© Strojniški vestnik 48(2002)1,41-48
ISSN 0039-2480
UDK 629.7.025.34:533.694.51:004.94
Predhodna objava (1.03)
© Journal of Mechanical Engineering 48(2002)1,41-48
ISSN 0039-2480
UDC 629.7.025.34:533.694.51:004.94
Preliminary paper (1.03)

Optimiranje dinamične uravnoteženosti krilca

Optimization of the Dynamic Balance of an Aileron

Mihael Mesarič - Franc Kosel

V prispevku je podana uporaba kriterija dinamične uravnoteženosti krilca, ki zagotavlja preprečitev vihranja[1] krila na letalih splošne kategorije. Na podlagi kriterija je bila z uporabo paketa za računalniško podprto konstruiranje Pro/ENGINEER določena potrebna masa balansirne uteži krilca letala. Rezultati dobljeni na modelu so bili eksperimentalno potrjeni. Z gradientno metodo optimizacije so bile določene izmere in namestitev balansirne uteži, da bi minimizirali maso krilca.
© 2002 Strojniški vestnik. Vse pravice pridržane.
(Ključne besede: krilca letalska, uravnoteženje dinamično, metode optimiranja, paketi programski)

This paper deals with the use of the aileron balance criterion as one of the criteria for providing freedom from wing flutter on general-category airplanes. Based on this criterion and using the Pro/ENGINEER computer-aided-design software, the required mass of the balance weight was obtained. The results from the model were confirmed by our experiments. By using the gradient-optimisation method, the optimum size and position of the balance weight with respect to the minimisation of the aileron mass were achieved.
© 2002 Journal of Mechanical Engineering. All rights reserved.
(Keywords: aileron, dynamic balance, optimization methods, computer software)

0 UVOD

Pri zasnovi letal je zaradi lahke gradnje treba analizirati tudi možnost nastanka aeroelastičnih pojavov ([1] do [5]). Tako je za letala splošne kategorije pri postopku pridobivanja ustreznih dovoljenj treba med drugim pokazati, da v uporabnem območju hitrosti letenja ne pride do vihranja krila. Vihranje je nestabilno samovzbujano nihanje deformabilnega telesa, ki je posledica aerodinamičnih in vztrajnostnih obremenitev ter vpliva elastičnih deformacij. V splošnem lahko vihranje krila razdelimo na oblike, ki zajemajo [3]:

- torzijsko in upogibno nihanje krila,
- gibanje krilca in torzijsko nihanje krila,
- gibanje krilca in upogibno nihanje krila.

Zapletenost pojava je spodbujala k iskanju poenostavljenih metod dokazovanja primernosti zasnove, da v uporabnem območju hitrosti letala ne pride do vihranja ([6] in [7]). Za letala splošne kategorije, z največjo hitrostjo strmoglavljenja $V_D < 133{,}7$ m/s (260 kt) so poenostavljeni kriteriji za preprečitev pojava vihranja krila, obrata krilc in divergence krila podani v [7] in temeljijo na statističnih analizah, preskusih modelov v vetrovniku ter na analitičnih raziskavah aeroelastičnosti na poenostavljenih modelih.

Za preprečitev pojava vihranja krila moramo biti pozorni na naslednje tri parametre: dinamično

[1] Pogosto se za vihranje uporablja tudi tujka “flutter”.

0 INTRODUCTION

During the airplane-design process it is necessary to investigate the possibility that aeroelastic phenomena may occur as a result of a lightweight structure ([1] to [5]). In order to certify the airplane in the general category it is necessary to demonstrate that the airplane is free of flutter in its operational speed range. Flutter is an unstable self-sustained oscillation of an elastic body that comprises aerodynamic, elastic and inertial forces. In general there are three kinds of wing flutter [3]:

- torsional–flexural flutter,
- torsional aileron flutter,
- flexural aileron flutter.

The complexity of the flutter phenomenon has prompted efforts to find simplified methods for establishing freedom from flutter in the operating speed range of the airplane ([6] and [7]). Reference [7] is intended to serve as a guide to small-airplane designers (dive speed $V_D < 133.7$ m/s i.e. 260 kt) in the areas of prevention of flutter, aileron reversal and wing divergence. The data in [7] rely upon statistical studies, wind-tunnel tests of models and simplified analytical studies.

The prevention of wing flutter is achieved by paying careful attention to three parameters: aileuravnoteženost krilc, torzijsko prožnost krila in mrtvi hod krilc.

