UDC: 629.735.3:533.6

DOI: http://dx.doi.org/10.7708/ijtte2022.12(3).10

EXPERIMENTAL DETERMINATION OF AERODYNAMIC CHARATERISTICS OF LIFT AND DRAG IN THE WIND TUNNEL OF AIRCRAT B787 USING THE „FORCE BALANCE“ METHOD

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Received 1 April 2022; accepted 26 July 2022

Abstract: The experimental determination of aerodynamic characteristics of lift and drag of B787 aircraft using the „Force Balance“ method was carried out in the subsonic wind tunnel „Miroslav Nenadović“ of the Faculty of Mechanical Engineering, University of Belgrade. This experimental testing most faithfully represents a real case, and the simulated conditions correspond to the geographic location of Nikola Tesla Airport in Belgrade. This method of testing is considered to be the most reliable. Aerodynamic characteristics were obtained by testing the aircraft model. The reconstruction of the wind field for the intended location was, as with most current assessments, carried out using a numerical model which enables the precise determination of wind zones with adequate characteristics. The accuracy of determining the roughness of the terrain and the influence of obstables were taken into account during the assessment. All the assessments were carried out with the average annual wind speed, as well as on the basis of data on the maximum wind gust in the past hundred years. A numerical three-dimensional meso model was used which was confirmed in our conditions as well. Following that the methodology of testing was determined, the setup in the wind tunnel was made and the experiment was performed. The experiment was carried out for eight directions for the value of the wind strength which was obtained using the numerical model. The measurement was performed using the „Force balance“ method for measuring lift and drag. The load actuators with sensors were used for measuring the forces of lift and drag during the testing. The actuators were connected to the computer via sensors and the data were recorded in real time. The obtain results of aerodynamic characteristics, lift and drag, fall within the range od expected value. On the diagrams shown, it can be observed that the trend of the curves is of a satisfactory character. This methodology of experimental aerodynamics presented in the paper proved to be very reliable for future experimental analyses.

Keywords: eperimental aerodynamics, lift, drag, force balance method, wind tunnel.

1. Introduction

The experimental determination of aerodynamic characteristics of lift and drag of B787 aircraft using the „Force Balance“ method was carried out in the subsonic wind tunnel „Miroslav Nenadović“ of the Faculty of Mechanical Engineering, University of Belgrade. This experimental testing most faithfully represents a real case,

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and the simulated conditions correspond to the geographic location of Nikola Tesla Airport in Belgrade. This method of testing is considered to be the most reliable. Aerodynamic characteristics were obtained by testing the aircraft model.

The reconstruction of the wind field for the intended location was, as with most current assessments, carried out using a numerical model which enables the precise determination of wind zones with adequate characteristics. The position of the platform was determined based on these characteristics. The accuracy of determining the roughness of the terrain and the influence of obstables were taken into account during the assessment. All the assessments were carried out with the average annual wind speed, as well as on the basis of data on the maximum wind gust in the past hundred years. A numerical three-dimensional meso model was used which was confirmed in our conditions as well.

The relief greatly affects the wind at lower altitudes (up to 100 m). The changed path of the wind is a consequence of the obstacles it encounters on its way. A special class of these surface winds are local winds. Knowledge of these winds are most important for assessing the technical capacity of the wind in a continental area. Wind is affected by roughness, natural or man-made obstacles and orography. The roughness of the earth's crust can slow down the wind in a particular location. Forests and large cities can significantly reduce the wind speed, whereas flat surfaces, such as bodies of water, airport runways, highways, do not significantly affect it or have minimal effect on it.

In order to assess the impact of roughness on the wind, the classes of roughness are applied which are expressed by a coefficient that corrects the wind speed. The roughness is classified into several categories. Each class is defined by the roughness coefficient and the energy index. The roughness coefficient is:

- 0.0002 for bodies of water;
- 1.6 for a city zone with tall buildings.

Natural and artificial obstacles (objects, trees, relief) significantly reduce the wind speed and create air current turbulence in the immediate vicinity of the obstacle. The turbulence zone can have a width equal to three times the height of the obstacle. Therefore, it is also important to take into account the sufficient distance of the platform in order to reduce the impact of turbulence as much as possible.

