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Design of a six-component strain gauge balance for testing aircraft models in the hypersonic wind tunnel

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A six-component strain gauge balance is designed for the purpose of testing aircraft models in the hypersonic wind tunnel T–34 of the VTI VJ. Stress and strain analyses are presented, as well as the values of the output signals obtained from the measuring bridges. All the problems related to providing required test conditions and the ways of overcoming them are described.

Key words: **wind tunnels, measuring equipment, strain gauge balance.**

Designations and symbols

RX – axial force, N
RY – side force, N
RZ – normal force, N
DL – rolling moment, Nm
DM – pitching moment, Nm
DN – yawing moment, Nm
F,X – force, N
M – bending moment, Nm
ℓ – length, m
A – area, m^2
I – moment of inertia, m^4
W_p – polar moment of inertia, m^3
W – moment of resistance, m^3
τ – tangential stress, N/m^2
σ – bending stress, N/m^2
σ_{02} – yield stress, N/m^2
σ_D – tensile strength, N/m^2
E – modulus of elasticity, N/m^2
G – modulus of elasticity in sliding, N/m^2
ε – elongation
ν – factor of safety
k_t – straing gauge sensitivity factor
e – measuring bridge output signal, V
U – measuring bridge supply voltage, V
c – width of the rectangular cross section, m
d – height of the rectangular cross section, m
a_1 – width of the internal beam, m
b_1 – length of the internal beam, m
a_2 – width of the external beam, m
b_2 – length of external beam, m
ℓ_1 – strain gauge distance from the center of strain gauge balance - for *RY, RZ, DN, DM*, m
ℓ_3 – half of the height of the internal beam, m
ℓ_4 – height of the external beam, m
ℓ_x – longitudinal distance of the external beams, m

Indices

x – axial force
y – side force
z – normal force
ℓ – rolling moment; external beam
m – pitching moment, internal beam
n – yawing moment
t – strain gauge
uk – total value
max – max. value

Introduction

The internal six-component monobloc strain gauge balance VTI–10C is designed for the purposes of testing aircraft models in the hypersonic wind tunnel T-34. The performance of the strain gauge balance must be in compliance with the following requirements:

- Deformations in the particular section of the balance caused by the primary component must be significantly higher compared to the deformations caused by the secondary component
- Symmetry of the measuring bridges, i.e. the strain gauge position symmetry must be obtained
- Sufficiently high value of output signals must be obtained under stationary operating conditions.

The design load of the strain gauge balance is presented in Table 1.

Table 1

RX (N)	RY (N)	RZ (N)	DL (Nm)	DM (Nm)	DN (Nm)
71	112	224	2.35	3.8	1.9

The strain gauge balance is manufactured out of one piece, by shaping particular sections to obtain 'single component' transducers. Strain gauge balance material is high-quality ARMCO PH13.8–Mo steel, with high mechanical

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performances, good machinability, and high corrosion resistance. The mechanical properties of this steel are presented in Table 2.

Table 2

E (N/m^2)	G (N/m^2)	σ_{02} (N/m^2)	σ_D (N/m^2)
$2\cdot10^{11}$	$8\cdot10^{10}$	$1.313\cdot10^{9}$	$7\cdot10^{8}$

Wind tunnel tests performed in hypersonic tunnels are followed by difficulties, which is not the case with tests in trisonic tunnels.

Behind the shock wave, the total temperature is approximately 720 K. During the test, a model is heated down the air stream and the air circulates from the model basis towards the area where the strain gauge balance is placed.

The second problem related to hypersonic wind-tunnel tests are low values of aerodynamic forces that can be significantly lower than the model weight. As a result, permanent low frequency oscillations of the model are present during the test, and the portion of the model inertia forces in the tested aerodynamic forces can be significant. Electronic filters are used in data processing to overcome this problem.

The third problem is the creation of high transition loads at starting and stopping wind tunnels. To solve this problem in the T-34 tunnel, a model support is used to insert a model into the wind tunnel test section after the air stream stabilization, and to pull it out before the airflow stops.