- Kriterij za dinamično uravnoteženost krilca je razmerje med masnim deviacijskim momentom I_{OY} glede na tečajno os krilca in vzporednico z osjo trupa letala, ki poteka skozi vozel prve upogibne lastne oblike nihanja krila ter osnim masnim vztrajnostnim momentom krilca okrog tečajne osi I_Y. Mejna vrednost parametra I_{OY}/I_Y je odvisna od največje dovoljene hitrosti strmoglavljenja letala V_D.
- Parameter torzijske prožnosti krila je odvisen od hitrosti letala V_D. Izračunamo ga iz porazdelitve zasuka krila obremenjenega z enotskim torzijskim momentom.
- Ohlapnost krilca ob drugem zadržanem krilcu ne sme preseči dane vrednosti.

V prispevku se bomo omejili na izpolnitev kriterija dinamične uravnoteženosti krilca, pri čemer bomo optimirali izmere in lego uteži za uravnoteženje krilca, da bi minimizirali maso krilca.

ron balance, wing torsional flexibility and aileron free play.

- The aileron balance criteria are obtained from the aileron product of inertia I_{OY} about the wing's fundamental bending-node line and the aileron-hinge line as well as the aileron's mass moment of inertia I_Y about its hinge line. A limit for the parameter I_{OY}/I_Y is set as a function of the dive speed V_D.
- A torsional flexibility parameter for the wing is established as a function of V_D. It is calculated from the wing-twist distribution per unit of applied torque.
- The total free play of each aileron with the other aileron clamped to the wing must not exceed the specified maximum.

This paper deals with achieving the aileron balance criteria and presents the optimisation of the size and position of the required balance weight in order to minimise the aileron weight.

1 DINAMIČNO URAVNOTEŽENJE KRILCA

1 DYNAMIC BALANCE OF THE AILERON

Gibalno enačbo krilca zapišemo [8] v obliki:

The equation of motion of the aileron is given [8] as:

$$H_a + H_{Fa} = I_Y \ddot{\delta}_a - 2 I_{OY} \left(rq + \dot{p} \right) \quad (1),$$

kjer so H_a - moment aerodinamične obremenitve okrog tečajne osi, H_{Fa} - moment krmilne sile, I_Y - masni vztrajnostni moment krilca okrog tečajne osi ter *p, q r* - kotne hitrosti krilca okrog vzdolžne, prečne in navpične osi letala. Z δ_a je označen odklon krilca, z I_{OY} pa masni deviacijski moment glede na tečajno os *Y* in vzporednico z osjo trupa letala, ki poteka skozi vozel prve upogibne lastne oblike nihanja krila (sl. 1). Iz gibalne enačbe (1) je razvidno, da dobimo zaradi vztrajnosti krilca, pri kombiniranem vrtenju okrog prečne in navpične osi oziroma pri kotnem pospešku okrog vzdolžne osi letala, moment, ki odklanja krilce. Pri upogibnem nihanju krila, se dinamično neuravnoteženo krilce odklanja, tako da zmanjšuje aerodinamično dušenje in s tem spodbuja nastanek vihranja pri manjših hitrostih leta. Povezavo med gibanjem krilca in odklonom krilca zmanjšamo, če zmanjšamo vrednost masnega deviacijskega momenta I_{OY}, kar je torej pogoj za dinamično uravnoteženje krilca.

Masno središče samega krilca je običajno precej za tečajno osjo. Krilce lahko dinamično uravnotežimo tako, da pomaknemo tečajno os krilca nazaj oziroma dodamo balansirno utež. Balansirna utež je običajno nameščena na podaljšku na sprednjem zunanjem robu krilca, ali je pri aerodinamično čistejših izvedbah vgrajena v sprednji rob krilca. Pri namestitvi balansirne uteži moramo izpolniti trdnostne zahteve, podane v predpisih.

where H_a and H_{Fa} are the aerodynamic and control moments about the hinge line, respectively, and I_Y is the mass moment of inertia of the aileron about its hinge line. The values *p, q* and *r* represent the angular velocity of the aileron in roll, pitch and yaw, respectively. δ_a describes the aileron deflection, whereas I_{OY} is the aileron product of inertia about the wing's fundamental bending-node line O and the aileron-hinge line Y (Figure 1). Equation (1) reveals that during a simultaneous pitching and yawing motion or during angular acceleration of the airplane about its longitudinal axis, inertia forces induce a hinge moment that deflects the aileron. During bending vibration of the wing, the aerodynamic damping of the wing is reduced due to the deflection of the dynamically unbalanced aileron and this initiates the flutter at lower airspeeds. As a consequence of equation (1), lowering the value of the aileron product of inertia I_{OY} reduces the inertial coupling between the aileron motion and deflection. Therefore, the aileron product of inertia can be regarded as a criterion of the dynamic balance of the aileron.

