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Izpopolnjena metoda uravnoteženja modela propelerja v vetrnem kanalu

An Advanced Balancing Methodology for the Propeller of a Wind-Tunnel Model

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Prispevek obravnava učinkovit postopek uravnoteženja, ki je bil razvit zato, da z njim popravimo asimetričnost nastavljivega kota kraka propelerja v razponu od -5 do +35 . Ker s standardnim postopkom uravnoteženja (ISO 1940-1) ni bilo moč doseči zahtevane kakovosti, smo razvili novo tehniko uravnoteženja. Študija propelerjeve neuravnoteženosti je razkrila številne pomembne podrobnosti, ki jih moramo posamično proučiti za potrebe zapletene naloge uravnoteženja. V znanih dokumentih ISO so te podrobnosti omenjene, ne pa tudi natančno opisane. Novi osnutek uravnoteženja pa določa naslednje: sprejemljive tolerance (glede oblike, izsrednosti in hrapavosti), zaporedje poteka uravnoteženja in prednostne naloge, spodnjo mejo neuravnoteženega preostanka, potrebno opremo in postopke, korekcijo neuravnoteženosti in preverjanje rezultatov.

(Ključne besede: veterni kanali, uravnoteženje propelerjev, stopnje kakovosti, dinamično obnašanje)

The focus of this paper is a versatile balancing procedure, developed to compensate for the asymmetries of a propeller blade's settable angle, in the range -5 to +35 . The standard balancing procedure (ISO 1940-1) was found to be inconsistent with the required quality grade, so a new balancing technique was created. A case study of propeller unbalance revealed a set of important details that must be uniquely assessed for such a complex balancing task. For the existing ISO notes, most of these details are descriptive rather than comprehensive. The new balancing concept defines the following: acceptable tolerances (shape, run-out and roughness), balancing order and priorities, a lower margin of residual unbalance, balancing accessories and regimes, unbalance correction and the verification of the results.

(Keywords: wind-tunnels, airplane propellers, balancing control, quality control, dynamic behaviour)

0 UVOD

V postopku razvijanja novega turbopropelerskega letala običajno proučujemo delovanje modela z motorjem v vetrnem kanalu. Hitrost propelerja tovrstnega modela običajno preseže 10.000 min^{-1}. Pri tolikšni hitrosti pa na dinamično obnašanje modela vplivajo različni dejavniki, na primer resonanca motorja, frekvenca vrtenja krakov, neuravnoteženost propelerja, naravna stanja upognjenosti in torzičnosti propelerja, plapolanje in drugo. Med temi dejavniki ima poseben pomen kakovost propelerjeve uravnoteženosti, ki pomeni glavni vir sil vzbujanja.

Z iskanjem nove metode uravnoteženja smo pričeli, ko so testne meritve pokazale, kako lahko

0 INTRODUCTION

The development of a new turbo-prop aircraft usually involves wind-tunnel research with a powered model. The propeller speed with such a model typically exceeds 10,000 rpm. At such a speed, the dynamic behavior of the model is influenced by various factors, for example, power-group resonance, blade-pass frequency, propeller unbalance, flexural and torsional blade natural modes, flutter and so on. From among all these factors, the quality of the propeller balance is of particular importance, as the main generator of excitation forces.

The research process for a new balancing methodology began when the first test measurement skoraj popolno uravnotežen propeler ob novi nastavitvi kota krakov dramatično pade iz tolerance. Kljub natančno uporabljenemu postopku uravnoteženja ISO (1940-1) nismo mogli izboljšati nastalega stanja, to pa zaradi vplivov geometrijske oblike priležnih elementov in porazdeljenosti mase, ki sta preprečili nastanek potrebne kakovosti. (Več podatkov o tem problemu je v razdelku 1).

Ker je bilo treba ustvariti dobro uravnotežen propeler, ki bi ustrezal različnim kotnim nastavitvam, sta se kot mogoči rešitvi pokazali dve možnosti:

- posamično uravnoteženje za vsako kotno nastavitev posebej (zapletena in dolgotrajna, vendar včasih edina mogoča rešitev);
- neka nova metoda uravnoteženja, ki bi zagotavljala sprejemljivo stopnjo kakovosti za vse kotne nastavitve.

