

# External Six-Component Strain Gauge Balance for Low Speed Wind Tunnels

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The external six-component wind tunnel balance designed and manufactured in the Military Technical Institute is described in this paper. The balance is of a platform type. Aerodynamic load which acts on a model in the wind tunnel test section is transferred into the set of six load cells. The relations between the aerodynamic load and the forces measured using the balance load cells are presented. All load cells are gauged with foil strain gauges. The results of the balance calibration are shown. The balance calibration was done using dead weights.

*Key words:* wind tunnel, strain gauge balance, load cell, calibration.

## Introduction

A wind tunnel balance is a structural elastic device designed to measure aerodynamic load generated on a model during a wind tunnel test. Also, a wind tunnel balance supports a model in the wind tunnel test section. One of the balance main functions is to resolve the total aerodynamic load into a number of components (generally between three and six). Many types of wind tunnel balances are possible and each of them is appropriate to a particular set of circumstances. The balance type can be defined by the location at which it is placed. If a balance is placed inside a model, it is referred to as an internal balance [1-6] and if it is located outside of a model or a wind tunnel test section, it is referred to as an external balance.

External balances can be designed as one-piece or multi-piece balances. The one-piece balances are usually referred to as side-wall balances as used in half-model tests [7,8]. The multi-piece external balances usually comprise single forces transducers connected by a framework. Usually, there is plenty of space available around the wind tunnel test section and the construction of an external balance can be optimized with respect to measurement requirements such as optimized sensitivity, stiffness and decoupling of load interactions.

Wind tunnel balance accuracy is a result of a very fragile chain of conditions such as balance design and a balance calibration system. By adequately choosing the balance concept and adequately designing several functional parts of the balance, highly predictable behaviour can be achieved. The accuracy of the calibration equipment and calibration procedures determines directly the accuracy of a wind tunnel balance [9-14].

The external strain gauge platform- and pyramidal-type balances with computer separation of forces and moments

are described in [15]. This computer separation allows for a significant reduction of the calibration procedure and for considerable improvement of measurement accuracy of roll, pitch and yaw moments. The six-component pyramidal type external balances with strain gauge load cells for the low speed wind tunnel in the Korea Aerospace Research Institute and for the low speed wind tunnel in the University Teknologi Malaysia are shown in [16, 17]. These two balances are with a virtual balance moment at the centre of the wind tunnel test section. The external balance with six strain gauge load cells for the measurements in the Subsonic and Transonic Facilities (TA-2) in the Institute of Aeronautics and Space in Brazil can be seen in [18]. The external balances can be used in different types of wind tunnel measurements, and very often they are used in the testing of full-scale automobiles [19].

The six-component external wind tunnel balance, presented in this paper, is designed in the Military Technical Institute (VTI, Belgrade). The load sensing elements are high precision, strain gauged load cells with excellent repeatability and linearity characteristics. The geometrical construction of the load sensing systems allows the complete separation and independent measurement of the six components of the aerodynamic load: lift force, drag force, side force, pitching moment, rolling moment and yawing moment. All balance load cells are made and gauged in the VTI. The balance calibration was done in the T-38 wind tunnel calibration hall.

## Balance design

The external balance is designed for use in wind tunnels with rectangle test sections with dimensions 0.4-0.6 m x 0.4-0.6 m. The recommended speed range for wind tunnel

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testing is up to 50 m/s. The balance is of a platform type, Fig.1. The measuring section which consists of three vertical and three horizontal load cells is situated under the floor of the wind tunnel test section. Table 1 shows the design loads of the balance [20].

