



Design of an Optimal Tilt Measurement Unit for Wind Tunnel Balance

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Abstract

The wind tunnel is one of the most widely used equipment in the design of flight vehicles to investigate the aerodynamic pre-flight behavior of these vehicles. On the other hand, one of the most essential parts of the wind tunnel is the balance tilt measurement unit which measures the orientation of the balance at movements with high accuracy. There are several ways to design the tilt measurement unit of wind tunnel balance. One of them is to use a proper and efficient accelerometer with considerations in selecting, and installing accelerometers for designing the tilt measurement unit of wind tunnel balance. These Considerations are necessary to reduce the measuring error and make the test results reliable. In this paper, the important parameters in implying the accelerometer for the design of the tilt measurement unit for wind tunnel balance of Shiraz University are investigated. At first, the effective parameters will be presented and then the proper accelerometers can be used in practice are introduced. In the following, several ways to install and use these accelerometers will be presented and then the most optimal design method will be selected.

Keywords: Wind tunnel, balance, tilt measurement unit, accelerometer; calibration.

Introduction

Wind tunnels are utilized in the analysis of an aircraft's behavior at various flight velocities. The importance of wind tunnels lies in the extraction and examination of aerodynamic forces and moments on each flying vehicle [1]. In other words, designers rely on wind tunnels to ensure the accuracy and efficiency of their designs. The aerodynamic data of each vehicle is critical for implementation in the design of the aircraft's control system [2]. Among these, dynamic balancing is a crucial aspect of wind tunnels, where a model is installed and aerodynamic forces and moments are measured at different angles of attack and various wheel positions. The proper installation and calibration of the balance are essential for minimizing potential errors, and it is considered a crucial pre-launch activity in wind tunnel testing [3]. Therefore, it is imperative to use a suitable angle sensor to measure the angle of attack and wheel position for dynamic balancing purposes [4].

There are various methods for designing an angle sensor, such as electrolytic angle sensors [5], gyroscopes [6], optical methods [7], laser-based methods [8], and the use of accelerometers. Proper sensor connection and calibration are also of great importance [9]. In 2000, On [10] introduced a new optical method and claimed to measure tunnel wind angle deviations with an accuracy of 0.006/0 degrees. He was able to eliminate the error caused by the bending of the tunnel wind balance during testing. This method uses a light beam whose deviation from equilibrium is proportional to the change in the angle of the balance. In 2002, Wang [5] investigated the behavior of three electrolytic angle sensors for measuring tunnel wind attack angles in the laboratory and selected the most optimal ones. Additionally, these angle sensors were compared with an accelerometer, which was estimated to have one order of magnitude lower accuracy. Therefore, although these sensors have a lower cost, their performance is unacceptable. In 2008, Röger [6] presented a system for measuring dynamic balance angle using a gyroscope (Gyro attitude position system) and evaluated its performance. He was able to eliminate the error caused by the bending of the balance in calculations. In 2019, Yang and his colleagues [11] designed a complementary nonlinear filter using quaternions, which reduced measurement errors. Initially, the system was tested in a wind tunnel using a PI control system to eliminate noise. The accuracy of measuring pitch and roll angles using this method was calculated to be approximately 0.05/0 and 0.08/0 degrees, respectively.

Today, accelerometers have numerous applications in the industry. These include smart watches, underwater computers, new generation safe engines [12], or stable engines, computer gaming consoles [13], smart mobile phones [14], animal motion studies [15], human studies [16]-[18], motion correction devices [19], and various methods of navigation and guidance ([20] and [21]). One of the most important and essential applications of accelerometers is their use in designing tunnel wind angle sensors. The high accuracy and repeatability of accelerometers make them suitable tools for designing angle sensors. These sensors measure the direction vector of gravity, pitch angle, and roll angle.

However, the application of angle measurement using accelerometers is limited to static or quasi-static conditions. In quasi-static conditions, other errors may occur at high frequencies and during amplitude drops ([22] and [23]). During installation and use of accelerometers on the balance for angle measurement, accelerometer calibration is of great importance. The most common method of using accelerometers for designing angle sensors is using three-axis accelerometers and the inverse tangent relationship [25]. However, there are also various other methods that may have advantages.