Prva možnost je preprosta ponavljajoča se uporaba standardnega postopka; druga možnost bi bila bolj dobrodošla, a je težko izvedljiva.

Motivacija za premostitev tehničnih in znanstvenih izzivov je bila dovolj velika in prvi korak v raziskavi je bila poglobljena študija spremenljive strukture propelerjeve zgradbe ter študija dejavnikov, ki vplivajo na kakovost uravnoteženosti.

1 DEJAVNIKI, KI ZMANJŠUJEJO KAKOVOST URAVNOTEŽENOSTI

Shema propelerjeve zgradbe (sl. 1) je večplastna; sestoji iz zadnje (01) in prednje (02) puše, ki vpenjata štiri vgrajene krake propelerja (03). Štirje vijaki z valjasto glavo (04) trdno povezujejo prednjo in zadnjo pušo. V zadnjo pušo je izvrtana osrednja odprtina z dvema simetričnima utoroma, ki se prilegata glavni gredi motorja. Ti štirje deli (01 do 04) sestavljajo jedro sestave propelerjeve zgradbe. Preostali deli – matica (05), blokirni obroč (06), vrtavka (07) in pritrdilni vijaki (08) – so drugotnega pomena, četudi njihova uravnoteženost močno vpliva na celotno zgradbo propelerja.

Kraki propelerja so oblikovani v zmanjšanem merilu izvirnih krakov. Izdelani so iz titana 6Al-4V; poprave mase ali oblike niso dovoljene. Vsak krak je z vrhnjim delom vstavljen med zadnjo (01) in prednjo (02) pušo. Vpadni kot določimo z natančnim zavojem ob osi kraka; vsi štirje kraki so nameščeni pod enakim kotom.

Kakor je omenjeno že v uvodu, so vzroki za asimetričnost propelerjevih nastavljivih delov, ki povzroča neuravnoteženost, naslednji:

showed how an almost perfectly balanced propeller dramatically dropped out of tolerance when a new blade-angle setting was applied. However, a strictly applied ISO-proposed balancing procedure (1940-1) provided a poor result, because of the influences of the adjacent parts' geometry and mass distribution, which prevented the required quality grade being achieved. (For more details, see Section 1).

Since it was necessary to obtain a well-balanced propeller for the whole range of angle settings, two options arose as possible solutions:

- Individual balancing for each angle setting (although complicated and time consuming, sometimes the only possible solution),
- Some new balancing methodology that will guarantee an acceptable quality grade across the whole range of angle settings.

The former alternative is a simple, repeated application of a standard procedure, and the latter one, although much preferable, is difficult to realize.

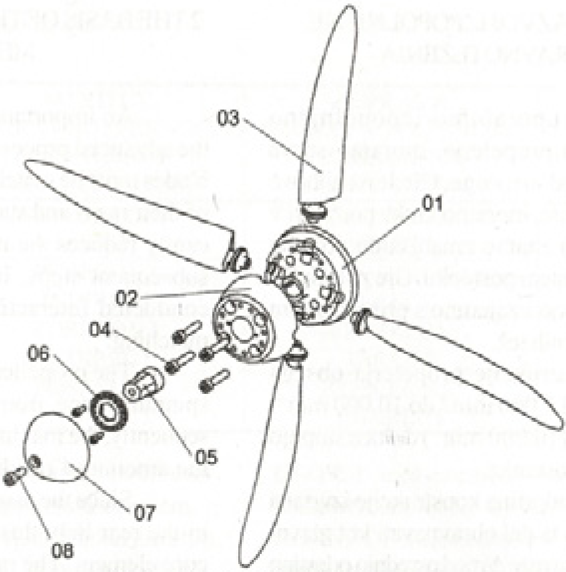
The motivation to overcome the technical and scientific challenge was strong enough, and the first step was to make an in-depth study of the propeller assembly's reconfigurable structure and the factors that affect the balance quality.