The centre of gravity of the aileron generally lies well behind the hinge line. The aileron can be dynamically balanced by shifting the hinge line aft or by adding a balance weight. This balance weight is usually placed on a special arm sticking out in front of the control surface or it is integrated into the leading edge of the aileron in an aerodynamically cleaner design. Strength requirements for the balance-weight attachment must also be fulfilled.

Na preprečevanje vihranja ugodno vpliva povečanje masnega vztrajnostnega momenta krilca okrog tečajne osi. Zato je kot poenostavljeni kriterij za preprečitev vihranja na letalih splošne kategorije v [7] definirano razmerje med masnim deviacijskim in vztrajnostnim momentom krilca I_{OY}/I_Y. Vrednost razmerja je odvisna od največje hitrosti strmoglavljenja letala in je dobljena na podlagi:

- statističnih analiz geometrijskih, vztrajnostnih in elastičnih lastnostih letal, pri katerih se je med letom pojavilo drhetnje, in na temelju uporabljenih metod za odpravo vihranja,
- omejenega števila preskusov poltogih modelov v vetrovniku,
- analitičnih raziskav aeroelastičnosti na dvodimenzionalnem modelu.

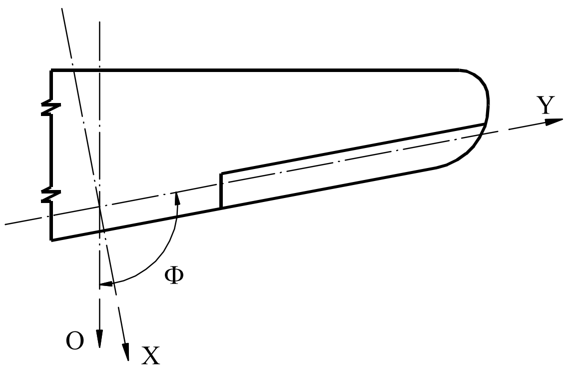
V primeru, da tečajna os ni pravokotna na vzdolžno os letala (sl. 1), dobimo masni deviacijski moment glede na osi Y in O z naslednjo transformacijo:

The prevention of flutter is also helped by an increase in the mass moment of inertia of the aileron about its hinge axis. Hence, the ratio between the aileron product of inertia and the mass moment of inertia I_{OY}/I_Y is defined as simplified flutter-prevention criteria in [7]. The value of the ratio depends on the design dive speed and it is obtained on the basis of:

- a statistical study of the geometric, inertia and elastic properties of those airplanes that have experienced flutter in flight, and the methods used to eliminate the flutter;
- limited wind-tunnel tests conducted with semi-rigid models;
- analytic studies based on a two-dimensional model.

If the aileron-hinge axis is not perpendicular to the longitudinal axis of the airplane (Fig. 1) the mass product of inertia with respect to the Y and O axes is calculated using the transformation given below:

$$I_{OY} = I_{XY} \sin\Phi - I_{YY} \cos\Phi \qquad (2).$$



Sl. 1. *Definicija tečajne osi Y in osi O, vzporedne z osjo trupa letala, ki poteka skozi vozel prve upogibne lastne oblike nihanja krila*

Fig. 1. *Definition of hinge line Y and the wing's fundamental bending-node line O*

2 REZULTATI IN RAZPRAVA

Optimalne izmere in lego balansirne uteži smo določili za krilce lahkega letala splošne kategorije, za katerega lahko uporabimo kriterij dinamične uravnoteženosti krilca podan v [7]. Glavne izmere krilca, narejenega iz armirane plastike, so prikazane na sliki 2. Tečajna os je pravokotna na vzdolžno os letala, globina krilca pa se klinasto zmanjšuje proti koncu krila. Balansirna utež je vgrajena v sprednji rob krilca, pri čemer znaša notranji premer zaokrožitve sprednjega roba krilca 12 mm.

Za določitev ustreznega masnega deviacijskega in vztrajnostnega momenta krilca smo uporabili paket za računalniško podprto konstruiranje Pro/ENGINEER. Sprva smo preračunali vrednosti za krilce brez uteži in jih primerjali z izmerjenimi.