The intensity of the decrease in wind speed due to encountering an obstacle is significant. It is affected by the dimensions of the obstacle, as well as the permeability of the obstacle.

The fact that orography significantly affects the wind speed, i.e. the wind speed can be significantly increased between two tall buildings (the 'tunnel' effect), was also taken into account. The speed increases can be up to 40% compared to the environment.

The wind is defined by the intensity and direction. Both of these quantities change intensively in time. Based on the data from meteorological stations that register data on wind intensity and direction changes usually in ten-minute intervals, as well as based on our own measurements, a wind rose is shown, which contains a display of wind speed and its determining direction. The variation of wind speed is also of great importance. The analyses of changes in wind speed indicate that stormy winds are very rare in this area and moderate or weak winds are the most common.

For the area of Belgrade (the confuence of the Sava and the Danube) the typical wind variation is described by the Weibull distribution (Figure 1). This distribution represents a location with a maximum mean wind speed of 5,16 m/s and a coefficient of the two-parameter Weibull distribution κ=2. The maximum speed averaged over all wind directions is 7,59m/s while the mean speed averaged over all wind directions is 2,74 m/s. The most common speed is 1,17 m/s and it says that the wind will blow at that speed about 65% of the time. By summing each of the speeds multiplied by the probability of its own occurrence, the average speed for the observed location is obtained, which is 3,83 m/s and it represents the modal value of the distribution. The maximum measured speed at this location is 14,8 m/s (53,28 km/h).

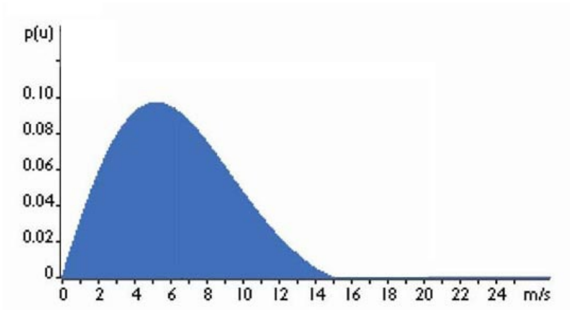

Fig. 1.
Weibull Distribution of Wind Speed Frequency

However, the statistical representaion of wind speeds varies, both in wind speed and in shape. The basis for the analysis of the physical and mechanical characteristics of the wind in Belgrade was anemographic data on wind speed from the main meteorological stations (GMS). The availability of this data is very important when interpreting the results, the data for Belgrade are given in the following table.

Table 1
Wind Speed for Belgrade

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	ANN
94,0	98,9	99,9	100	100	100	100	100	100	100	99,6	98,5	99,2

The average frequency of occurrence of individual wind speeds on an annual basis, measured at a height of 10 m is given in percentages in the following table.

Table 2
The Average Frequency of Occurrence of Individual Wind Speeds

	0	0,3	1	2	3	4	5	6	7	8	9	10	11
%	0,027	0,055	0,304	0,290	0,158	0,081	0,041	0,024	0,012	0,005	0,002	0,001	0

The processed data show that the maximum frequencies appear at wind speeds in the range of 0 to 3 m/s. The occurrence of average hourly wind speeds according to anemographic data on an annual level measured at a height of 10 m is given in percentages in the following table.

Table 3
The Occurrence of Average Hourly Wind Speeds

	0	0,3	1	2	3	4	5	6	7	8	9	10	11
%	100	97,3	91,7	61,4	32,3	16,6	8,5	4,3	1,9	0,8	0,3	0,1	0

It can be seen from the data that the average hourly wind speeds at a height of 10 m above the ground, with an intensity of 0.3 m/s occur almost throughout the year, and that the speed of 9 m/s occurs only one day during the year.