Description of the strain gauge balance

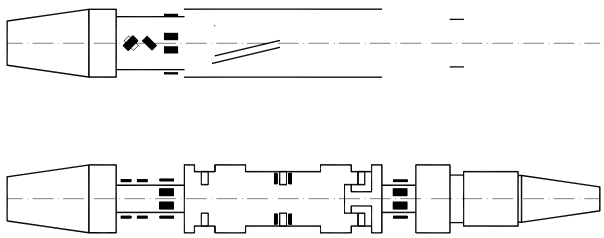
The strain gauge balance is an elastic system the purpose of which is to transmit external aerodynamic loads to the mounting sting and to enable the measurement of the total load applied to the tested model.

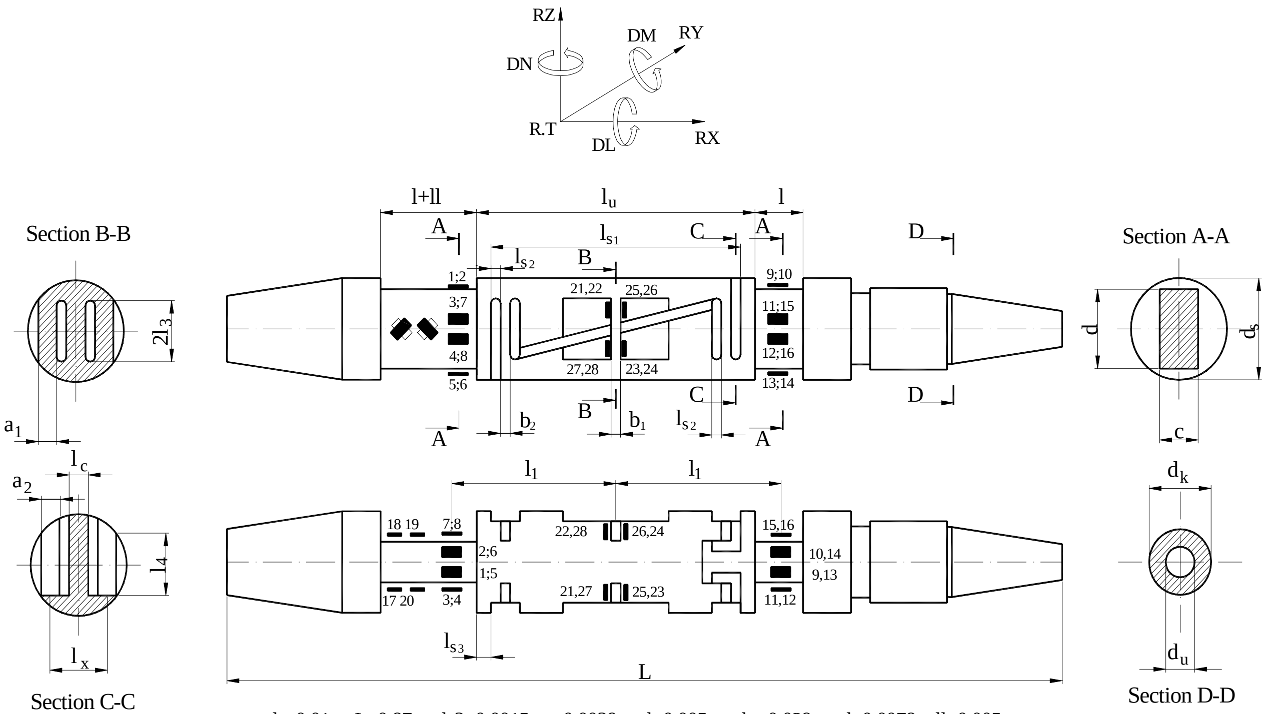
The internal balance is installed on the support system through a mounting sting, by its referent part. The measuring part of the balance is positioned inside the model (Fig.1).

Figure 1. Sting, balance and the model installation

The measurement of the components of the external aerodynamic load applied to the model is based on the strains created in the particular sections of the internal balance. These strains are recorded by the resistance strain gauges placed at the measuring stations of the balance.