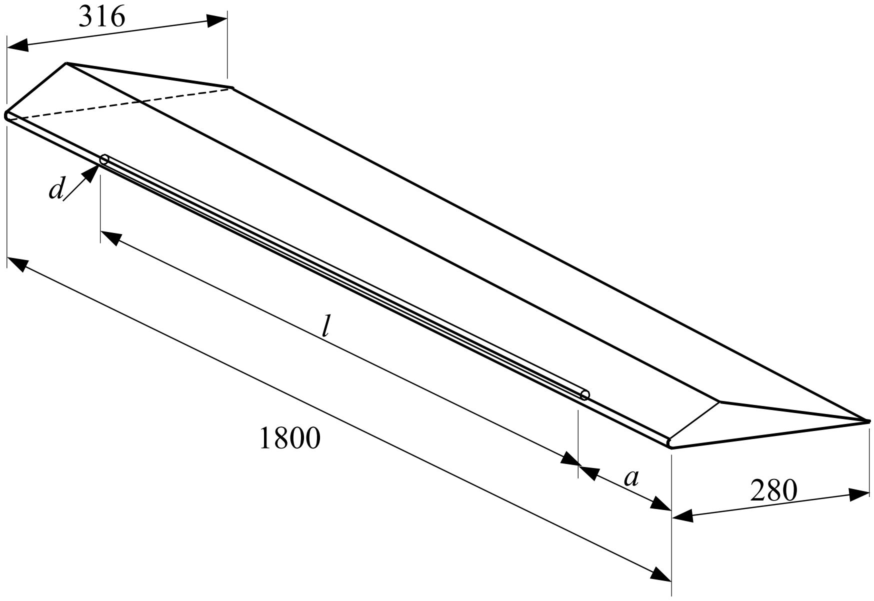
Glede na podatke o gostoti posamezne plasti armirane plastike in pene [9] smo s

2 RESULTS AND DISCUSSION

The optimum size and position of the balance weight was determined for the aileron of a general-category airplane for which the use of the aileron balance criteria given in [7] is adequate. The main dimensions of the aileron, which is made of fibre-reinforced material, are presented in Figure 2. The hinge axis is perpendicular to the airplane's longitudinal axis and the aileron chord is tapered towards the wing tip. The balance weight is integrated into the aileron's leading edge, with an inner diameter of 12 mm.

The corresponding mass product and moment of inertia of the aileron were determined using the Pro/ENGINEER computer-aided-design software. As a first step, the values for the aileron without the balance weight were determined and compared to the measured values.

With the available density data for an individual layer of fibre-reinforced composite and foam [9], and us-



Sl. 2. *Glavne izmere levega krilca*
Fig. 2. *Main dimensions of left aileron*

programom določili maso strukture krilca, ki znaša 1,369 kg. Maso nanesene barve smo ocenili kot razliko do mase krilca brez uravnotežne palice, ki znaša 1,745 kg. Predpostavili smo, da je barva enakomerno porazdeljena po površini krilca. Nato smo primerjali izračunane in izmerjene vrednosti lege masnega središča (preglednica 1). Lego masnega središča krilca brez uravnotežne palice smo določili z merjenjem sile v podpori in z obešanjem krilca [9]. Pri merjenju sile v podpori smo uporabljali napravo Zwick Z050 s sondo za merjenje sile do 100 N, tip KAP-S K1 0,05N proizvajalca System Technik GmbH. Z obešanjem, kakor je prikazano na slikah 3*a* in 3*b*, smo določili lego masnega središča vzdolž razpona krilca y_t ter po globini krilca x_t. Navpično razdaljo med masnim središčem in tečajno osjo z_t pa smo določili z obešanjem krilca okrog tečajne osi in zadnjega roba krilca [9].

Vrednosti masnih vztrajnostnih momentov krilca smo določili na podlagi meritev periode lastnega nihanja krilca. Najprej smo določili masni vztrajnostni moment I_{X_T} okrog osi X_T, ki je vzporedna

ing the software, the mass of the aileron structure was found to be 1.369 kg. The mass of the paint represents the difference between the measured mass of the aileron without the balance weight (1.745 kg) and the calculated mass of the aileron structure. It was assumed that the paint is distributed evenly over the aileron surface. Thereafter, the calculated position of the aileron's centre of gravity was compared with the measurements (Table 1). The centre of gravity of the aileron without the balance weight was experimentally determined by measurements of the force at the support and by the hanging aileron [9]. Measurements of the support force were conducted on a Zwick Z050 Universal Testing Machine using a KAP-S K1 0.05N force transducer manufactured by System Technik GmbH. Figures 3*a* and 3*b* represent estimations of the centre-of-gravity position of the aileron along the span y_t and along the chord x_t. The vertical distance between the hinge line and the centre of gravity z_t was established by hanging the aileron about its hinge line and trailing edge [9].

The experimental determination of the corresponding mass moments of inertia is based on a measurement of the period of the free oscillation of the aileron. At first the mass moment of inertia I_{X_T} about the X_T axis was determined.