This article aims to design an efficient angle sensor for use in wind tunnel dynamic balancing by conducting necessary investigations and selecting a suitable accelerometer. In order to design an angle sensor with appropriate accuracy and measurement range, the type of accelerometer, its orientation, and initial position must be selected properly. The results have shown that during construction and installation, the axes of the accelerometer may have errors of up to 1.0 degrees, which can be eliminated by proper accelerometer orientation. One of the solutions for designing an angle sensor is using three-axis MEMS accelerometers and using tangent formulas [26]. However, this article also mentions cases where the use of two-axis accelerometers may improve the design quality.

The current article consists of the following sections: In section 2, the theory of using accelerometers for designing a suitable angle sensor for wind tunnels is presented. In this section, coordinate axes and gravity acceleration components, as well as existing relationships for calculating angles and calibrating accelerometers, are provided. In section 3, the experimental results of a calibrated accelerometer are presented as an example to better understand the behavior and measurements of accelerometers. In section 4, the necessary features of a suitable accelerometer for use in a wind tunnel dynamic balancer are introduced. After that, in section 5, MEMS accelerometers are reviewed and introduced. In section 6, all methods of connecting different types of accelerometers (single-axis, dual-axis, tri-axis, and multi-axis) to the dynamic balancer are demonstrated visually with relevant explanations. In section 7, available and efficient accelerometers for designing and constructing wind tunnel angle sensors are introduced and compared. Finally, in the conclusion section, the most suitable available accelerometer for use in the Shiraz University wind tunnel is selected and introduced as an example.

Theory

The most common method of defining orientation is by using the angles of roll (ϕ) and pitch (θ) according to the definitions in aeronautical concepts. As shown in Figure 1, the angle (ϕ) is considered as the roll angle, as it is directly measured by the accelerometer. The $s_1s_1s_3$ coordinate system is the body frame attached to the measurement system and rotates with it, while the $x_0y_0z_0$ coordinate system is the inertial and stationary frame.

Figure 1: Definition of coordinate systems and angles on a dynamic balancing accelerometer

As shown in Figure 1, the relationship between gravity acceleration (g) and its components () is represented in equations (1) to (4).

(1)



(2)

(3)

(4)

The most accurate formulas for calculating roll and pitch angles are (5) and (6) [25]:

(5)

(6)

Where are the accelerometer components in the body frame. On the other hand, the placement and initial position of the accelerometer are crucial for the accuracy of the angle sensor [27].

As mentioned in the introduction, the use of accelerometers in angle sensor design requires calibration. This enables measuring two important parameters of the accelerometer's analog output signal, which include offset and gain. One of the simplest ways to calibrate accelerometers is using the following equations (7) to (9).

(7)

(8)

(9)

In the above equations, represent the voltage signal corresponding to the axes . and , indicate the offset and gain of the signal , respectively. The calibration process of accelerometers enables determining the uncertainty of angle measurements ([28] and [29]). In cases where there are severe vibrations, the use of accelerometers can be problematic. The effect of these vibrations can be reduced by applying a second-order low-pass filter to the measurements [30].

Various methods for calibrating accelerometers have been studied and analyzed in different references. Generally, the main principle of calibrating accelerometers is that in a static and level position, the sum of the measured accelerations by the accelerometer is equal to the magnitude of the gravitational vector. As shown in equations (7) to (8), 6 parameters must be determined for calibrating accelerometers that are placed in 6 or 12 different orientations [31]. Figure 2 shows the wind tunnel balance and the installed model at Shiraz University.

Figure 2: Shiraz University wind tunnel balance and the installed model

In the following figures, various placement configurations and proposed initial positions for accelerometers are shown based on the number of sensitive axes.

Test results of an accelerometer from Analogue Device:

In this section, the experimental results of a calibrated accelerometer are presented as a sample to provide a better visual understanding of its behavior and measurements. This accelerometer is from Analogue Device. Figure 3-A shows the acceleration measurements along the s_1 axis. As observed, the measured value is around -0.3 m/s^2 .

a

b c

Figure 3: a) Analogue Device sensor measurement unit, b) Acceleration measurements along the s_2 axis, c) Acceleration measurements along the s_1 axis.

Figure 3-B shows the acceleration measurements along the s_2 axis. As shown, the measured value is around -0.7 m/s^2 . In Figure 4, the acceleration measurements along the s_3 axis are presented. As seen, the measured value is around -9.83 m/s^2 .

Figure 4: Acceleration measurements along the s_3 axis.

In Figure 5-a, the results of the measured pitch angle over time are shown. The measured angle is around 1.8 degrees. In Figure 5-b, the results of the measured roll angle over time are shown. The measured angle is around 0.42 degrees.

b) a)

Figure 5: a) Results of pitch angle measurements by accelerometer b) Results of roll angle measurements by accelerometer.