Fig. 2.
Belgrade Nikola Tesla Airport

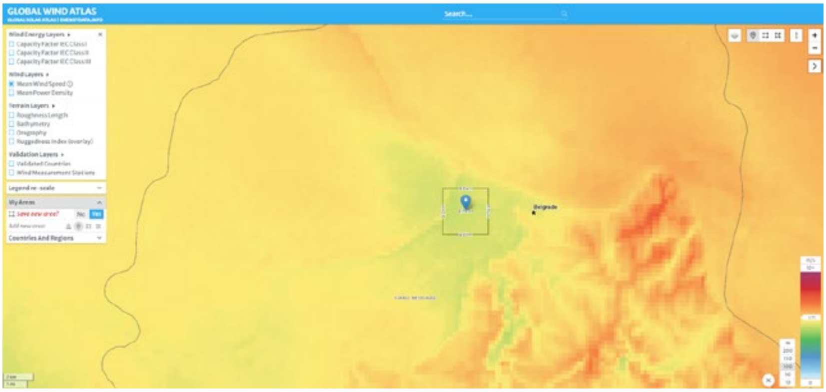

Fig. 3.
Wind Energy Layers Screenshot for Location Belgrade Nikola Tesla Airport

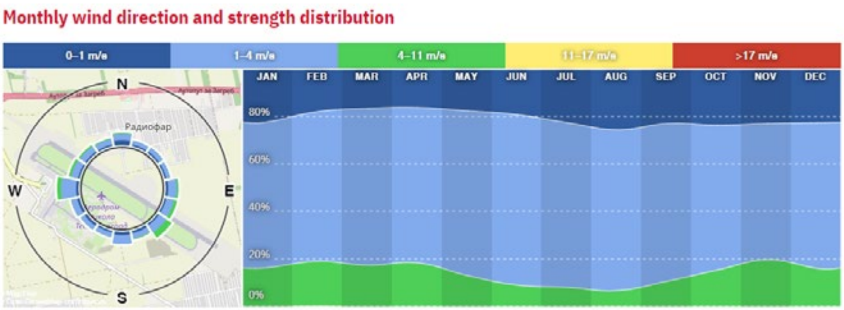

Fig. 4.
Monthly Wind Direction and Strengh Distribution

Fig. 5.
Annual Wind Statistics for Belgrade Nikola Tesla Airport

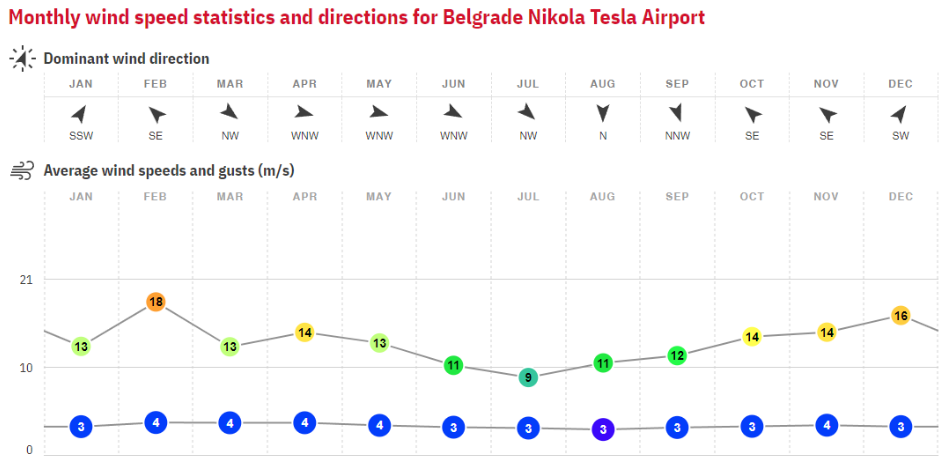

Fig. 6.
Monthly Wind Speed Statistics and Direction for Belgrade Nikola Tesla Airport

Based on all the data presented, a wind rose is shown:

N	6,40	3,87	1,12
NNE	2,20	0,73	0,33
NE	1,80	0,59	0,27
ENE	3,80	1,25	0,57
E	7,70	2,56	1,16
ESE	6,50	2,15	0,98
SE	14,80	4,88	2,22
SSE	8,80	2,90	1,32
S	5,20	1,90	0,66
SSW	2,80	0,88	0,42
SW	4,30	1,42	0,72
WSW	8,80	2,90	1,45
W	13,70	4,52	2,06
WNW	8,60	2,66	1,32
NW	11,30	3,73	1,85
NNW	14,70	6,89	2,35