The measurement of the normal force and the pitching moment, as well as the side forces and the yawing moment is obtained through the forward and the backward measuring station shaped as a single central beam (Fig.2). These components are proportional to the moments created at two cross sections of the balance, with the referent point positioned in the middle of the distance from the measuring stations where the strain gauges are applied. This type of force element enables the measurement of the components lying in two perpendicular planes, as well as the measurement of the rolling moment using the strain gauges in the measuring station closer to the model. The disadvantages of this type of balance are impossibility of mechanical separation of components acting in the same plane, partial functional dependence of the values of forces and moments acting in the same plane, creation of the longitudinal elongation slope at the surface where the strain gauges are cemented to the flexure. Also, since components are separated electrically for this kind of balance, the strain gauges must be positioned accurately.





ds=0.01m, L=0.87m, ls3=0.0015, c=0.0039m, l=0.005m, lu=0.029m, d=0.0078m ll=0.005m, lx=0.006m, a1=0.0017m, l1=0.017m, lc=0.0021m, b1=0.00098m, ls1=0.026m, dk=0.00645m, a2=0.0019m, ls2=0.001m, du=0.00345m, b2=0.00098m, l3=0.003m, l4=0.006m

Figure 3. Internal six-component straing gauge balance VTI-10C

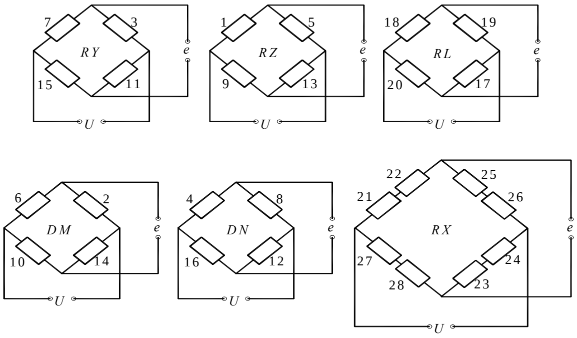


Figure 4. Measuring bridges

Table 3

I_y (m^4)	I_z (m^4)	W_y (m^3)	W_z (m^3)	W_p (m^3)
$1.542\cdot10^{-10}$	$3.856\cdot10^{-11}$	$3.955\cdot10^{-8}$	$1.977\cdot10^{-8}$	$3.041\cdot10^{-8}$
M_z (Nm)	M_m (Nm)	M_y (Nm)	M_n (Nm)	M_l (Nm)
3.808	3.8	1.904	1.9	2.35
σ_z (N/m^2)	σ_m (N/m^2)	σ_y (N/m^2)	σ_n (N/m^2)	τ_l (N/m^2)
$962.929\cdot10^5$	$960.906\cdot10^5$	$963.293\cdot10^5$	$960.906\cdot10^5$	$772.5\cdot10^5$
ε_z	ε_m	ε_y	ε_n	ε_l
$481.5\cdot10^{-6}$	$480.5\cdot10^{-6}$	$481.5\cdot10^{-6}$	$480.5\cdot10^{-6}$	$5.099\cdot10^{-4}$
e_z (V)	e_m (V)	e_y (V)	e_n (V)	e_l (V)
$5.778\cdot10^{-3}$	$5.765\cdot10^{-3}$	$5.778\cdot10^{-3}$	$5.765\cdot10^{-3}$	$6.118\cdot10^{-3}$

Level of the bridge output signal for RX

The beam geometry characteristics, forces applied to the internal and external beams of the axial force element, elongations at the area where the strain gauges are cemented and the expected value of the output signal from the bridge are presented in Table 4.

Table 4

I_m (m^4)	I_l (m^4)	W_m (m^3)
$1.333\cdot10^{-13}$	$1.49\cdot10^{-13}$	$2.721\cdot10^{-10}$
X_m (N)	X_l (N)	
10.97	12.26	
ε_x	e_x (V)	
$3.024\cdot10^{-4}$	$3.629\cdot10^{-3}$	

Stress analysis at the backward measuring station for the components *RY, RZ, DN, DM, DL*

The maximum values of normal, tangential and total stresses at the farthest point of the rear measuring station of the balance and the corresponding factor of safety, with respect to the maximum work done for the deformation [1], are presented in Table [5].

Table 5

σ_{max} (N/m^2)	τ_{max} (N/m^2)	$\sigma_{uk}=\sqrt{\sigma_{max}^2+3\cdot\tau_{max}^2}$ (N/m^2)	$\nu_D=\dfrac{\sigma_D}{\sigma_{uk}}$
$4721\cdot10^5$	$772.5\cdot10^5$	$4907\cdot10^5$	1.43

Stress analysis at the external beam of the axial force element

The external beam loads with respect to the components *RX, RY, RZ, DL, DM* and *DN* are presented in Figs.5,6,7,8,9 and 10, respectively. The cross section characteristics and the load distributions are presented in Table 6.