The results obtained by the accelerometer show significant vibrations, which are visible in the figures. These noises are caused by the natural behavior of the accelerometers, and they can be smoothed out using common filters.

Suitable features of accelerometers for dynamic balance angle measurement.

Accelerometers can be single-axis, dual-axis, tri-axis, or multi-axis. The use of multi-axis accelerometers (more than three axes) can increase their accuracy by up to 13% [27]. If the correct method is used for angle measurement, increasing the number of sensitive axes can improve accuracy. The axes of the accelerometer may not be perpendicular in certain cases (e.g. in accelerometers with multiple axes). The selection of the number of accelerometer axes for angle measurement depends on the desired range of the angle sensor, the type of angle sensor, and the mathematical equations used to obtain the angles. As mentioned before, increasing the number of sensitive axes of the accelerometer can improve the measurement accuracy. However, instead of using a three-axis accelerometer with three sensitive axes, using two two-axis accelerometers with two sensitive axes may have higher accuracy, despite the increase in cost, as in some cases, the accuracy of installing the third axis of three-axis accelerometers is not high, and the noise of acceleration measurement along the third axis is higher, which can increase the error in angle measurement.

In cases where only one angle is measured, but multiple sensitive axes are used, to increase the measurement accuracy, none of the sensitive axes should overlap with the desired angle axis [25]. If one sensitive axis is sufficient for angle measurement and a small angle with high precision is desired, the sensitive axis should be horizontal. If a large angle (greater than 45 degrees) is to be measured, the sensitive axis should be vertical.

When two sensitive axes are used for angle measurement, if there is one angle to be measured, one sensitive axis should be horizontal and the other vertical, and when there are two angles to be measured, both sensitive axes should be horizontal.

On the other hand, accelerometers are more suitable for making dynamic balance angle sensors if their power supply voltage is more stable. Another criterion for selecting accelerometers is to have a lower bandwidth, which reduces the measurement noise [32]. Table 1 shows the characteristics of suitable accelerometers for making dynamic balance angle sensors for wind tunnels:

Table 1: Specifications of suitable accelerometers for designing dynamic balance angle sensors for wind tunnels

2 g Working range

2g

Bias stability

Standard

(in the range of 30 degrees) Linearity

2000 g Shock tolerance in the environment

For use in balance, it must be selected with high accuracy (should be small) Sensor size

must be provided with high accuracy and stability Required sensor power

Using MEMS accelerometers for dynamic balance angle sensors

When using MEMS sensors, problems such as thermal drift, long-term drift, and installation errors between sensors can occur. If the installation error between sensors is inevitable, it must be compensated before use in the laboratory using precise calibration tables.

In some types of accelerometers, in addition to the calibration performed by the manufacturer, another calibration step is also required during testing by the user.

If a three-axis accelerometer is used to measure one or two angles, it is necessary to first identify the axis with the most error and noise (in many cases, the s_3 axis of the accelerometer has this feature) and not use it in calculations. Therefore, for example, for measuring an angle in one axis, it is better to use the arrangement shown in figure 6-a instead of figure 6-b, so that the s_3 axis with more noise is not included in the calculations. Therefore, in order to reduce the installation error of sensitive axes, it is better to use the arrangement shown in figure 6-a instead of figure 6-b.

b) a)

Figure 6: a) Accelerometer arrangement (axis of rotation is s_2 axis) b) Accelerometer arrangement (axis of rotation is s_3 axis)



If measurements are to be made in two axes and the pitch angle (θ) needs to be measured with higher accuracy, it is better to use the arrangement shown in figure 7-a. If the roll angle (ϕ) needs to be measured with higher accuracy, it is better to use the arrangement shown in figure 7-b.

a b

Figure 7: a) Accelerometer arrangement (measuring angle θ by axis increases the accuracy of this angle.) b) Accelerometer arrangement (measuring angle θ by axis reduces the accuracy of this angle.)

Using suitable accelerometers and arrangements, it is possible to achieve an accuracy of less than 0.1 degree in angle measurements. Arrangements shown in figures 9 to 11 are suitable for reducing the effects of errors caused by the non-uniformity of materials used in manufacturing accelerometers, and in some cases, they can reduce the measurement error of angles up to one degree.