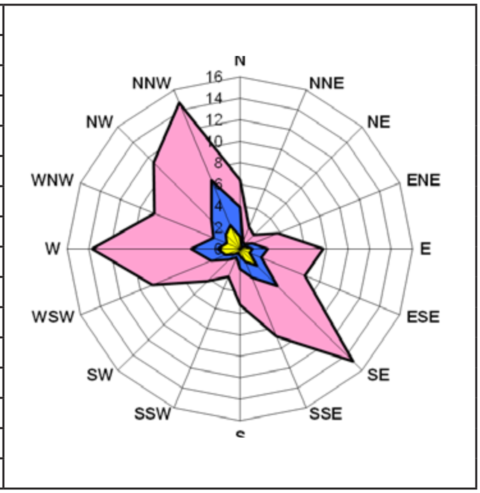

Fig. 7.
Wind Rose for the Location of Nikola Tesla Airport

2. Description of the Wind Tunnel SB-1

The testing was carried out in the aeronautics laboratory „Miroslav Nenadović" in the subsonic wind tunnel SB-1 with a return channel (of the Prandtl type) at the Faculty of Mecanical Engineering, University of Belgrade (Kostic *et al.*, 2017). The cross-section of the collector changes from the stilling chamber, where it is the largest, to the cross-section of the working part. This change in cross-section has the effect of accelerating the undisturbed current field with minimal losses and local velocity deviations. The wind tunnel has an installed power of 200 kW with a propulstion group consisting of one electric motor and a revitalized four-blade propeller of the Thunderbolt P47A aircraft.

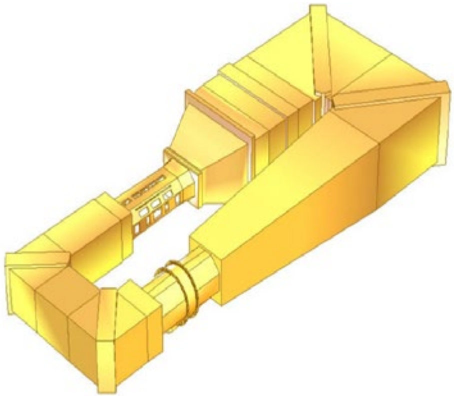

Fig. 8.
Schematic View of the Subsonic Wind Tunnel SB-1

The dimensions of the working part are 2.90 x 2.10 x 6.0 [m]. The basic task of the working part is to achieve the most homogeneous current field of the velocity vector, in terms of direction and intensity, and the least degree of turbulence as well as a certain pressure and temperature, i.e. to create conditions as in a free atmosphere. Since the wind tunnel has the narrowest cross-section in the working part, the highest flow speed is achieved in it.

The wind tunnel is equipped with electronic measuring equipment and it is intended for both fundamental and exploitation and industrial testings up to speeds of 116 [m/s]. The data acquisition and exquisition system consists of: a PCM-PFM 2 digital anemometer connected to a stationary Pitot tube installed in the working part of the wind tunnel, an eight-channel QuantumX MX840A that monitors all the auxiliary parameters, a 60-channel multimanometer with BOSH BMP280 sensors, PIV Litron Lasers with the Model 640050 camera system, the Dell Precision T7600 super computer station (Cores 24, 256GB RAM memory) where all sensor parameters are monitored and saved in real time.

It is very easy to place the model on the rotating platform in the working part of the wind tunnel which achieves optimal testing conditions.

The model is placed on a turntable which ensures rotation and placement of the entire model in the desired wind direction.

The measurement was performed using the „Force balance" method for measuring lift and drag. The method uses two load actuators with sensors, one for measuring the force of lift and the other one for measuring the force of drag. The actuators are connected to a computer via sensors and the data are recorded in real time.