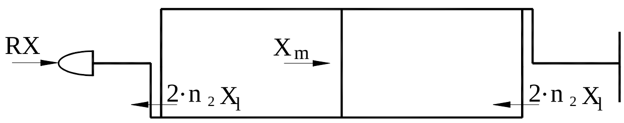


Figure 5. Components of the axial force

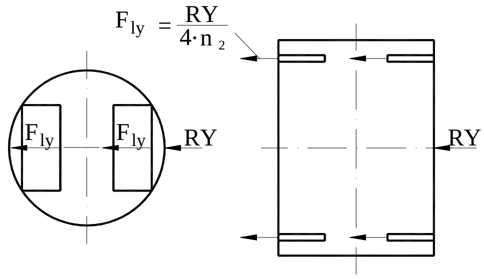


Figure 6. Components of the side force

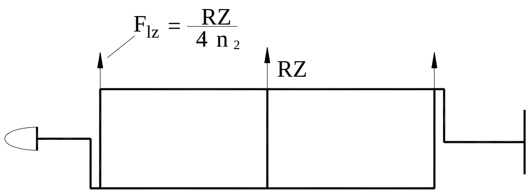


Figure 7. Components of the normal force

Table 6

A_l (m^2)	W_{ys} (m^3)	W_{zs} (m^3)	M_{lx} (Nm)	σ_{lx} (N/m^2)	F_{ly} (N)
$0.019 \cdot 10^{-4}$	$3.041 \cdot 10^{-10}$	$5.896 \cdot 10^{-10}$	0.0368	$1210 \cdot 10^5$	28
M_{ly} (Nm)	σ_{ly} (N/m^2)	σ_{lz} (N/m^2)	F_{ll} (N)	σ_{ll} (N/m^2)	F_{lm} (N)
0.084	$1425 \cdot 10^5$	$300.75 \cdot 10^5$	195.83	$1052 \cdot 10^5$	79.1
σ_{lm} (N/m^2)	F_{ln} (N)	M_{ln} (Nm)	σ_{ln} (N/m^2)		
$424.816 \cdot 10^5$	39.55	0.1187	$2012 \cdot 10^5$		

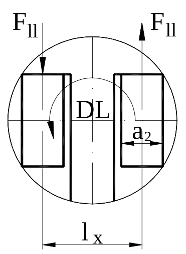


Figure 8. Components of the rolling moment

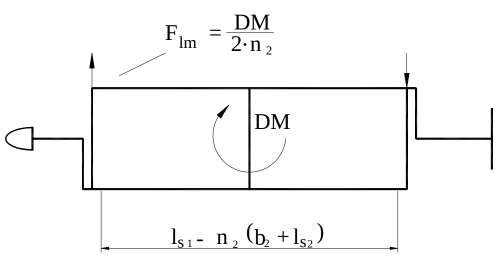


Figure 9. Components of the pitching moment

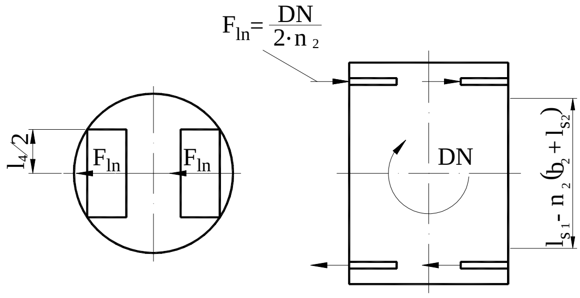


Figure 10. Components of the yawing moment

The value of the total stress in the external beam is

$$\sigma_{ukl} = \sigma_{lx} + \sigma_{ly} + \sigma_{lz} + \sigma_{ll} + \sigma_{lm} + \sigma_{\ln} = 6424 \cdot 10^5 \text{ N/m}^2 \quad (1)$$

The safety factor of the external beam is

$$\nu_{lD} = \frac{\sigma_D}{\sigma_{ukl}} = 1.1 \quad (2)$$

Stress analysis of the critical cross sections of the balance

Cross section (C-C), at the end of the axial force element, and (D-D) at the beginning of the taper for the connection with the sting

The cross section characteristics and the load distributions in the plane *RZ-DM* and *RY-DN*, as well as the corresponding factor of safety are presented in Table 7.