Preglednica 1. *Primerjava izračunanega in izmerjene lege masnega središča*
Table 1. *Comparison between the calculated and measured position of the centre of gravity*

	Izračunano Calculated	Izmerjeno Measured	Odstopanje Deviation
x_t - za šarnirno osjo x_t - behind hinge line	45,6 mm	46,7 mm	2,4%
y_t - od širšega roba krilca y_t - from wider aileron edge	882,2 mm	881,8 mm	0,05%
z_t - pod šarnirno osjo z_t - below hinge line	37,0 mm	37,7 mm	1,9%

z osjo *X* (sl. 1) in poteka skozi masno središče krilca. Pri tem smo krilce položili na trikotno podporo na razdalji *l* od stranice, na katero je bila pritrjena vzmet togosti *k* (sl. 4*a*). Uporabili smo dve različni vzmeti, ki sta bili vedno natezno obremenjeni, njuno togost pa smo pomerili na napravi Zwick Z050 [9]. Na podlagi merjenja periode nihanja smo masni vztrajnostni moment okrog osi X_T izračunali po enačbi:

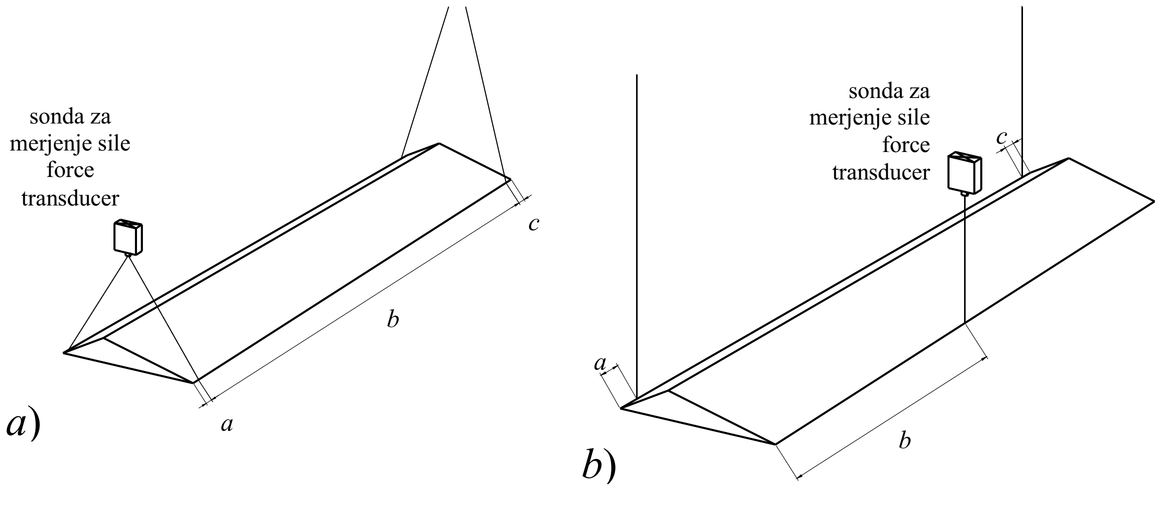
The X_T axis is parallel to the *X* axis (Figure 1) and goes through the aileron's centre of gravity. The aileron was supported at a distance *l* from the side where a spring with stiffness *k* was attached (Figure 4*a*). Two different tensionally loaded springs were used, the stiffness of the springs was experimentally established on the Zwick 050 [9]. Using the measured values of the period of the oscillations, the mass moment of inertia about the X_T axis was calculated with the equation given below:

$$I_{X_T} = kl^2\left(\frac{T_0}{4\pi}\right)^2 - ml_{MS}^2 \qquad (3),$$

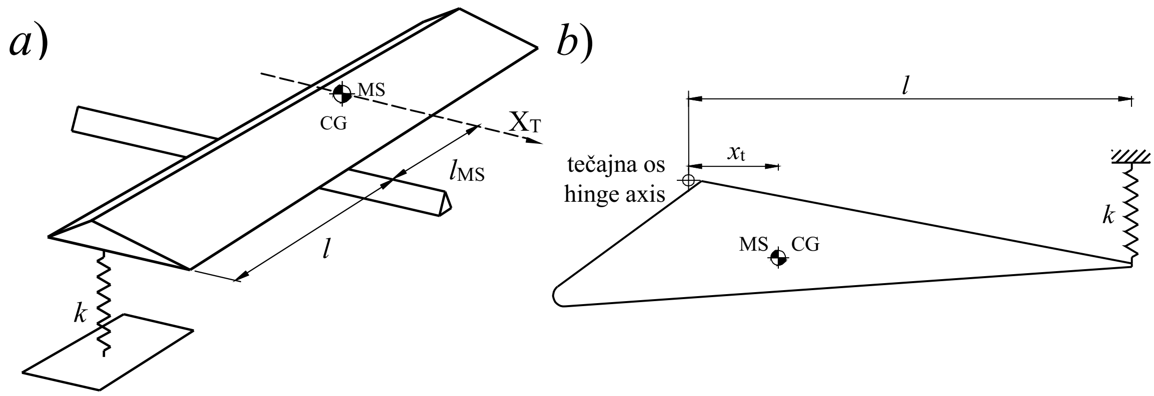
kjer je l_{MS} razdalja med masnim središčem MS in trikotno podporo. Za določitev masnega vztrajnostnega momenta krilca okrog tečajne osi smo vzmet pritrdili na zadnji rob krilca (sl. 4*b*). Iz izmerjenega časa periode nihanja smo prek izraza:

where l_{MS} is the distance between the aileron's centre of gravity and the support. In order to determine the mass moment of inertia about the hinge line, the spring was attached at the aileron's trailing edge (Fig. 4*b*). Using the measured values of the period of the oscillations, the mass moment of inertia about the hinge axis was evaluated with:

$$I_Y = kl^2\left(\frac{T_0}{2\pi}\right)^2 \qquad (4)$$



Sl. 3. *Določitev lege masnega središča po razponu (a) in globini (b) krilca z merjenjem sile v podpori*
Fig. 3. *Determination of the position of the centre of gravity along the aileron span (a) and chord (b) by measurement of the support force*



Sl. 4. *Določitev masnega vztrajnostnega momenta krilca okrog osi X_T (a) ter okrog tečajne osi (b)*
Fig. 4. *Determination of the aileron mass moment of inertia about X_T axis (a) and hinge axis (b)*

Preglednica 2. *Primerjava izračunane in izmerjene vrednosti masnega vztrajnostnega momenta*
Table 2. *Comparison between the calculated and measured values of the mass moment of inertia*

		Izračunano Calculated	Izmerjeno Measured	Odstopanje Deviation
I_{X_T}	okrog osi X_T about axis X_T	0,4871 kgm^2	0,5146 kgm^2	5,6%
I_Y	okrog šarnirne osi *Y* about hinge axis *Y*	0,0195 kgm^2	0,0197 kgm^2	1,0%

Preglednica 3. *Masa in izmere simetrično nameščene in optimalne jeklene balansirne uteži*
Table 3. *Mass and size of symmetrically placed and optimum balance weight made of steel*

Jeklena balansirna utež Balance weight made of steel	masa uteži mass of weight	dolžina uteži *l* length of weight *l*	premer uteži *d* diameter of weight *d*	masa krilca aileron mass
simetrično nameščena symmetrically placed	1,140 kg	1234 mm	12 mm	2,885 kg
optimalna lega optimum position	1,045 kg	1129 mm	12 mm	2,790 kg

izračunali masni vztrajnostni moment I_Y okrog tečajne osi *Y*. Primerjava med izračunanimi in izmerjenimi vrednostmi masnih vztrajnostnih momentov je podana v preglednici 2.

Ugotovljeno odstopanje izračunanih vrednosti lege masnega središča in masnih vztrajnostnih momentov od izmerjenih vrednosti je manjše od 3%, kar potrjuje kakovostne vhodne parametre in ponuja možnost določitve potrebne balansirne uteži. Nekoliko večje je le odstopanje med izmerjeno in izračunano vrednostjo masnega vztrajnostnega momenta I_{X_T}, kar pripisujemo večji masi stranic krilca.

Glede na načrtovano največjo dovoljeno hitrost leta iz diagrama v [7] razberemo, da mora biti parameter dinamične uravnoteženosti krilca $I_{OY}/I_Y < 1,75$. S programom smo tako določili izmere in maso simetrično nameščene jeklene balansirne uteži (preglednica 3).

V nadaljevanju smo s paketom Pro/ENGINEER po gradientni metodi optimirali izmere in lego balansirne uteži z namenom, da bi minimizirali potrebno maso. Pri optimizaciji jeklene balansirne uteži smo najprej spreminjali dolžino *l*, premer *d* ter oddaljenost uteži *a* od stranice krilca, ki je bližje koncu krila (sl. 2). Balansirna utež ima obliko valja, zato se mora pri povečanju premera os uteži pomakniti proti sredini krilca, tako da utež nalega na notranji površini spodnje in zgornje skodele krilca (sl. 5). Optimalne izmere in masa jeklene palice so podane v preglednici 3.