1 FACTORS THAT REDUCE THE BALANCE QUALITY

The design of a propeller assembly (Fig. 1) is a complex one, consisting of a rear (01) and a front (02) hub that clamp together four embedded blades (03). Four cylinder-head bolts (04) fix the rear and the front hub tightly together. A central hole is bored in the rear hub, with two symmetrical keyways to fit the engine's main shaft. These four items (01–04) form the core structure of the propeller assembly. The remaining assembly parts: the nut (05), the locking plate (06), the spinner (07) and the fixing bolts (08) are of secondary importance, although their balance seriously affects the complete assembly.

The propeller blades are shaped as a scaled-down version of the original blades. They are made of titanium 6Al-4V, and no mass or shape correction to the body is permitted. Each blade is head-nested between the rear (01) and the front (02) hub and the attack angle is adjusted by a precise twist about body axis, the same amount for all blades.

As mentioned in the introduction, the asymmetry of the propeller's adjustable parts, resulting in the unbalance, originates from:



Sl.1. *Sestava propelerja*
Fig. 1. *Propeller assembly*

- geometrična asimetričnost pritrditvenih točk (teža vsakega kraka znaša približno 1/6 celotne teže propelerja). Odstopanje lege težišča posameznega kraka je preveliko, kadar je večje od šestkratne tolerance propelerja;
- ohlapen stik med priležnimi deli (Netočne tolerance reže bodo povzročile enak učinek, kakor je opisan v prejšnji točki);
- razlika v teži (Vsak krak je enkraten element z določeno porazdelitvijo mase, zaradi katere ima krak tudi svojo lastno maso in statični moment; vsakršna razlika v tovrstnih značilnostih posamičnih krakov povzroči določeno začetno neuravnoteženost);
- nenatančna nastavitev kota (Razlike v nastavitvi začetnih kotov krakov prav tako povzročijo znatno neuravnoteženost).

Glede na te ugotovitve, bi morala nova metoda uravnoteženja določiti naslednje:

- preglednico sprejemljivih toleranc (glede oblike, izsrednosti in hrapavosti);
- zaporedje poteka uravnoteženja in prednostne naloge za vse posamezne dele;
- spodnjo mejo neuravnoteženega preostanka (bolj strogo kakor v priporočilih ISO),
- potrebno opremo in postopke;
- navodila za popravo neuravnoteženosti;
- natančnost nastavitve kota kraka;
- preverjanje rezultatov.

Tako bi nastal izpopolnjen postopek, ki bi omogočal zadovoljivo uravnoteženje.

- geometrical asymmetry of the clamping points (the weight of each blade is approximately 1/6 of the assembly weight). When the variation of the blade's centre-of-gravity position becomes greater than six times the assembly's tolerance it becomes excessive.
- a loose contact between adjacent parts. (Inaccurate tolerances of the gap will cause the same effect as the previous point);
- weight difference. (Each blade is a unique part with a particular mass distribution resulting in its own mass quantity and static moment; any difference in these attributes for opposed blades imposes a certain initial unbalance);
- an inaccurate angle setting. (The dispersion of the blades' preset angle is also a source of significant unbalance).

According to these explanations, the main task for the new balancing methodology would be to propose:

- a table of acceptable tolerances (shape, run-out and roughness),
- a balancing order and priorities for all items,
- a lower margin for residual unbalance (more rigorous than the ISO recommendations),
- balancing accessories and regimes,
- instructions for unbalance correction,
- an accuracy for the blade-angle setting,
- a verification of the results,

so that an advanced procedure would provide satisfactory balancing results.

2 PODLAGA ZA RAZVOJ IZPOPOLNJENE METODE URAVNOTEŽENJA

Preden lahko uporabimo izpopolnjeno metodo uravnoteženja propelerja, moramo sprva opraviti pomembno uvodno nalogo. Glede na njihove mase in statične momente, moramo krake postaviti v ustrezne dvojice; s tem znatno zmanjšamo potrebo po popravi mas v nadaljnjem postopku. Gre za rutinski postopek, ki ga izvedemo vzajemno s primerjanjem in kombiniranjem različnih tež.