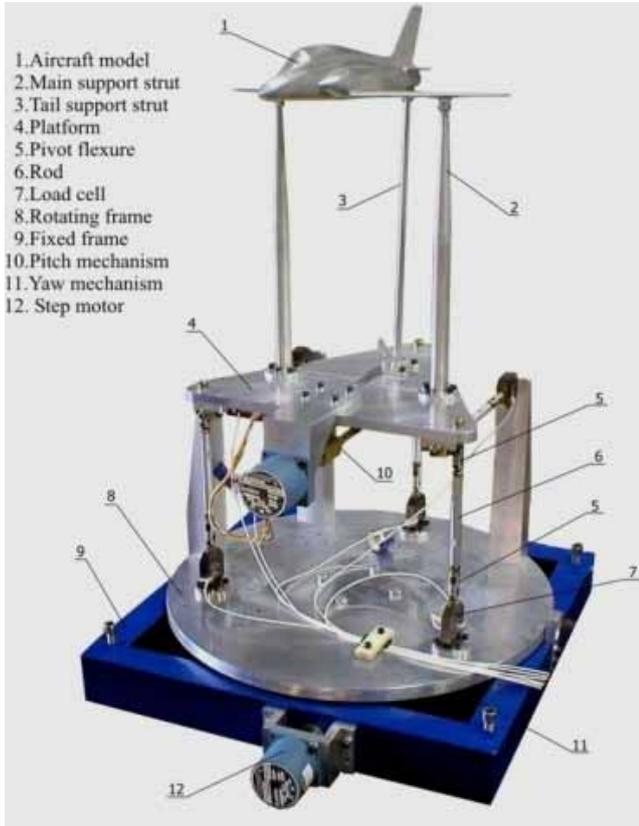


Figure 1. Six-component external balance

The balance consists of the triangle platform connected to the rotating frame through the rods and pivot flexures. A wind tunnel model is connected to the triangle platform by two support struts: the main support strut and the tail support strut. A model movement in the pitch and yaw is fully automated by two step motors with the control unit based on the PC computer. The pitch mechanism is placed on the rotating frame and the yaw mechanism is placed on the fixed frame. The model position mechanism in pitch is of a parallelogram type with a leading screw. The model position mechanism in yaw consists of the worm gearing. The chosen design enables a model position in pitch in the range of  $-20^\circ$  to  $+30^\circ$ , as well as in yaw in the range of  $-180^\circ$  to  $+180^\circ$ .

Table 1. The balance design load

Balance component	Design load
Lift force, (N)	150
Drag force, (N)	100
Side force, (N)	75
Pitching moment, (Nm)	7
Rolling moment, (Nm)	7
Yawing moment, (Nm)	7

Forces and moments that act on a model are shown in Fig.2, where  $V$  is free stream velocity. The main and tail support struts transfer aerodynamic load to the set of the load cells via the triangle platform. All load cells are connected to the data acquisition system. In order to minimize mechanical interference between the measured components, the components of the aerodynamic load are applied to the load cells via rods provided with elastic pivot flexures.

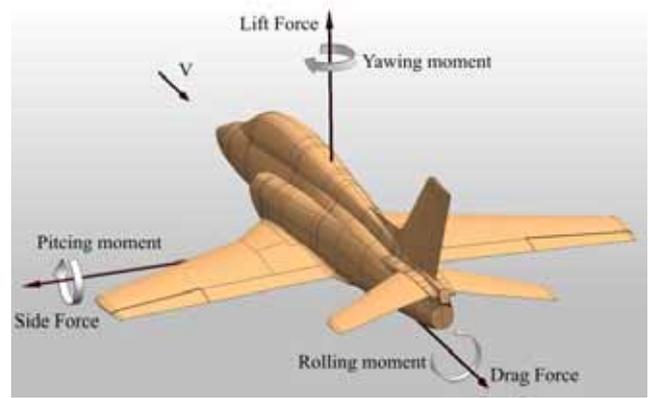


Figure 2. Forces and moments on a wind tunnel model

Arrangement of the six load cells is shown in Fig.3, where  $c_1$ ,  $c_2$ ,  $f$ ,  $l$  and  $n$  are the lengths used in the definition of the relation between the components of aerodynamic load and the forces measured in the load cells,  $O$  is the model referent point,  $O_1$  is the balance referent point,  $x$ ,  $y$  and  $z$  are the system axes,  $X$  is the drag force,  $Y$  is the side force,  $Z$  is the lift force,  $L$  is the rolling moment,  $M$  is the pitching moment,  $N$  is the yawing moment,  $XD$ ,  $XL$ ,  $YY$ ,  $ZPD$ ,  $ZPL$  and  $ZZ$  are the forces measured by the load cells.