Table 7

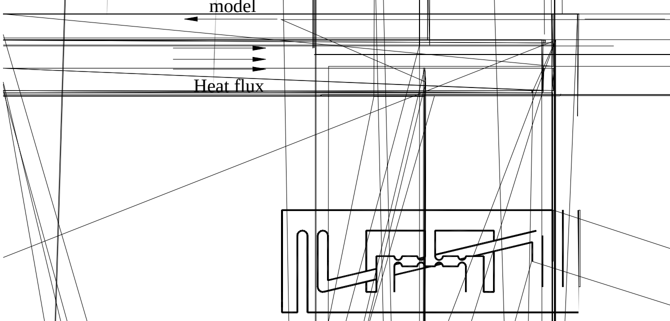
Plane	I_y (m^4)	I_z (m^4)	σ_z (N/m^2)	σ_y (N/m^2)	ν_D
Cross section *C-C*					
RZ-DM	$2.7 \cdot 10^{-10}$	—	$1241 \cdot 10^5$	—	5.64
RY-DN	—	$4.4 \cdot 10^{-11}$	—	$3050 \cdot 10^5$	2.39
Cross section *D-D*					
RZ-DM	$8 \cdot 10^{-11}$	—	$4845 \cdot 10^5$	—	1.45
RY-DN	—	$8 \cdot 10^{-11}$	—	$2422 \cdot 10^5$	2.89

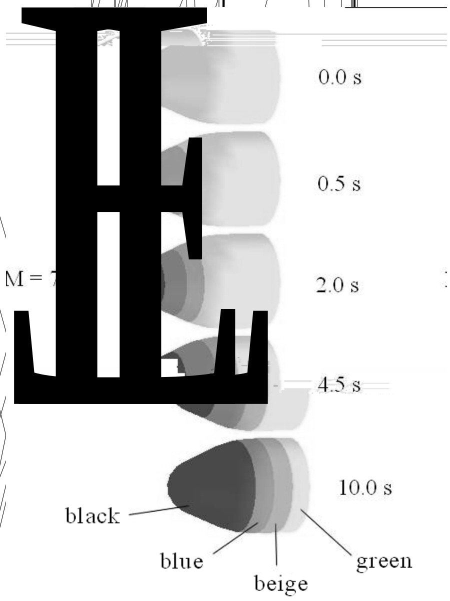
Distinctive features of the hypersonic wind tunnel test of the aerodynamic forces

Due to a high total temperature created at the top of the model, behind the shock wave, heating of the model down the air stream and air circulation from the model basis towards the area of the balance, the bridges of the front and the rear part of the balance will be exposed to different temperature levels.

The measuring bridges are formed from foil “self compensating” strain gauges, of the Micro–Measurement company, series TK, manufactured from Karma, Ni-Cr alloy, with kt=2. They are designed for static measurements with either a long duration period and the temperature range 4–493 K, or a short duration period and the temperature range up to 673 K.

The strain of the internal beam of the axial force element caused by ununiform heating of the front and rear parts of the balance is presented in Fig.11a by a dotted line. A constructive way of decreasing this deformation is presented in Fig.11b.





ga)b)

Projekat šestkomponentne monoblok aerovage za ispitivanje modela letelica u hipersoničnom aerotunelu T-34

Za potrebe ispitivanja modela letelica u hipersoničnom aerotunelu T-34 u VTI VJ projektovana je šestkomponentna monoblok aerovaga. U radu su dati rezultati proračuna čvrstoće aerovage kao i nivoi izlaznih signala sa mernih mostova. Navedeni su problemi vezani za uslove rada u hipersoničnom aerotunelu koje aerovaga mora da zadovolji i način njihovog prevazilaženja.

Ključne reči: **vazdušni tuneli, merna oprema, aerovage.**

Projet de la balance aérodynamique monobloc à six composantes pour examiner les maquettes d'aéronefs en soufflerie hypersonique T-34

Une balance aérodynamique monobloc à six composantes est conçue pour examiner les maquettes d'aéronefs en soufflerie hypersonique T-34 dans l'Institut Militaire Technique de l'Armée Yougoslave. Les résultats de l'analyse de résistance sont donnés aussi bien que les niveaux des signaux de sortie provenant des jauges. On a aussi décrit les problèmes concernant les conditions de travail en soufflerie hypersonique et les méthodes de les surmonter.

Mots-clés: **souffleries, équipement de mesaure, balances aérodynamiques.**