Delovanje konstrukcije propelerja obsega širok razpon vrtenja, od 2.000 min^{-1} do 10.000 min^{-1}, in tako največja hitrost (10.000 min^{-1}) določa stopnjo neuravnoteženega preostanka.

Ker je osrednja odprtina konstrukcije izvrtana v zadnjo pušo, moramo ta del obravnavati kot glavni element. Velikost radialne reže Δ med osrednjo odprtino in glavno gredjo, mora biti takšna, da ustvarja manj kot polovično vrednost dovoljenega specifičnega neuravnoteženega preostanka (1). Zadnja puša iz aluminijske zlitine se mora precej tesno prilegati jeklenemu vretenu, ki ustvarja uravnoteženost (sl. 2).

2 THE BASIS OF THE ADVANCED BALANCING METHODOLOGY

An important introductory activity precedes the advanced process of balancing the propeller. The blades must be matched in appropriate pairs, in terms of their mass and static moment, which then significantly reduces the need for any mass correction in subsequent steps. It is a routine operation that is conducted interactively by using weigh-compare matching.

The propeller assembly operates over a wide spinning range, from 2,000 rpm to 10,000 rpm. Consequently, the maximum speed (10,000 rpm) dictates the amount of residual unbalance.

Since the assembly's central hole is machined in the rear hub, this part should be considered as a core element. The radial gap, Δ, between the central hole and the main shaft, must be less than half the value of that allowed for specific residual unbalance (1). There is quite a tight tolerance in the fit of the aluminum-alloy rear hub on the steel-made balancing-tool mandrel (Fig. 2).

$$\Delta = \frac{1}{2}\varepsilon^{G\,6.3}_{10.000\ \mathrm{RPM}} \approx 3\ \mu\mathrm{m} \qquad (1).$$

Poleg strogo določenih zahtev glede oblike vretena in njegovega imenskega premera (sl. 3), moramo uvesti še nekaj dodatnih kriterijev:

- hrapavost površine mora biti pod mejo 0,2 μm (kar omogoča gladko drsenje),
- celotna izsrednost mora biti pod mejo 3 μm (kar se ujema z normativi ISO [1]),
- specifični neuravnoteženi preostanek mora biti pod mejo 3 μm.

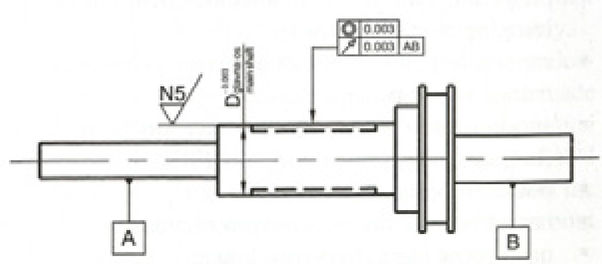
Glede na meritvene in poprave postopke lahko kasneje sestavne dele in posamezne sklope celotnega propelerja razdelimo v tri stopenjske skupine:

Besides the strictly defined requirement for the mandrel shape and the nominal diameter (Fig. 3), a few additional criteria must be introduced:

- a surface roughness below 0.2 μm (which guarantees smooth sliding),
- an overall run out below 3 μm (which complies with ISO norms [1]),
- a specific residual unbalance below 3 μm.

Later on, the items and subassemblies of the propeller assembly can be classified into three order groups, according to the measuring and correcting procedure:

Sl. 2. *Vreteno*
Fig. 2. *Mandrel*



Sl. 3. *Tolerance vretena*
Fig. 3. *Mandrel tolerances*

Preglednica 1. *Vrstni red uravnoteženja*
Tabel 1. *Balancing order*

SESTAVNI DEL ITEM	MERITEV NEURAVNOTEŽENOSTI UNBALANCE MEASUREMENT	POPRAVA NEURAVNOTEŽENOSTI UNBALANCE CORRECTION	STOPNJA ORDER
ZADNJA PUŠA REAR HUB	NEPOSREDNA DIRECT	NEPOSREDNA DIRECT	I
PREDNJA PUŠA FRONT HUB	POSREDNA INDIRECT	NEPOSREDNA DIRECT	II
VRTAVKA SPINNER	POSREDNA INDIRECT	NEPOSREDNA DIRECT	II
KRAKI BLADES	POSREDNA INDIRECT	POSREDNA INDIRECT	III