Selecting the Best Accelerometer Arrangement

In order to choose the best accelerometer arrangement, in addition to the mentioned factors, it is necessary to try different arrangements through trial and error. Different methods of installing accelerometers on the wind tunnel balance are shown in the following figures, which depends on the number of accelerometer axes. It should be noted that in order to measure angles in the complete range of 0 to 360 degrees, the accelerometer vector must be examined. If the angle falls within the range of 90- to 90+, the accelerometer vector will be positive, and otherwise it will be negative. In this case, the accelerometer must have two axes[27]. Accelerometers are divided into single-axis, dual-axis, tri-axis, and multi-axis categories based on the number of sensitive axes. In the following figures showing the arrangement of accelerometers, the sensitive axes are identified as s_1 , s_2 , s_3 , and s_4 . The coordinates x_0 , y_0 , and z_0 form the inertial coordinate system, and the angle between the sensitive axes of the accelerometer (s_1 , s_2 , s_3 , and s_4) and these axes is called the pitch angle and roll angle. In other words, the angle between one of the sensitive axes of the accelerometer and the x_0 axis is called the pitch angle, and the angle between one of the sensitive axes of the accelerometer and the y_0 axis is called the roll angle. In many accelerometer arrangements, the sensitive axes are initially aligned with the coordinate system axes, and after the wind tunnel balance rotation, an angle is created between these axes, which is the desired angle for measurement. In the following, a set of equations will be presented, the final result of which is similar to equations (5) and (6). However, depending on the different accelerometer arrangements, the use of some of these equations can reduce the computational error to an acceptable level. The measurements required in the wind tunnel include pitch angles (or angle of attack in the case of flow parallel to the tunnel wall) and roll angles, which are determined by the presented equations and figures with θ and ϕ , respectively. Although the angle ψ is not applicable in wind tunnel calculations, it is included in this section for completeness. It should be noted that the angle ψ is not the rotation angle around the z_0 axis, but the angle between the sensitive axis and the z_0 axis. Because measuring the rotation around the z_0 axis (yaw angle) is not possible using an accelerometer.



(10)

(11)

(12)

(13)

(14)

(15)

(16)

(17)

(18)

(19)

Explanation of the Parameters Mentioned in the Above Equations in Figures 8 to 15. The arrangements presented in these figures are various methods of installing accelerometers on the wind tunnel balance. Table 2 presents the different arrangements and identifies the best equation for each arrangement.

Table 2: Equations for Calculating Angles for Different Arrangements

Optimal Equation Number for Calculating Angles	Arrangement Number
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θ : Equation (10) Figure 8-a

Ψ : Equation (17) Figure 8-b

θ : Equations (16), (15), and (10) Figure 9-a

θ : Equation (10) ϕ : Equation (11)

Figure 9-b

θ : Equation (10) ϕ : Equation (13)

Figure 10-a

θ : Equation (12) ϕ : Equations (14) and (11)

Figure 10-b

θ : Equations (16), (15), and (10)

Figure 11-a

θ : Equations (5), (12), and (10) ϕ : Equations (14), (6), (13), and (11)

Figure 11-b

θ : Equations (16), (15), and (10)

Figure 12-a

θ : Equations (5), (12), and (10) ϕ : Equations (14), (6), (13), and (11)

Figure 12-b

θ : Equations (20), (18), and (17)

Figure 13-a

θ : Equations (5), (12), and (10) ϕ : Equations (14), (6), (13), and (11)

Figure 13-b

θ : Equations (16), (15), and (10)

Figure 14-a

θ : Equations (5), (12), and (10) ϕ : Equations (14), (6), (13), and (11)

Figure 14-b

θ : Equations (19), (18), and (17)

Figure 15

Table 3 provides additional information on the initial positioning of the accelerometers for different arrangements. In this table, the symbol \parallel indicates alignment between two axes, and the symbol \nparallel indicates non-alignment at the time of accelerometer installation.