Balansirna utež je postavljena tako, da se dotika stranice krilca, ki je bliže koncu krila (a = 0 mm). S tako namestitvijo uteži se najbolj zmanjša vrednost masnega deviacijskega momenta. Optimalni premer balansirne uteži je 12 mm, s čimer je os uteži najbolj oddaljena od tečajne osi. V primeru

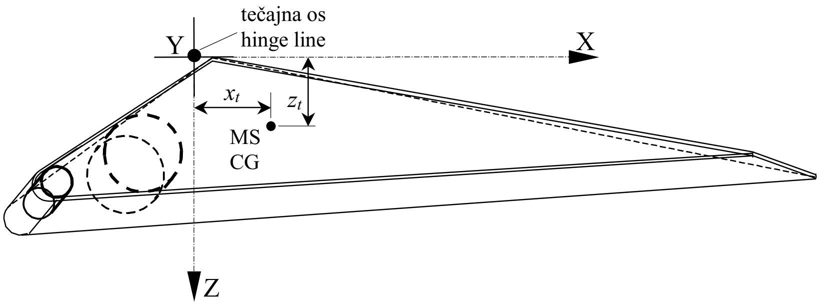
A comparison between the calculated and measured values of the mass moments of inertia is given in Table 2.

We observed that the position of the centre of gravity and the values of the mass moment of inertia of the aileron obtained with the software are in good agreement with the measured values, the deviation being only 3%. The difference between the calculated and measured value of the mass moment of inertia I_{X_T} is somewhat larger, probably as a result of the higher mass of the two sides of the aileron.

The limiting value of the parameter of dynamic balance of the aileron I_{OY}/I_Y is obtained from the diagram in [7] according to the design dive speed, and must not exceed 1.75. Using the software, the corresponding size and mass of the balance weight placed at the leading edge, and symmetrically with respect to the aileron span, was determined and is given in Table 3.

Subsequently, the optimisation of the size and position of the balance weight with respect to the minimisation of the mass was performed with the Pro/ENGINEER software, by applying the gradient-optimisation method. The first part of the optimisation process for the balance weight, which was made of steel, was the variation of the length *l*, the diameter *d* and the distance *a* between the balance weight and the outward side of the aileron. The balance weight has a cylindrical form. If its diameter is enlarged, the balance weight is placed further aft so that its surface touches the inner surface of the aileron's skin (Figure 5). As a result of the optimisation we obtained a balance weight made of steel with the dimensions given in Table 3.

To achieve the best position, the balance weight has to be aligned with the outer side of the aileron (a = 0 mm). In this way the value of the product of inertia of the aileron is mostly reduced. Furthermore, the diameter of the balance weight must be 12 mm, since in this case the largest distance



Sl. 5. *Vpliv premera balansirne uteži na namestitev znotraj krilca*
Fig. 5. *Effect of balance-weight diameter on its position inside the aileron*

povečanja premera je treba balansirno utež premakniti proti tečajni osi, kar zmanjšuje masni vztrajnostni moment krilca in ugoden prispevek balansirne uteži k masnemu deviacijskemu momentu krilca.

Tudi v primeru dodatnega parametra, notranjega polmera balansirne uteži smo dobili enak rezultat optimiranja balansirne uteži, vgrajene v krilce. Maso balansirne uteži smo zmanjšali za 8,3%, maso celotnega krilca pa za 3,3%. Masno središče dinamično uravnoteženega krilca leži x_t = 7,2 mm za tečajno osjo.

Tudi v primeru svinčene balansirne uteži je optimalni premer 12 mm ter namestitev na skrajni zunanji konec krilca. Zaradi večje gostote je potrebna dolžina palice manjša (770 mm), kar ugodno vpliva na masni deviacijski moment I_{OY}. V primerjavi s simetrično nameščeno balansirno utežjo je v tem primeru masa uteži zmanjšana za 11%, celotnega krilca pa za 4,4%. Masno središče dinamično uravnoteženega krilca s svinčeno utežjo leži 8,2 mm za tečajno osjo.

Glede na to, da kriterij dinamične uravnoteženosti krilca vsebuje masni deviacijski moment, je optimalna lega balansirne uteži na skrajnem sprednjem in zunanjem koncu krilca pričakovana. Z optimizacijo smo za obravnavani primer poiskali še optimalno razmerje med dolžino in premerom uteži.

between the balance weight and the hinge line is achieved. If the diameter of the balance weight is enlarged it must be placed further aft. As a consequence, the mass moment of inertia as well as a favourable contribution of the balance weight to the product of inertia would be reduced.

After including another parameter, i.e. the inner radius of the balance weight, the same optimum size and position of the weight were obtained. After the optimisation, the mass of the balance weight and of the whole aileron were reduced by 8.3% and 3.3%, respectively. The centre of gravity of the dynamically balanced aileron lies x_t = 7.2 mm aft of the hinge line.

With the balance weight made of lead, the same optimum diameter of 12 mm and placement at the outer end of aileron were obtained. Due to higher density, the necessary length of the balance weight was shorter (770 mm), which had a positive effect on the product of inertia I_{OY}. Compared to the symmetrically placed balance weight, the masses of the balance weight and of the whole aileron in this case were reduced by 11% and 4.4%, respectively. The centre of gravity of the dynamically balanced aileron with the balance weight made of lead lies x_t = 8.2 mm aft of the hinge line.