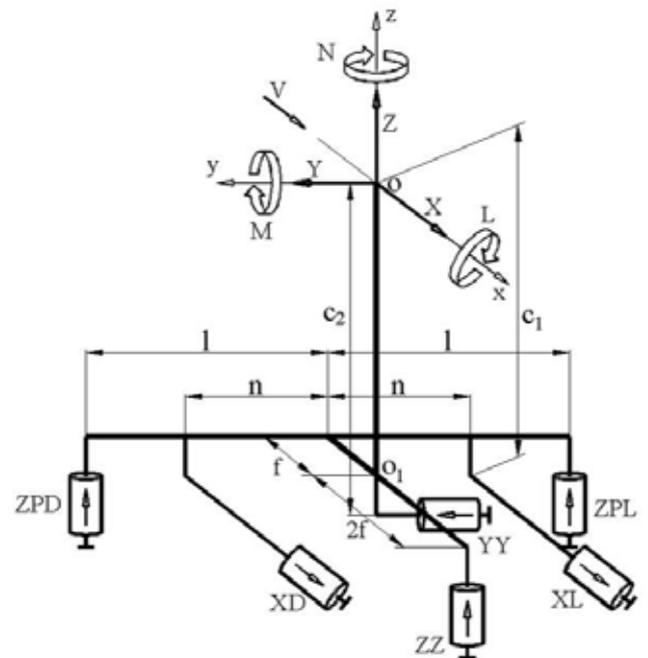


Figure 3. Arrangement of the load cells

The relations between the components of the aerodynamic load and six forces measured by the load cells are given in the equation below:

$$X = XD + XL$$

$$Y = YY$$

$$Z = ZPD + ZPL + ZZ$$

$$L = c_2 \cdot YY + l \cdot ZPD - l \cdot ZPL$$

$$M = -c_1 \cdot XD - c_1 \cdot XL + f \cdot ZPD + f \cdot ZPL - 2f \cdot ZZ$$

$$N = -n \cdot XD + n \cdot XL$$

(1)



Figure 4. Effect of aerodynamic load on the load cells

The rolling moment, pitching moment and drag force effect on the corresponding load cells is shown in Fig.4. The load cells which are loaded are marked with red colour.

### Single-force load cells

Three vertical and three horizontal load cells are based on the measurement of the bending stress. This type of load cells has one main advantage: bending moment always produces a positive and negative stress of the same magnitude. The same magnitudes of the stress make the application of full Wheatstone bridge with two gauges in the tensile strain field and two in the compressive strain field easier. This configuration gives a high output signal for a given strain level and, if the gauges are bonded close together, it minimizes thermal effects.