Table 3: Initial Positioning of Accelerometers for Different Arrangements

Initial Positioning of Accelerometers Arrangement Number

Figure 8-a

Figure 8-b

Figure 9-a

Figure 9-b

Figure 10-a

Figure 10-b

Figure 11-a

Figure 11-b

Figure 12-a

Figure 12-b

Figure 13-a

Figure 13-b

3/35 3/35

Figure 14-a

3/35 3/35

Figure 14-b

7/54 7/54

Figure 15

In the following, we will discuss some aspects of the mentioned arrangements:

1. The arrangements of Figures 8-a, 9-a, 9-b, and 11-a are well-known and commonly used.
2. The arrangement of Figure 8-b is a common method for measuring angles using a single-axis accelerometer.
3. The arrangements of Figures 10-a and 10-b are suitable for measuring the full range of two angles using only two sensitive axes. The difference between these two is that the arrangement of Figure 10-b is more suitable for measuring angles around $\theta = 0$ and $\phi = 90$, while the arrangement of Figure 10-a is more suitable for measuring angles around $\theta = 90$ and $\phi = 0$.
4. If high accuracy in angle measurement is required, the use of arrangements of Figures 11-a and 12-a is not recommended.

The arrangements shown in Figures 8-a and 8-b depict single-axis accelerometers. It should be noted that when using single-axis accelerometers, the orientation of the sensitive axis is dependent on the angle that needs to be measured. In Figure 8-a, the goal is to measure the angle of attack of the balance, while in Figure 8-b, the goal is to measure the angle of rotation of the balance.

a b

Figure 8: Single-axis accelerometer arrangements a) Single-axis accelerometer with an angle range of b) Single-axis accelerometer with an angle range of

In the following and in Figures 9 and 10, two-axis accelerometers are shown. If properly connected, these accelerometers have the ability to measure two angles simultaneously. The angle range measured by these accelerometers is dependent on their connection.

Although Figures 9-a and 9-b are similar to each other, they have differences that make their performance different. In Figure 9-a, the goal is to measure the pitch angle, while in Figure 9-b, both pitch and roll angles are measured simultaneously. In Figure 9-a, the initial position of the sensitive axis s_2 is aligned with the z_0 axis. However, in Figure 9-b, the initial position of the sensitive axis s_2 is aligned with the y_0 axis, which enables the accelerometer to measure the roll angle.

b) a)

Figure 9: a) Two-axis accelerometer with an angle range of b) Two-axis accelerometer with an angle range of

b) a)

Figure 10: a) Two-axis accelerometer with an angle range of b) Two-axis accelerometer with an angle range of

If it is necessary to reduce the number of sensitive axes of the accelerometer to increase speed or decrease computations, the layouts of Figures 10-a and 10-b may be suitable. In Figures 11 to 13, three-axis accelerometers are shown.

b) a)

Figure 11: a) Three-axis accelerometer with an angle range of b) Three-axis accelerometer with an angle range of

Layouts 13-a and 13-b provide the possibility to use all sensitive axes when measuring an angle, which can slightly increase accuracy. However, to use these two layouts, the error of the installation angle of the coordinate axes must be less than 0.05 degrees. (During the construction of the accelerometer, the axes are installed with this accuracy, or compensation is done numerically). Otherwise, if the installation error is greater than 0.05, these layouts may not only increase accuracy, but also decrease it.

b) a)

Figure 12: a) Three-axis accelerometer with an angle range of b) Three-axis accelerometer with an angle range of

b) a)

Figure 13: a) Three-axis accelerometer with an angle range of b) Three-axis accelerometer with an angle range of

Multi-axis accelerometers shown in Figures 14 and 15 are used to increase angle measurement accuracy up to 13%. This increase in accuracy is the result of additional information provided by the fourth axis of the accelerometer to the user. Since the construction and materials used for all sensitive axes of the multi-axis accelerometer are the same, the uncertainty of each of these axes can be considered approximately the same. Using this assumption, the uncertainty of the measurement axes of the accelerometer can be determined and the measurement accuracy can be increased [33].

b) a)

Figure 14: a) Multi-axis accelerometer with an angle range of b) Multi-axis accelerometer with an angle range of

Figure 15: Multi-axis accelerometer with an angle range of

In general, it is better to choose an appropriate accelerometer with a lower measurement range to increase measurement accuracy and resolution. Also, other factors such as the required voltage, thermal stability of the accelerometer, and accelerometer bias must be considered when choosing the appropriate accelerometer. In the following, various types of accelerometers available in the market are compared and a suitable accelerometer for a wind tunnel dynamic balancing angle sensor is proposed.

If two two-axis MEMS accelerometers of ADXL202E type ([25] and [34]) are used, using equations (1) and (2), the error will not exceed 0.18 degrees in measuring angles between 0 to 90 degrees.

