\varphi_{f.vps}$ – angle of incidence of the fuselage from the vertical surface of aircraft

"+" – right wing;

"-" – left wing;

– additional geometric twist angle expansion in the airfoil section where leveling points from permanent strain (left and right wing) are located

$$\left.\begin{aligned} \Delta\alpha_{9-10} &= \arctan \frac{\Delta h_{9-10} - \Delta h^{*}_{9-10}}{L_{9-10}} + \varphi_{\text{clf}}, \\ \Delta\alpha_{13-14} &= \arctan \frac{\Delta h_{13-14} - \Delta h^{*}_{13-14}}{L_{13-14}} + \varphi_{\text{clf}}, \\ \Delta\alpha_{17-18} &= \arctan \frac{\Delta h_{17-18} - \Delta h^{*}_{17-18}}{L_{17-18}} + \varphi_{\text{clf}}. \end{aligned}\right\} \quad (18)$$

The main influence on the change in aerodynamic characteristics of the wing shows a deviation of the geometric twist from the given one. Calculation of the twist angle expansion in the given sections are relatively (18) added with the geometric twist angles given in these sections, and are substituted in equation (3) to calculate the coefficients of expansion $A_1, \ldots, A_n$ and circulation of the wing span.

The same methods of calculation were used to find out the expansion of the aerodynamic coefficients of An-24 from wing strain (leveling pasports were used).

Additional data for calculation were the geometric characteristics of An-24 [12]. In the case of a strain wing the geometric twist wing Gtw changes. Twist range change is restricted by the leveling points in the controlled sections. access-mi leveling measurements in the controlcross-notation. The results of calculations are shown on fig. 2. The dotted line shows the geometric twist points of the master wing that were given by the developer.

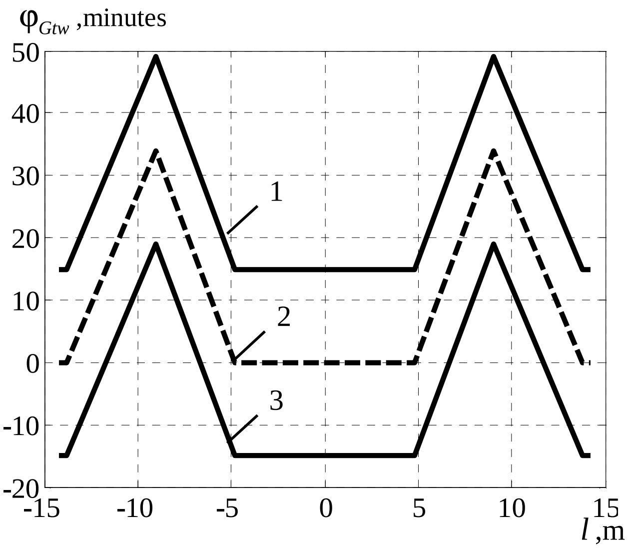

Fig. 2. Acceptable range of the geometric wing twist:
1 – upper limit of the geometrical wind twist;
2 – the given geometrical twist of the master wind;
3 – lower limit of the geometrical wind twist

Analysis of the results shows that the leveling points in the control sections deviate from the master twist angle from 6 to 15 minutes. Also the calculations and the distribution of circulation and the aerodynamic expansion coefficients of the strained wing, which has the most adverse limit of the deviation from the geometric twist.

Calculations are made for the flight speed M=0,15 and for the given angle of attack $\alpha = 2^{''}$.

Fig. 3 shows the reasons that change circulation along the span of master and strained wing of An-24.

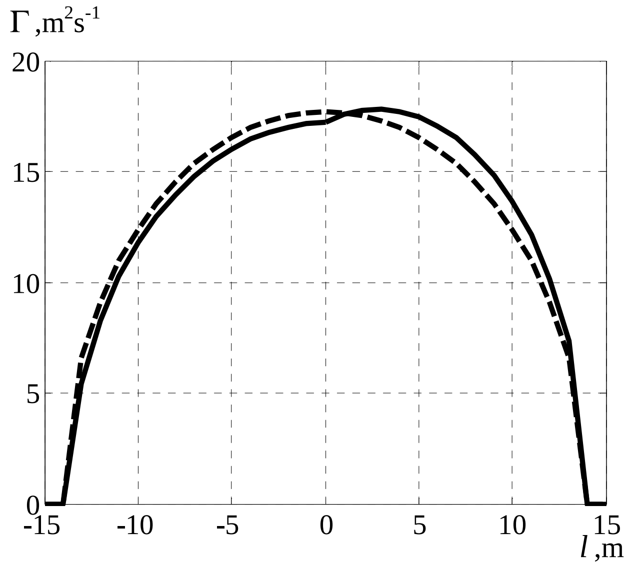

Fig. 3. Circulation distribution change spanwise on the example of An-24:
--- the standard wing;
— the deformed wing

As it can be seen on the figure, the change in the geometric twist spanwise leads to the circulation redistribution. In this case for the right wing was set by the marginal positive twist, while the left for the negative.