NEPOSREDNA meritev – meritev neuravnoteženosti določenega sestavnega dela z ustreznim orodjem
POSREDNA meritev – meritev neuravnoteženosti z uporabo kakega drugega dela ali sklopa propelerja
NEPOSREDNA poprava – poprava ugotovljene neuravnoteženosti na določenem neuravnoteženem delu propelerja
POSREDNA poprava – neuravnoteženost določenega dela je popravljena na drugem delu propelerja

Osrednje novosti izpopolnjene metode uravnoteženja so:

- uravnoteženje posameznih delov propelerja (namesto enkratnega uravnoteženja celotnega propelerja),
- strogo določene geometrijske tolerance (popolna usklajenost s potrebami kakovosti uravnoteženja),
- seznam prednostnih nalog (vsak del je uravnotežen v skladu z izhodišči *predhodne določitve* uravnoteženosti),
- vnaprej določene ravnine za popravo mase (dosežena kakovost se ne sme zmanjšati ob ponovni namestitvi krakov propelerja)
- dosledna zasnova neuravnoteženega preostanka (določen tako natančno, da omogoča neobčutljivost za spremembe kotov propelerjevih krakov)

Glede na prednostne naloge uravnoteženja lahko oblikujemo vrstni red postopkov uravnoteženja, ki je predstavljen v preglednici 2, pri čemer smo predlagani neuravnoteženi preostanek izračunali z enačbama (2) in (3).

PREDLAGANI SPECIFIČNI NEURAVNOTEŽENI PREOSTANEK

DIRECT measurement – a single-part unbalance measurement using the appropriate balancing tool
INDIRECT measurement – an unbalance measurement, using some other part or subassembly as a tool
DIRECT correction – a correction of the detected unbalance on that particular part
INDIRECT correction – an unbalance of one part is corrected on some other part

The core innovations of the advanced balancing methodology are:

- a decomposed propeller balancing (instead of an overall balancing),
- strictly defined geometrical tolerances (total compliance with the required balance quality),
- a queue of balancing priorities (each part is balanced as *originally allocated* on the pre-balanced platform),
- predefined plains of mass correction (the achieved quality should not be spoiled by the blades' resettlement)
- a firm frame of residual unbalance (as sharp as needed in order to be insensitive to different blade angles)

Regarding the balancing priorities, the balancing-procedure schedule can be formed as presented in Table 2, where the proposed residual unbalance is calculated from the following formulas (2) and (3).

PROPOSED SPECIFIC RESIDUAL UNBALANCE

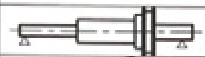
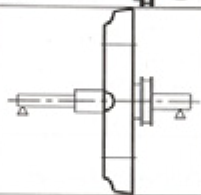
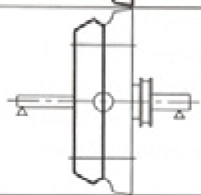
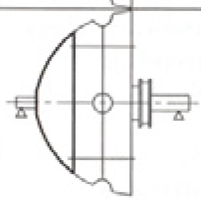
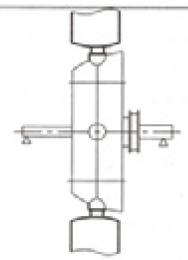
$$\varepsilon = \varepsilon^{G\,6.3}_{10.000\ \mathrm{RPM}} = 6\ \frac{\mathrm{g}}{\mathrm{kg}} \tag{2}$$

PREDLAGANI NEURAVNOTEŽENI PREOSTANEK

PROPOSED RESIDUAL UNBALANCE

$$\mathbf{U} = m\varepsilon = \mathrm{m}[\mathrm{kg}]6\left[\frac{\mathrm{g}}{\mathrm{kg}}\right] \tag{3}$$