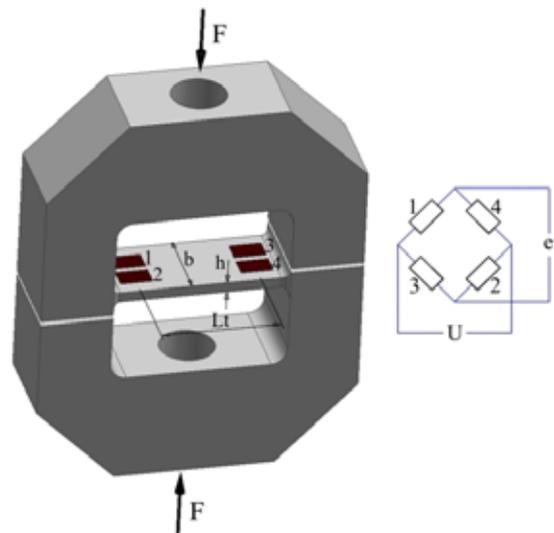


Figure 5. Single-force load cell

All balance load cells were designed with the same design principle. The only difference between them is their load range. The dimensions of the measuring sections were defined according to the load cell range. A single-force load cell is shown in Fig.5, where  $F$  is a force that acts on the load cell,  $L_t$ ,  $b$  and  $h$  are distinctive dimensions of the measuring element,  $e$  is an output signal from the load cell and  $U$  is excitation voltage. Load cells ranges were determined according to the balance components load range. Horizontal load cells are in the range of 100 N while vertical load cells are in the range of 200 N. Material used for cells is high-quality ARMCO PH 13.8-Mo steel, with high mechanical characteristics and high corrosion

resistance. The experience in designing strain gauge balances in the VTI showed that this stainless steel is one of the best choices of material. The selected material has a strong influence on the hysteresis, creep and repeatability of the force transducers.

Bending stress and strain at the strain gauges location are:

$$\sigma_b = \frac{1}{2} \cdot \frac{F \cdot L_t}{b \cdot h^2}, \quad (2)$$

$$\varepsilon = \frac{\sigma_b}{E}$$

Where:  $\sigma_b$  is the bending stress,  $\varepsilon$  is the strain and  $E$  is the modulus of elasticity.

The value of the strain in the horizontal load cells is:

$$\varepsilon_1 = 966.7 \cdot 10^{-6} \frac{\mu\text{m}}{\text{m}}, \quad (3)$$

while in the vertical load cells it is:

$$\varepsilon_2 = 920.5 \cdot 10^{-6} \frac{\mu\text{m}}{\text{m}}. \quad (4)$$

The selection of strain gauges was done in accordance with the values of the measured strain and the dimensions of the measuring sections. The gauge selection process consists of determining the particular available combination of parameters which is most compatible with the environmental and other operating conditions and at the same time best satisfies the balance and operating constraints. The process of gauge selection generally involves compromises. The selection of the optimum strain gauges is an iterative process, moving between the requirements of the load cell and the characteristics of the available strain gauges. The selected strain gauges for all load cells are TK-06-S082R-350 [21].

The optimum strain gauge excitation level depends on the size and type of the strain gauge. Excitation voltage should be as high as possible to get a high output signal, but high excitation voltages heat up the gauge and can produce associated errors. The selected strain gauges and load cells material allow maximum excitation voltages of 20 V [22]. The excitation voltage of 6 V was selected for all load cells. The nominal values of the output signals from the load cells are:

$$e_1 = k \cdot U \cdot \varepsilon_1 = 11.6 \text{ mV} \quad (5)$$

$$e_2 = k \cdot U \cdot \varepsilon_2 = 11.97 \text{ mV} \quad (6)$$

where  $e_1$  and  $e_2$  are the output signals from the horizontal and vertical load cells, respectively, and  $k$  is the strain gauges sensitivity factor.

Before the external balance was assembled, the load cells had been calibrated. The achieved accuracy, for each load cell, was 0.05 % of the cell full scale.

### Calibration of the balance

The calibration process relates the recorded output of the balance measuring bridges to a specified and defined force vector applied to the balance. To obtain the highest quality data during a wind tunnel test, great care has to be taken in both the design of a balance and the choice of calibration methods. The most commonly used method of calibration

consists of the manual application of dead weights. Calibration increments of dead weights are applied to the balance at precise locations relative to the balance reference centre. This process is used for both positive and negative loadings at various stations. The selection of calibration loads is one of the most important elements in the calibration process. Ideally, a balance should be calibrated over only those loads expected during a specific wind tunnel test program. For the most calibration programs, combined load effects must also be developed.

The balance calibration and the wind tunnel test balance data reduction algorithms used in the VTI are a generalization developed upon the concept presented by Galway [23]. This method was further developed and lately it has become known as the "Single-Vector Force Calibration Method" [24]. The generalized calibration method developed in the VTI permits more than one composite load vector to be applied [25,26].