Therefore, on the right plane circulation exceeded the master's one, and on the left it was lower. Such a redistribution of the circulation leads to changes in the characteristics of aero-dynamical coefficients of the wing.

To study this case an assertion of the lift coefficient occurred to 0,85%, the coefficient of the induced drag reduced to 0,15% , and appeared the expansion of the roll and yaw coefficients.

This confirms the suggestion that the residual strain of the wing lead to the creation of asymmetric moments of the airplane.

Further research has focused on the nature of the change of the aerodynamic coefficients of the strained wing when the flight mode is changed as well. A following numeric experiment experiment was conducted:

- for a given flight speed (M = 0,15) the angle of attack ranges from 0 to 10°;
- at a given angle of attack $(\alpha = 6{,}5^o)$, that corresponds to the maximum flight quality of An-24 in a cruise configuration, the speed flight changed within M=0,15 ÷ 0,65.

The strain of the wing was limited to the geometric twist (fig. 2). Positive expansion of twist was set to the right wing, negative to the left. The positive results obtained are shown in fig. 4, 5, 6.

Fig. 4 shows the change in the expansion of the lift coefficient and induced drag depending on the angle of attack (M=0,15).

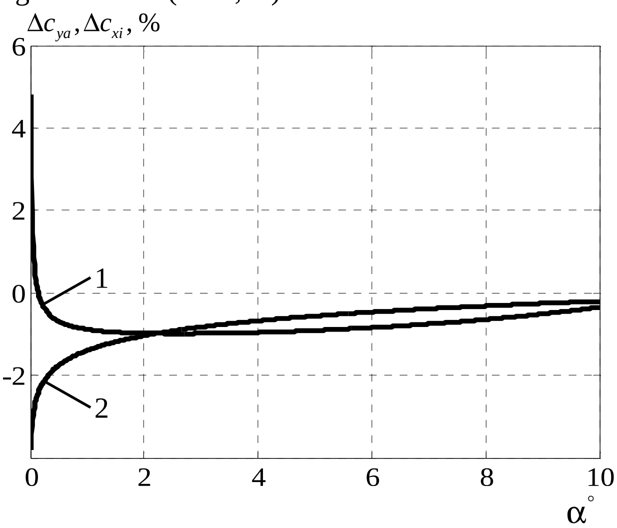

Fig. 4. Expansion of the coefficients Δc_{ya}, Δc_{xi} caused by the wing strain:
1 – Δc_{xi};
2 – Δc_{ya}

As the fig. 4 shows, the changie in the geometric wing twist affect the abovementioned coefficients. So much for the lift coefficient at low expansion angles of attack reaches up to -4%, and with increasing angle of attack, it is nearly falling up to -0,2%, indicating a decrease in the wingstrain effect on the lift coefficient at high angles of attack.

The effect of the wingstrain on the induced drag coefficient appears at small angles of attack. A significant decrease in the induced drag from 5,2% to -1% with the angle of attack from 0 to 2° and with the further increase in the angle of attack a slight increase in the coefficient to -0,15% at α = 10 ° is seen.

Fig. 5 shows the variation of the coefficients of roll and yaw moments, conditioned be residual wingstrain.

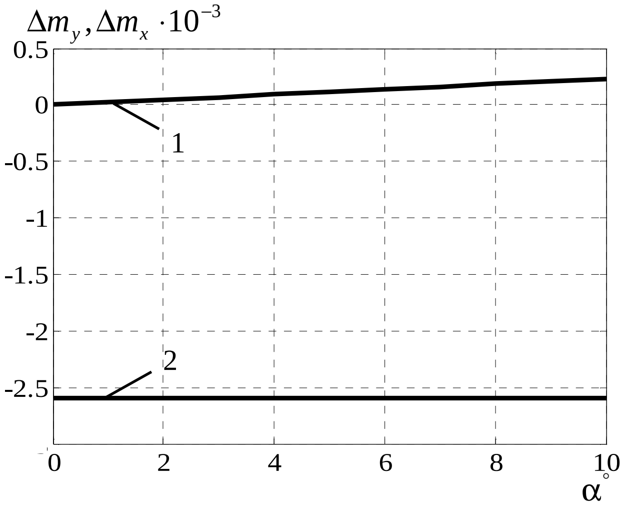

Fig. 5. Expansion of the coefficients of the assymetric moments caused by the wingstrain:

1 – Δm_y;

2 – Δm_x

As it can be seen, the coefficient Δm_x does not depend on the angle of attack, while the coefficient Δm_y has the a lower meaning and increases monotonically with the increase of angle of attack (M = 0,15).

Fig. 6 shows the variation of the coefficients expansion of the lift and the induced drag on the flight speed. As it can be seen the residual the strain of the wing leads to a slight decrease in the lift coefficient(-0,31%), a value which remains constant with the change in the M number and only slightly reduces the coefficient of the inductive resistance of the wing (-0,53%), and whose value is already affecting the number of M (angel of attack 6,5^{o}).

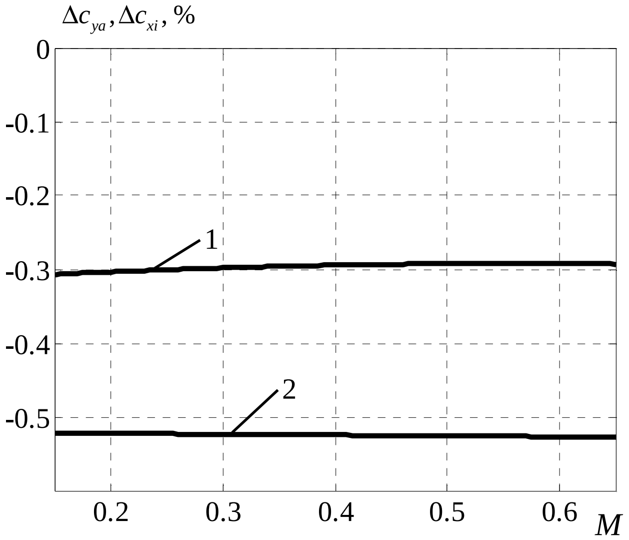

Fig. 6. Expansion of the coefficients Δc_{xi}, Δc_{ya} from the wingstrain at different flight speed:

1 – Δc_{ya};

2 – Δc_{xi}

The effect of flight speed on the change of the coefficients of asymmetric moments, are shown on fig. 7. The fig. 7 shows that the flight speed affects the asymmetric rolling moment, as with increasing speed increases and the value of the moment.

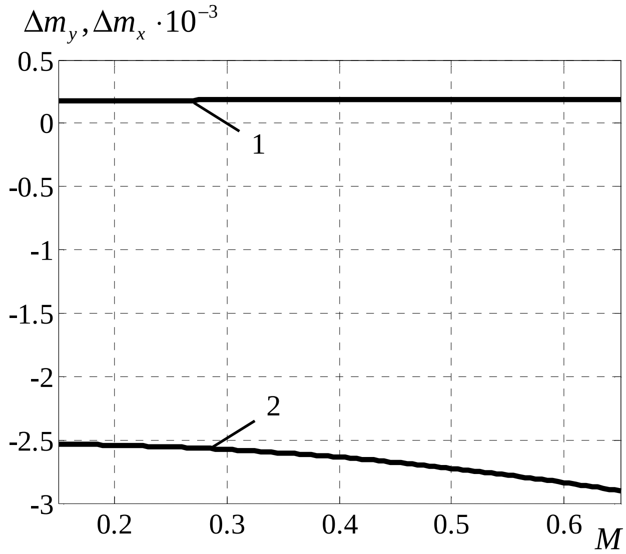

Fig. 7. Expansion of the moment coefficients from the wingstrain at different flight speed:

1 – Δm_y;

2 – Δm_x

Coefficient of the yawing moment also depends on flight speed and its significance as previously lower than the coefficient of the roll moments.

Conclusions

Researches have shown that permanent wingstrain affects the circulation distribution spanwise. The consequence of this process is the appearance of asymmetric roll and yaw moments and the fall of the lift coefficient of the wing with a slight decrease in the coefficient of induced drag. For compensations of the acquired asymmetric moments of the residual strain of the wing, it is necessary to trim plane and find the trimmed control deflections.

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