Preglednica 2. *Postopek uravnoteženja*
Tabel 2. *Balancing procedure*

STOPNJA ORDER	SESTAVNI DEL ITEM	PRIPOMOČEK TOOL	SLIKA DRAWING	PREDLAGANI NEURAVNOTEŽENI PREOSTANEK PROPOSED RESIDUAL UNBALANCE (G 6,3 - ISO 1940) g
0	VRETENO MANDREL	-		0,78
I	ZADNJA PUŠA REAR HUB	VRETENO MANDREL		1,32
II	PREDNJA PUŠA FRONT HUB	VRETENO + ZADNJA PUŠA MANDREL + REAR HUB		0,90
II	VRTAVKA SPINNER	VRETENO + ZADNJA PUŠA + PREDNJA PUŠA MANDREL + REAR HUB + FRONT HUB		0,30
III	KRAKI BLADES	VRETENO + ZADNJA PUŠA + PREDNJA PUŠA MANDREL + REAR HUB + FRONT HUB		DOLOČEN NA PODLAGI PREJŠNJIH REZULTATOV TO BE DEFINED ACCORDING TO PRELIMINARY RESULTS

3 REZULTATI IZPOPOLNJENE METODE URAVNOTEŽENJA

Postopek uravnoteženja, določen v preglednici 2, smo izvedli do vključno celotne II.stopnje. Tu pa se začne najbolj negotova faza nove metode; negotovost je povezana z uravnoteženjem nastavljivih krakov. Začetno meritev izvedemo za najbolj običajno kotno nastavitev [15°] (sl. 4). Ugotovljeno neuravnoteženost potem popravimo na najbolj zunanjih ravninah ZADNJE in PREDNJE PUŠE (sl. 5). Neuravnoteženi preostanek približamo predlaganemu preostanku (pregl. 3, osenčena vrsta). Vpadni kot nato povečamo do skrajnih vrednosti,

3 THE RESULTS OF THE ADVANCED BALANCING METHODOLOGY

The balancing procedure, specified in Table 2, is realized up to the last issue of order II. At this stage the most uncertain phase of the new method definition starts; this is connected with the balancing of the re-settable blades. An initial measurement is conducted for the most common angle setting [15°] (Fig. 4). The detected unbalance is then compensated in the outer-most planes of the REAR and FRONT HUB (Fig. 5). The residual unbalance is tuned close to the proposed one (Table 3, shaded row). Afterwards, the attack angle is changed to the extreme values [-5°]

Preglednica 3. *Spreminjanje neuravnoteženega preostanka glede na vpadni kot (začetni rezultati)*
Tabel 3. *Fluctuation of residual unbalance vs. attack angle (initial results)*

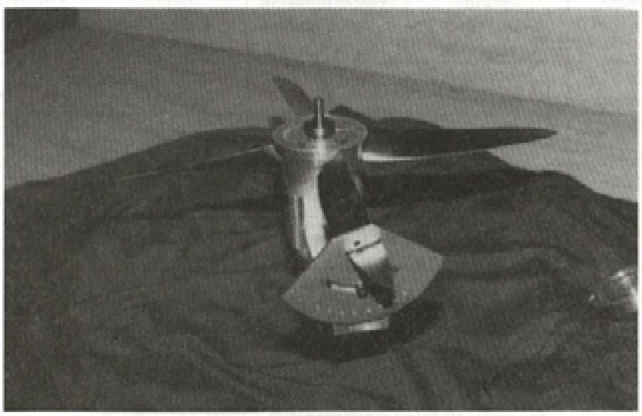
Vpadni kot Attack angle	Vrsta dejavnosti Sort of activity	Predlagani rezultat Proposed		Dobljeni rezultat Attained		Ocena Evaluation
		Stopnja kakovosti Qual. grade	Neuravnoteženi preostanek Resid. Unbal.	Stopnja kakovosti Qual. grade	Neuravnoteženi preostanek Resid. Unbal.	
°	opis description	preostanek residual	g	dovoljeno permitted	g	-
+ 15	uravnoteženje balancing	G 6,3	6,0	G 4,3	4,5	sprejemljivo acceptable
- 5	preveritev inspection	G 6,3	6,0	G 8,6	9,0	**nesprejemljivo unacceptable**
+ 35	preveritev inspection	G 6,3	6,0	G 7,7	7,2	**nesprejemljivo unacceptable**

[-5°] in [+35°], zdaj preverjanje neuravnoteženosti pokaže znatno povečanje neuravnoteženega preostanka, kar pa ni sprejemljivo (pregl. 3).