Fig.6 shows the set up for the calibration of the six-component balance. The calibration body was mounted on the supporting struts, replacing a wind tunnel model. The calibration body was made from two crossed beams on which the measured load application points were positioned very accurately. During the calibration, each component was loaded at least 5 increments from zero to the maximum load. The coefficients of the calibration matrix were calculated for each component by the least-squares method using the data from the complete representative load subset.



Figure 6. Calibration of the six-component external balance

In the mathematical model selected for the calculation of the calibration matrix for the new balance, the output signals are expressed as functions of the applied loads:

$$\{e\} = [C]\{F\} \quad (7)$$

where  $\{e\} = \{e_{ZPD}, e_{ZPL}, e_{ZZ}, e_{XL}, e_{XD}, e_{YY}\}^T$  is the

$$[C] = \begin{bmatrix} 7.84296 \cdot 10^{-6} & 2.67539 \cdot 10^{-8} & 2.60566 \cdot 10^{-8} & -1.11741 \cdot 10^{-7} & 2.20897 \cdot 10^{-7} & -5.18028 \cdot 10^{-8} \\ 4.39524 \cdot 10^{-8} & 7.98568 \cdot 10^{-6} & 4.55817 \cdot 10^{-8} & -2.51020 \cdot 10^{-7} & -2.60434 \cdot 10^{-8} & -1.45441 \cdot 10^{-7} \\ -5.28450 \cdot 10^{-9} & -2.74084 \cdot 10^{-8} & 7.89606 \cdot 10^{-6} & 6.19845 \cdot 10^{-7} & 5.08105 \cdot 10^{-8} & -2.20494 \cdot 10^{-8} \\ -6.60848 \cdot 10^{-8} & 1.55969 \cdot 10^{-10} & 9.13932 \cdot 10^{-8} & 1.84165 \cdot 10^{-5} & 5.92386 \cdot 10^{-7} & 2.30471 \cdot 10^{-8} \\ -7.00291 \cdot 10^{-8} & 1.56519 \cdot 10^{-8} & -1.34279 \cdot 10^{-7} & -5.71505 \cdot 10^{-8} & 1.88196 \cdot 10^{-5} & -8.88533 \cdot 10^{-8} \\ 1.99289 \cdot 10^{-7} & 1.36100 \cdot 10^{-7} & 2.32718 \cdot 10^{-7} & -1.56258 \cdot 10^{-7} & -2.09407 \cdot 10^{-7} & 1.86023 \cdot 10^{-5} \end{bmatrix} \quad (8)$$

The accuracy achieved in the balance checkout is displayed on the graphs in Fig.7 where *Err* is the maximum difference between the applied and measured load and FS is the component full scale. The nominal component accuracies (displayed with lines on the graphs) are better than 0.5% FS.