3. Methodology

The effects of air current acting on the model in the working part of the wind tunnel are the resulting aerodynamic force and the corresponding aerodynamic moment. The resulting force and moment are decomposed into components in the direction of the axes of the adopted coordinate system (there are six of them in total). In addition to the basic task of measuring these components of forces and moments, the aerodynamic balances must enable the measurement of other equally important paramenters (e.g. angles of attack, turning angles, etc.) (Mitrovic, 2016).

These tasks are very complex. In order to obtain reliable and operationally usable results, construction of the aerodynamic balance must meet the following requirements:

- Separation of components – if, for example in a passenger airplane only 5% of the lift is „incorporated" into the drag, the measured drag could be as much as twice the actual.
- Accuracy and reliability – in the required range of speed measuring, Mach numbers, angles of attack, angles of turn, etc.
- Compactness, stability and strength – deflections of parts of the aerodynamic balance comstruction of only a few millimeters can, for example, in some cases lead to an impermissibly large change in the angle of attack of the model.

For the construction of aerodynamic balance it is necessary to know that they can be classified in several ways: according to the number of components that they can measure, according tho the method of measurement (the principles according to which the force transducers work) and according to the type (i.e. placement within the testing installation).

The model of the distribution of force dependence in connection elements shown in Figure 6 was chosen for the purpose of testing:

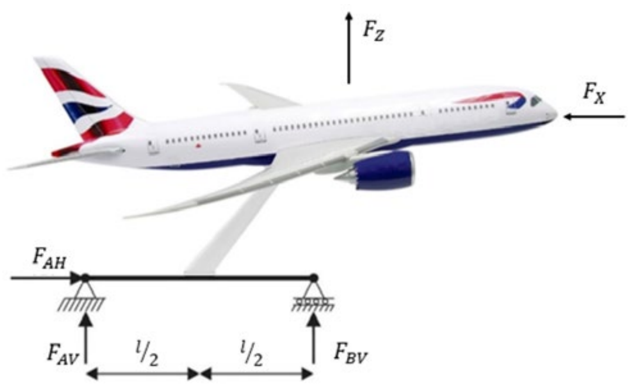

Fig. 9.
Load Distribution Model

Static equilibrium equations:

$$\sum_{i=1}^{n} F_{ix} \qquad \sum_{i=1}^{n} F_{iy} \qquad \sum_{i=1}^{n} M_A$$

That is:

$$F_{AV} + F_{BV} - G = 0$$
$$F_{AV} + F_{BV} = F_z$$
$$F_{AH} + F_X = 0$$
$$F_{BV} \cdot l + F_X \cdot h - G \cdot \frac{l}{2} = 0$$

where:

F_{AV}, F_{BV}	-	vertical components of forces in supports A and B
G	-	the entire system weight
F_{AH}	-	horizontal component of the drag in support A
F_X	-	component of the aerodynamic force of drag
F_Z	-	component of the aerodynamic force of lift
l	-	span between supports A and B
h	-	height of the point of attack of the aerodynamic force of drag

By changing the speed of the undisturbed current field, i.e. by changing the aerodynamic forces of lift and drag, the intensity of the forces in the fastening supports changes.

Experimental testing involves measuring the vertical and horizontal components of the forces in the supports, for different speed of air flow, in different positions of rotation.

A dedicated aerodynamic balance was constructed for the purpose of experimental testing which consists of:

- rigid spatial construction;
- four supports positioned on linear bearings in order to detect the vertical components of the forces; and
- one stationary support for measuring the aerodynamic force of drag.