The ADIS 16201 and Analog Device accelerometers can be used to build a dynamic balancing angle sensor, in which efforts have been made to eliminate thermal drift and other issues of MEMS accelerometers as much as possible [35] and it is suitable for building a suitable angle sensor. In addition, in the production of SCA100T accelerometer by Murata Electronics, efforts have been made to compensate for the problems of MEMS accelerometers as much as possible and it is suitable for building a suitable angle sensor.

If we use ADXL 330 and ADXL 327 accelerometers in building an angle sensor, the installation error between different axes may be between 0.05 to 1 degree [27]. This installation error between the axes of the accelerometer must be numerically compensated in the laboratory to reduce the angle measurement error as much as possible. Compensating for installation error along with using an appropriate accelerometer layout can reduce the angle measurement error up to 1 degree. Table 4 compares the results of four tested accelerometers. The acceleration range, shock range, and temperature range are important factors for an accelerometer that should be considered when building an angle sensor [36].

Table 4: Accelerometer Characteristics

Sensor Manufacturer	Sensor	Acceleration Range	Shock Range	Temperature Range
Endevco	7290 A -10	10g	5000g	121+55-
Analog Devices	ADXL210A	10g	2000g	85+40-
Silicon Design	SD2012-10	10g	2000g	85+40-
Motorola	M1220D	8g	high	85+40-

In table 5, the measured sensitivity of the accelerometers is compared. The change in sensitivity in 100Hz frequency is also compared.

Table 5: Measured Sensitivity

Sensor Sensitivity (

Shock Range

Supply Voltage (V)

7290 A -10 200 5000g 15

ADXL210A	100	1000g	5
SD2012-10	400	2000g	5
M1220D	250	high	5

In table 5, the measured sensitivity of the accelerometers is compared. The change in sensitivity in 100Hz frequency is also compared.

Table 6: Linearity of Accelerometer Behavior

Sensor Measurement Range Positive Sensitivity (

Negative Sensitivity (

Maximum Nonlinearity (%)

7290 A -10	4/19g	6/198	2/198	251/0
ADXL210A	8/17g	8/109	4/110	441/0
SD2012-10	3/13g	1/391	3/395	531/0
M1220D	8/10g	8/248	3/252	694/0

In Table 6, the working range and linearity of accelerometers have been compared. In addition, the sensitivity of accelerometers to positive and negative accelerations has been compared. The greater the difference in sensitivity between positive and negative directions, the more critical the behavior of the accelerometer in movements where the acceleration sign may change.

By examining Tables 4 to 6, it can be concluded that ADXL210 and Endevco7290A accelerometers have a more linear behavior due to their suitable manufacturing process and symmetrical geometry, and have a more symmetrical behavior in response to accelerations in different directions.

The SD2012 accelerometer has lower cross-axis sensitivities due to the presence of two symmetrical electrodes in its structure. The sensitivity changes of this accelerometer with temperature are higher due to the presence of nickel in its structure (the Young's modulus of nickel changes with temperature). The Endevco7290A accelerometer has the highest measurement range, but also has the highest resolution and lowest noise level.

Conclusion and summary:

As mentioned in the article, multiple criteria affect the selection of an accelerometer for designing a dynamic balance angle sensor for a wind tunnel. On the other hand, in order to increase the accuracy of

angle measurement by the designed angle sensor, the use of more accurate and naturally more expensive accelerometers is necessary. Therefore, one of the criteria for selecting an accelerometer is the required accuracy of the designed angle sensor. The following are the factors considered in selecting a suitable accelerometer for designing and building a dynamic balance angle sensor:

- 1- The number of angles to be measured by the angle sensor is two, the wheel angle and the attack angle.
- 2- The number of accelerometer axes used is two axes, and the measurement range of these accelerometers is chosen to be as small as possible while still larger than g. For example, in the Shiraz University wind tunnel, the accelerometer is placed on the dynamic balance of the wind tunnel as shown in Figure 9-b. With this placement, both the wheel angle and the attack angle are measured with acceptable accuracy.
- 3- The angle sensor's measurement accuracy is determined by factors such as accelerometer noise and the formula used to determine the angles. In using the layout shown in Figure 9-b in Shiraz University wind tunnel and using Table 2, the equations (10) and (11) are proposed for calculating the wheel angle and the attack angle, respectively.

After conducting necessary research and considering all relevant criteria for use in the Shiraz University wind tunnel, the Endevco model 7290 A -10 accelerometer was chosen. As mentioned in the article, this accelerometer has a high measurement range, low noise, and linear and symmetrical behavior, making it a suitable choice for use in the wind tunnel.

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