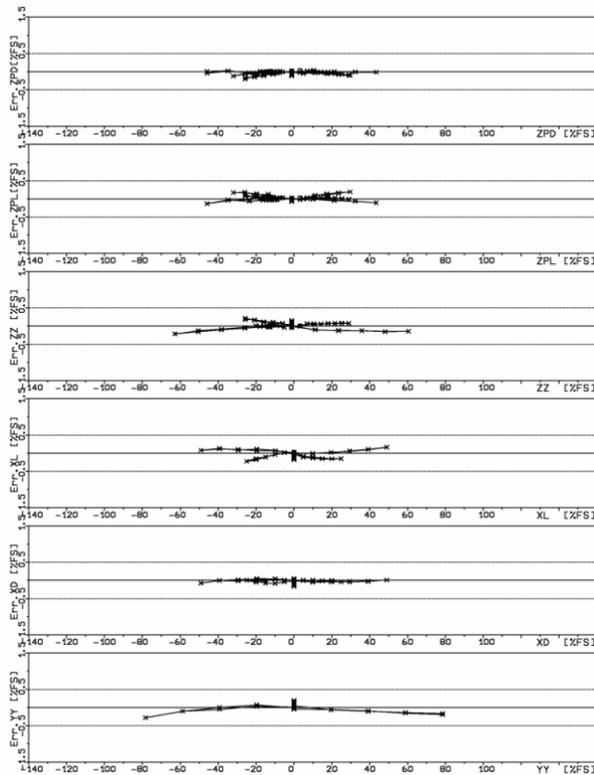


Figure 7. Accuracy achieved in the balance checkout

Tables 2 lists a summary of the achieved accuracy of each load cell as obtained in a checkout after the calculation of the calibration matrix, where  $F_{max}$  is the maximum applied load,  $F_{min}$  is the minimum applied load and *Std.d* is the standard deviation of errors. A checkout was performed on the same load subset that was used to calculate the matrix.

Table 2. Accuracy of the load cells

Load cell	ZPD	ZPL	ZZ	XL	XD	YY
Range (N)	200	200	200	100	100	100
$F_{max}$ (N)	87.00	87.00	121.09	49.03	49.03	78.4
$F_{min}$ (N)	-91.67	-91.67	-125.76	-49.03	-49.03	-78.45
<i>Err</i> (N)	-0.396	0.390	-0.444	-0.226	-0.162	-0.281
<i>Err</i> (% FS)	-0.198	0.195	-0.222	-0.226	-0.162	-0.281
<i>Std.d</i> (%FS)	0.056	0.064	0.080	0.082	0.039	0.084

vector of the output signals from the load cells,  $[C]$  is the balance calibration matrix and  $\{F\} = \{ZPD, ZPL, ZZ, XL, XD, YY\}^T$  is the vector of the balance load cells.

The matrix below shows the obtained calibration matrix:

$$[C] = \begin{bmatrix} 7.84296 \cdot 10^{-6} & 2.67539 \cdot 10^{-8} & 2.60566 \cdot 10^{-8} & -1.11741 \cdot 10^{-7} & 2.20897 \cdot 10^{-7} & -5.18028 \cdot 10^{-8} \\ 4.39524 \cdot 10^{-8} & 7.98568 \cdot 10^{-6} & 4.55817 \cdot 10^{-8} & -2.51020 \cdot 10^{-7} & -2.60434 \cdot 10^{-8} & -1.45441 \cdot 10^{-7} \\ -5.28450 \cdot 10^{-9} & -2.74084 \cdot 10^{-8} & 7.89606 \cdot 10^{-6} & 6.19845 \cdot 10^{-7} & 5.08105 \cdot 10^{-8} & -2.20494 \cdot 10^{-8} \\ -6.60848 \cdot 10^{-8} & 1.55969 \cdot 10^{-10} & 9.13932 \cdot 10^{-8} & 1.84165 \cdot 10^{-5} & 5.92386 \cdot 10^{-7} & 2.30471 \cdot 10^{-8} \\ -7.00291 \cdot 10^{-8} & 1.56519 \cdot 10^{-8} & -1.34279 \cdot 10^{-7} & -5.71505 \cdot 10^{-8} & 1.88196 \cdot 10^{-5} & -8.88533 \cdot 10^{-8} \\ 1.99289 \cdot 10^{-7} & 1.36100 \cdot 10^{-7} & 2.32718 \cdot 10^{-7} & -1.56258 \cdot 10^{-7} & -2.09407 \cdot 10^{-7} & 1.86023 \cdot 10^{-5} \end{bmatrix} \quad (8)$$

The accuracy achieved for the composite loads (calculated components of the aerodynamic load) is listed in Table 3.