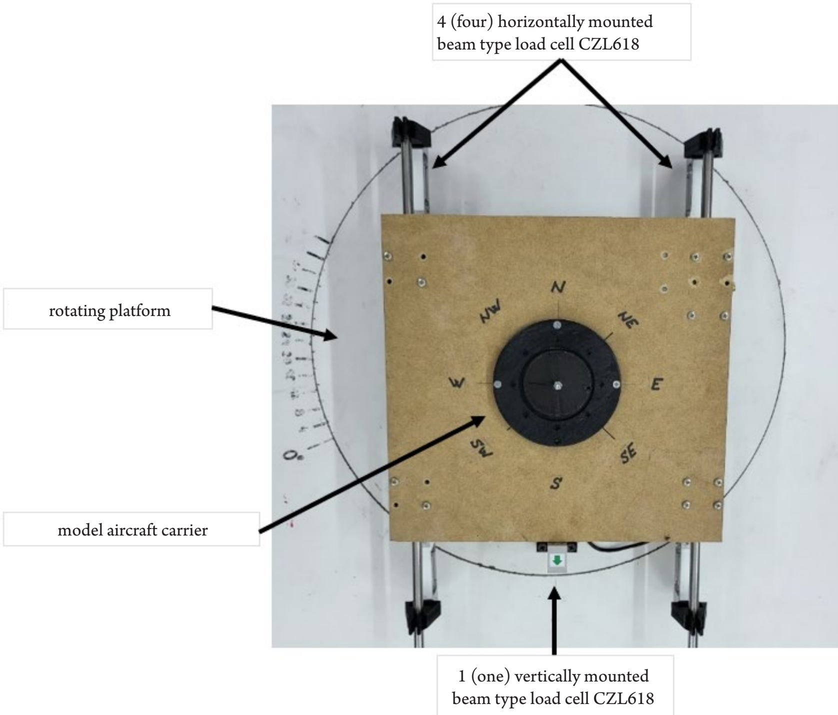

Fig. 10.
Construction of the Dedicated Aerodynamic Balance

The sensors are positioned according to the dimensions of the rotating plate of the aerodynamic balance. The distribution of vertical and horizontal loads, as a consequence of the complex vector component of the aerodynamic forces of lift and drag, is detected using the CZL618 force transducer:

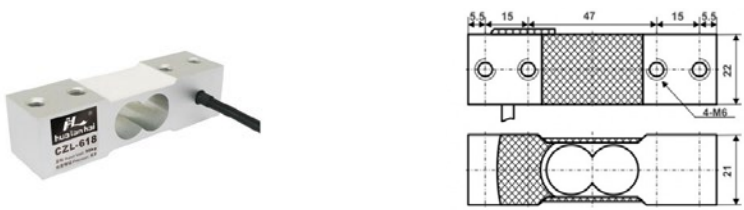

Fig. 11.
Sensor CZL618

Table 4
The Sensor Characteristics

Maximum Error	0,02% F.S.
Output	1.5±0.01mV/V
Non-linearity	0,02% F.S.
Repeatability	0,02% F.S.
Null	1% F.S.
Input Drag	1000±10Ω
Output Drag	1000±10Ω
Insulation Drag	>=5000MΩ(100VDC)
Power Supply	9~12V
Protection	IP65

Transducers are connected to a QuantumX MX840A full-bridge measurement acquisition unit as directed by the transducer documentation. Calibration of the transducer is performed in the Laboratory using the method of comparison with reference masses. Calibration values with real-time reading rates are included in the measurement protocol and test results tables. Software for data acquisition and processing is HBM CatmanEasy AP 3.51 (Nijemcevic *et al.,* 2017). The placement of the carrier model and the placement of the model aircraft are shown in the following figure.

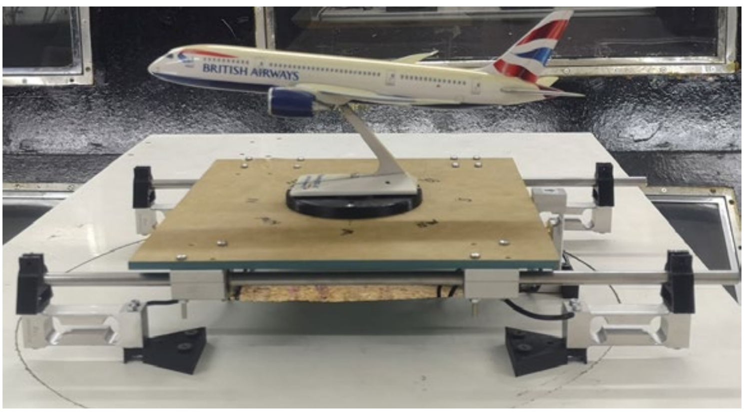

Fig. 12.
Display of the Model Placement in the Wind Tunnel

The testing was performed in the wind tunnel for all the mentioned platform rotation angles and the directions of the undisturbed current field (N, NW, W, SW, S, SE, E, NE) up to a maximum speed of 15 m/s.