Since the product of inertia is included in the aileron balance criteria the placement of the balance weight of the outmost outward and forward position inside the aileron is expected. However, with optimisation the ideal relation between the length and diameter of the balance weight was achieved for our case.

3 SKLEPI

Krilca v veliki meri vplivajo na vihranje krila zato moramo pri snovanju letala uporabiti rešitve, ki preprečujejo samovzbujana nihanja krila v uporabnem hitrostnem območju. Pri letalih splošne kategorije je eden od poenostavljenih kriterijev preprečevanja vihranja parameter dinamične uravnoteženosti krilca. Oblika krilca in lega tečajne osi sta zasnovana glede na aerodinamično učinkovitost krmila in velikost krmilnih sil. Krilce tako dinamično uravnotežimo z dodatno maso. Zato je pametno poiskati optimalne

3 CONCLUSIONS

The aileron greatly influences the occurrence of wing flutter. Therefore, during the airplane design, appropriate measures have to be taken in order to achieve freedom form flutter in the operational speed range. For general-category airplanes one of the simplified criteria for demonstrating freedom from flutter is the aileron balance criterion. Since the aileron shape and its hinge-line position are determined with respect to the aerodynamic effectiveness of the control surface and the magnitude of control forces, a balance weight must be added in order to dynamically balance the aileron. Hence, it is of primary interest to the engineer to optimise izmere in lego balansirne uteži, da bi minimizirali maso krilca.

Pri delu smo uporabili paket za računalniško podprto konstruiranje, ki ne ponuja samo možnosti za iskanje primerne zasnove, v našem primeru dinamične uravnoteženosti krilca, ampak tudi z metodami optimiranja določit optimalno zasnovo glede na dano ciljno funkcijo in kriterije. Pravilnost modela smo potrdili s preskusom, z optimiranjem izmer in lege pa smo maso balansirne uteži zmanjšali za 8,3 % oziroma 11 odstotkov. Nadaljnjo možnost za zmanjšanje mase krilca daje sočasno optimiranje krilca glede na dinamično uravnoteženost in nosilnost.

the size and the position of the balance weight in order to minimise the weight.

In our work the computer aided design software we used not only offers the possibility of finding a feasible solution but also an optimum design with respect to the goal function and restrictions. The accuracy of the model was confirmed by experiments. As a result of the optimisation of the size and position of the balance weight, its mass was reduced by 8.3% and 11%. A further reduction of the aileron mass could be achieved by simultaneous optimisation of the aileron with respect to the aileron balance criteria and structural strength.

4 LITERATURA
4 REFERENCES

[1] Bisplinghoff, R. L., H. Ashley in R.L. Halfman (1983) Aeroelasticity. *Dover Publications.*

[2] Försching, H.W. (1974) Grundlagen der Aeroelastik. *Springer-Verlag Berlin.*

[3] Stinton, D. (1997) The design of the aeroplane. *Blackwell Science.*

[4] Niu, M.C.Y. (1997) Airframe structural design. *Hong Kong Conmilit Press Ltd.*

[5] Dickinson, L. B. (1968) Aircraft stability and control for pilots and engineers. *Sir Isaac Pitman & Sons.*

[6] Advisory Circular No: 23.629-1A (1985) Means of compliance with section 23.629, Flutter. *Federal Aviation Administration*.

[7] Airframe and equipement engineering report No. 45 (1955) Simplified flutter prevention criteria for personal type aircrat. *FAA, Engineering and Manufacturing Division, Flight Standartds Service, Washington.*

[8] Etkin, B. (1972) Dynamics of atmospheric flight. *John Wiley & Sons, Inc.*

[9] Mesarič, M., F. Kosel (2000) Določitev masne uravnoteženosti krilca glede na kritično hitrost nastopa flutterja. Poročilo o raziskovalni nalogi (Research task report), Fakulteta za strojništvo, Ljubljana

Naslov avtorjev: mag. Mihael Mesarič
prof.dr. Franc Kosel
Fakulteta za strojništvo
Univerza v Ljubljani
Aškerčeva 6
1000 Ljubljana
miha.mesaric@fs.uni-lj.si
franc.kosel@fs.uni-lj.si

Authors' Address: Mag. Mihael Mesarič
Prof.Dr. Franc Kosel
Faculty of Mechanical Eng.
University of Ljubljana
Aškerčeva 6
1000 Ljubljana, Slovenia
miha.mesaric@fs.uni-lj.si
franc.kosel@fs.uni-lj.si

Prejeto:
Received: 13.9.2001

Sprejeto:
Accepted: 7.12.2001