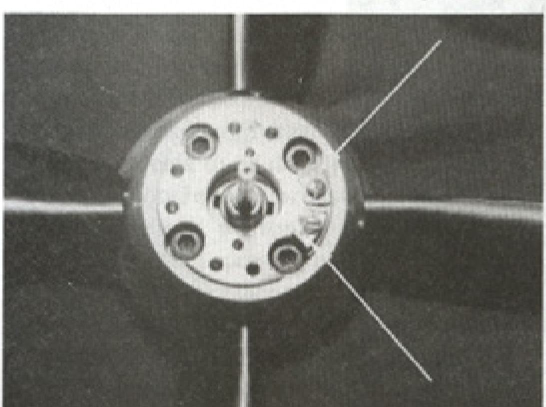
Standardna stopnja kakovosti G 6,3 (ISO 1940-1), ki jo pri zgradbi propelerja upoštevamo v prvi fazi (začetni rezultati, pregl. 3), ne ponuja primernega

and [+35°] and the unbalance check-up showed a significantly deteriorated residual unbalance, which is considered to be unacceptable (Table 3).

The standard quality grade, G6.3 (ISO 1940-1), applied to the propeller assembly in the first stage (initial results, Table 3), could not provide adequate



Sl. 4. *Prilagoditev vpadnega kota*
Fig. 4. *Attack-angle readjustment*



Sl. 5. *Popravne uteži za uravnoteženje krakov propelerja*
Fig. 5 *Correction weights for the blades' unbalance*

uravnoteženja za celoten razpon mogočih vpadnih kotov (-5° do +35°). **Zato določimo bolj zahtevno stopnjo kakovosti: približno G 1,5.** Zdaj ponovno uravnotežimo zgradbo propelerja (sl. 6) v skladu z novim kriterijem, nato pa preverimo nastalo stanje za celoten razpon vpadnih kotov (pregl. 4).

Zdaj so rezultati uravnoteženja, ki smo jih dosegli z upoštevanjem spremenjene stopnje kakovosti neuravnoteženega preostanka G 1,5, v okvirih predlaganih toleranc.

balance quality over the whole range of attack angles (-5° to +35°). **For this reason a more rigorous quality grade is established: approximately G1.5.** The propeller assembly is now rebalanced (Fig. 6) according to the newest criterion, and then verified for the whole range of attack angles (Table 4).

Now the balancing results achieved by the implementation of the new residual quality grade G1.5 are within the proposed tolerances.

4 PREIZKUS DELOVANJA

Preveritev dinamičnega delovanja modela smo izvedli v vetrnem kanalu (sl. 7), z vrtečimi se

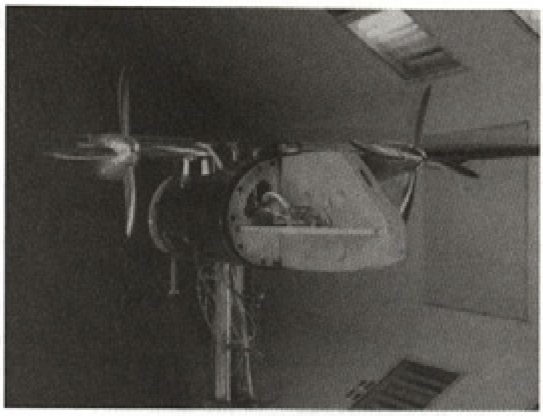
4 OPERATIONAL VERIFICATION

The inspection of the model's dynamic behavior was conducted in a wind tunnel (Fig. 7)

Preglednica 4. *Zmanjšano spreminjanje neuravnoteženega preostanka glede na vpadni kot (končni rezultati)*
Tabel 4. *Refined fluctuation of residual unbalance vs. blade angle (final results)*