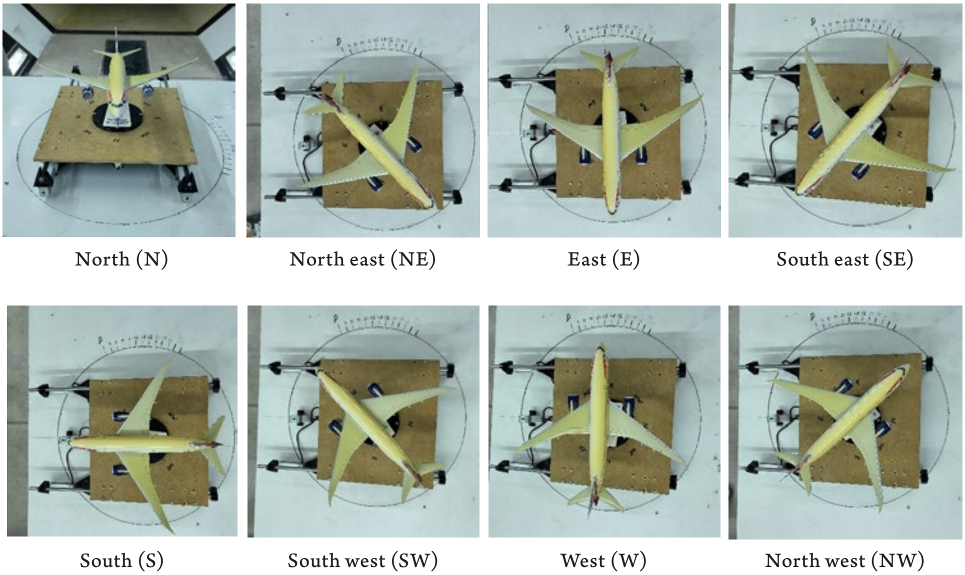

Fig. 13.
Positions of the Model during Testing

3.1. Results and Discussion

The testing was performed in the wind tunnel for all the mentioned platform rotation angles and the directions of the undisturbed current field up to a maximum speed of 15 m/s.