Table 3. Accuracy of the composite loads

Component	X	Y	Z	L	M	N
Range (N/Nm)	100	75	150	7	7	7
$F_{max}$ (N/Nm)	98.06	78.45	173.92	3.43	4.12	7.08
$F_{min}$ (N/Nm)	-98.06	-78.45	-154.09	-3.43	-4.12	-7.08
<i>Err</i> (N/Nm)	-0.338	-0.281	0.327	-0.062	0.061	-0.029
<i>Err</i> (% FS)	-0.338	-0.374	0.218	-0.886	0.871	-0.414
<i>Std.d</i> (% FS)	0.103	0.112	0.085	0.213	0.246	0.154

## Conclusion

The six-component external balance described in this article is the first platform type balance designed and manufactured in the VTI. It is shown that the balance has provided very good accuracy. Accurate measurement of the aerodynamic forces and moments is a major task in wind tunnels testing. Usually, design and manufacturing of wind tunnel balances are based on very contrasting requirements. The balance flexure elements should be optimized such that the magnitude of the strain response is approximately the same for the individual application of each component of the load. However, the magnitudes of the loads generated on a wind tunnel model in each balance component are not equivalent; therefore, the flexure elements do not have the same deflection in all directions. Ideally, each balance response signal should respond to its respective component of load and it should have no response to other components of the load. This is not entirely possible. The design of the described balance was optimized to minimize interaction effects.

The result of the calibration is a calibration matrix with six terms per load cells. This was the first calibration of the new balance. The achieved accuracy of all balance load cells in the set is approximately 0.25% within a designed load range (based on three standard deviations), or even better. The accuracy achieved for the composite loads is very satisfactory considering the balance type and its operational requirements. Combined load effects have to be included in the next calibration of the balance. It can be expected that the introduction of load cases with combined load effects will improve the accuracy of balance calibration.

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## Spoljašnja šestokomponentna aerovaga za aerotunele malih brzina

U radu je prikazana spoljašnja šestokomponentna aerovaga projektovana i izrađena u Vojnotehničkom institutu u Beogradu. Prikazana aerovaga spada u grupu spoljašnjih aerovaga sa platformom. Aerodinamičko opterećenje koje deluje na model u radnom delu aerotunela prenosi se na šest mernih ćelija. Prikazane su matematičke relacije između aerodinamičkog opterećenja i sila izmerenih u mernim ćelijama. Sve merne ćelije su sa folijskim mernim trakama. U radu su prikazani i rezultati etaloniranja aerovage. U toku etaloniranja opterećenja su unošena pomoću tegova.

*Ključne reči:* aerotunel, aerovaga sa mernim trakama, merna ćelija, etaloniranje.

## Внешние аэровесы из шести компонентов для низкоскоростных аэродинамических труб

В этой статье представлены внешние аэровесы из шести компонентов, разработанные и изготовленные в Военно-техническом институте в Белграде. Показанные аэровесы принадлежат группе внешних аэровесов с платформой. Аэродинамические нагрузки, действующие на модель в испытательной секции аэродинамической трубы должны быть переданы на шесть измерительных ячеек. Отображаются математические отношения между аэродинамической нагрузкой и силами измеренными в измерительных ячейках. Все измерительные ячейки имеют тензодатчики из фольги. В статье представлены и результаты калибровки аэровесов. Во время калибровки нагрузки добавлены с использованием набора весов.

*Ключевые слова:* аэродинамическая труба, аэровесы с тензодатчиками, измерительные ячейки, калибровка.

## Balance externe de soufflerie pour les souffleries de petites vitesses

Dans ce papier on a présenté la balance externe de soufflerie conçue et réalisée à l'Institut militaire technique à Belgrade. La balance présentée appartient à la catégorie des balances externes à plateforme. La charge aérodynamique qui agit sur le modèle dans la chambre d'essais de la soufflerie est transportée sur six cellules de mesurage. On a présenté les relations mathématiques entre la charge aérodynamique et les forces mesurées dans les cellules de mesurage. Toutes les cellules de mesurage sont munies des jauges à ruban en feuilles. Dans cet article on a donné aussi les résultats de l'étalonnage de la balance de soufflerie. Pendant l'étalonnage les charges étaient introduites à l'aide des poids.

*Mots clés:* soufflerie, balance de soufflerie à jauges à ruban, cellule de mesurage, étalonnage.