Vpadni kot Attack angle	Vrsta dejavnosti Sort of activity	Predlagani rezultat Proposed		Dobljeni rezultat Attained		Ocena Evaluation
		Stopnja kakovosti Qual. grade	Neuravnoteženi preostanek Resid. Unbal.	Stopnja kakovosti Qual. grade	Neuravnoteženi preostanek Resid. Unbal.	
°	opis description	preostanek residual	g	dovoljeno permitted	g	-
+ 15	uravnoteženje balancing	G 1,5	1,6	G 1,2	1,3	sprejemljivo acceptable
- 5	preveritev inspection	G 6,3	6,6	G 5,0	5,2	sprejemljivo acceptable
+ 35	preveritev inspection	G 6,3	6,6	G 4,4	4,6	sprejemljivo acceptable

Sl. 6. *Propelerska zgradba na stroju za uravnoteženje*
Fig. 6. *Propeller assembly on the balancing machine*



Sl. 7. *Model propelerja v vetrnem kanalu*
Fig. 7. *Propeller model in the wind tunnel*

Preglednica 5. *Celoten razpon vibriranja (10.000 min^{-1})*
Tabel 5. *Vibrations in the whole range (10,000 rpm)*

Merilno mesto Measuring point	Moč vibriranja Vibration severity (V_{RMS} mm/s)	Ocena Evaluation
leva gondola motorja left engine gondola	2,0	sprejemljivo acceptable
desna gondola motorja right engine gondola	1,8	sprejemljivo acceptable
trup fuselage	1,5	dobro good

propelerji, za celoten razpon hitrosti in vpadnih kotov. Vibriranje telesa modela je, ne glede na način delovanja in število vključenih energijskih enot, ostalo znotraj predlaganih mej ISO 10816-1, kar je bil tudi glavni cilj vseh dejavnosti uravnoteženja (pregl. 5).

5 SKLEPI

Na temelju rezultatov pridobljenih s standardno in izpopolnjeno metodo uravnoteženja, lahko sklenemo naslednje:

- Zaradi nezadovoljivega osnovnega postopka uravnoteženja in ne dovolj natančne določitve neuravnoteženega preostanka, z uporabo standardnega postopka uravnoteženja ne moremo dobiti sprejemljivih toleranc.
- Sprejemljive tolerance smo dobili z izpopolnjeno metodo, ki obsega resnično preverjanje vseh pomembnih toleranc, usklajevanje krakov propelerja, postopno izvedbo osnovnega uravnoteženja glede na prednostne naloge, natančno popravo mase in natančno določitev spodnje meje neuravnoteženega preostanka.

with spinning propellers for the whole range of speeds and attack angles. The vibrations of the model body, regardless of the regime and the number of engaged power units, were kept within the ISO 10816-1 proposed limits, which was the main goal of all the balancing activities (Table 5).

5 CONCLUSIONS

Based on the results obtained by standard and advanced balancing procedures one can conclude the following:

- Acceptable tolerances could not be obtained with the standard balancing procedure, because of the inconsistent elementary balancing and the insufficiently sharp residual margin.
- Acceptable tolerances were obtained with the advanced balancing procedure, consisting of a true inspection of all the relevant tolerances, blade matching, step-by-step elementary balancing with priorities, a precise mass correction and a sharp definition of the residual unbalance lower margin

- Izpopolnjen postopek uravnoteženja resnično pripomore k razumevanju pomembnih dejavnikov in lahko prepreči, da bi le-ti vplivali na kakovost uravnoteženosti nastavljivih sestavov.

- The advanced balancing procedure has real power in the stratification of all the influential factors, and can prevent them affecting the balance quality of reconfigurable structures

6 POJASNILO IN ZAHVALA

Opisano metodo uravnoteženja smo razvili in uporabili v postopku proučevanja indonezijskega turbo-propelerskega transportnega letala za srednje proge, z uporabo modela vetrnega kanala, ki smo ga izvedli na Letalskem institutu, VTI Žarkovo, ob pomoči Instituta za strojno dinamiko pri Fakulteti za strojništvo v Beogradu.

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The balancing equipment and other accessories were provided by the RoTech Company, Belgrade, a producer of balancing machines and vibrodiagnostic instruments.

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7 VIRI
7 REFERENCES

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