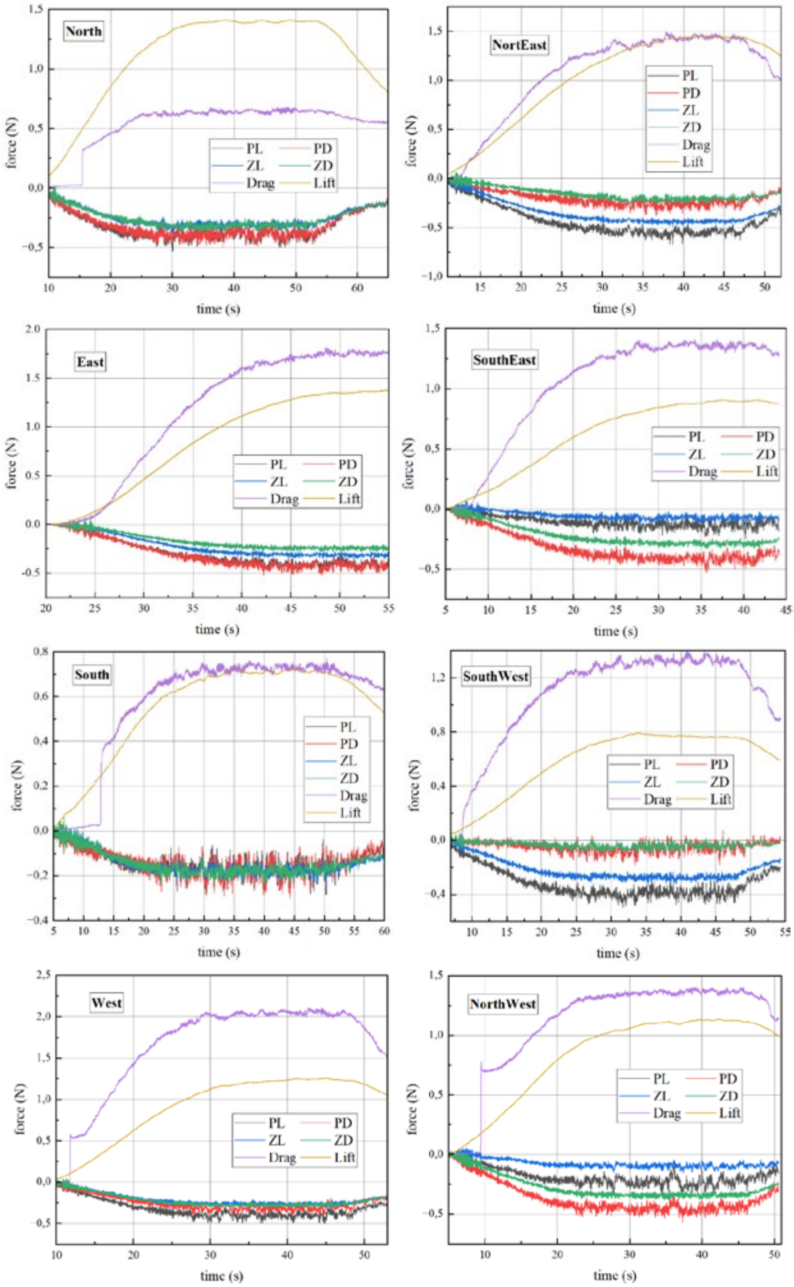

Fig. 14.
Testing Diagrams

Summary load of the structure in the wind field is presented below.

Direction of flow	Drag Fx [N]	Lift Fz [N]
N	0.6778	1.4105
NE	1.4901	1.4493
E	1.8195	1.3794
SE	1.4111	0.9062
S	0.7717	0,0402
SW	1.3957	0.7923
W	2.1106	1.2556
NW	1.4050	1.1357

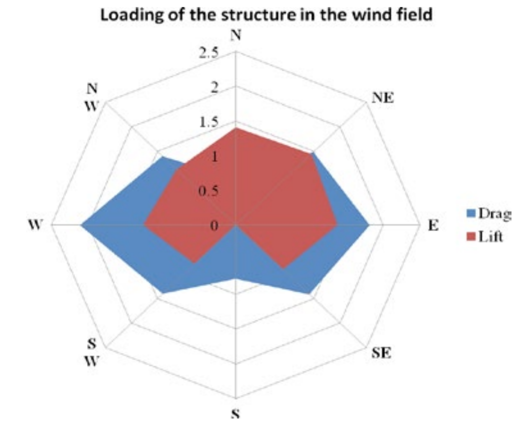

Fig. 15.
Summary Load of the Structure in the Wind Field

4. Conclusion

The model was placed on the rotating plaftorm in the working part of the wind tunnel and the testing was carried out.

By analyzing all the results it can be concluded:

- that the load distribution is optimized by even placement of masses in all elements of the B787 aircraft;
- that the load distribution of the supports, as well as the total vertical load, is within the limits, i.e. much lower than the permitted loads;
- that the load distribution is in the direction of flow of the undisturbed current field with extremes lower than the total load along the vertical axis;
- that the aerodynamic characteristics are less than theoretical settings of aerodynamics;
- that the force of drag and the force of lift are much less than the weight of the empty aircraft at 15 m/s wind speed (calculated by the similarity method the maximum force of drag Rx is 211,060 [daN] and the force of lift Rz is 144,930 [daN] while the weight of the empty aircraft G is 113.045,000 [daN]).

The obtained results of aerodynamic characteristics, lift and drag, fall within the range of expected values. It can be observed on the diagrams shown that the trend of the curves is of satisfactory character. The methodology presented in the paper proved to be very reliable for the future experimental analyses.

Acknowledgement

This research was supported by the Ministry of Education, Science and Technological Development, Republic of Serbia – projects: TR35035, TR36001, TR35046.

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