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A Review of the Different Standard Methods of Measuring the Tubular Braiding Angle

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ABSTRACT: The simplicity of the braiding, wide variety and high strength of the braid structure are the factors that make this structure, i.e., braid, so essential. These factors also make this structure widely used in various industries, such as aerospace, automotive, medicine, and industrial products such as umbrella ropes, composite boosters, aircraft engine vanes, and medical implants. Therefore, studying the mechanical properties of this structure and obtaining products with desirable mechanical properties has been considered by researchers and the subject of many types of research. Due to the importance of the braiding angle and its relation with the mechanical properties of the braid structures as the fundamental parameter, this paper evaluates different methods of measuring the tubular braiding angles. The braiding angle measurement has been done using different methods. These methods include two general categories called computational methods and image processing techniques. The different methods of each category, their advantages and disadvantages are investigated separately, then the most accurate methods can be selected by users according to the available facilities. This paper aims to provide a comparative summary of different methods of measuring the tubular braiding angle. This innovative review of these methods allows researchers and manufacturers to select and use the most appropriate method with the highest accuracy according to their conditions and facilities.

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1- Introduction

Tubular braid is a type of useful braid structure in various applications, including as a reinforcement in composites, due to its unique properties [1-3].

Many studies made on the mechanical properties of braid structures. The results of these studies showed that the various mechanical properties of different braid structures, such as the tensile properties, are directly related to the structural properties of the braid. Among the structural features, the braiding angle is significantly more effective than the others and is the most critical parameter. For example, as the braid angle increases, the tensile strength of that braid structure decreases. The braiding angle, defined as the angle between the filament and braid axes, is shown in Fig. 1 [4]. The braiding angle plays a significant role in investigating and modeling braided structures with different methods. Also, this is the most critical parameter in designing, modeling, and determining mechanical properties of braided fabrics and braided reinforced composite [5-17].

However, the value of the optimal braiding angle depends on the final use of the structure. The braiding angle depends on several braiding variables, such as the yarn dimensions, number of carriers, and mandrel diameter [18]. So, the final application of the structure determines the optimal braiding angle. The braiding angle is the most crucial factor in determining the mechanical properties of the braiding structure. Therefore, by changing the braiding angle, the

Fig. 1. The braid angle in a braided preform [4].

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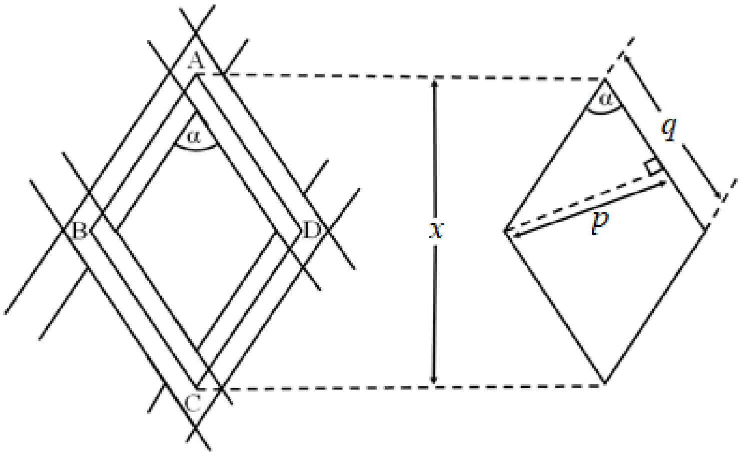


Fig. 2. A unit cell of a braid [22].

mechanical properties also change [19-21]. Given what has been said, accurate prediction and measurement of braiding angle are of particular importance. Because calculating its exact value helps engineers design the appropriate braid structure taking into account their desired characteristics. So far, several methods have been proposed for measuring the braiding angle. These methods are mathematical methods and image processing techniques. Each of these methods has its advantages and disadvantages. The most important considerations in measuring the braiding angle are accuracy and measurement time. Despite a long history of braid structure, not much research has been done on it. For this reason, in this study, we try to review, evaluate, and compare the methods of calculating and measuring the tubular braiding angles and give a general overview of the different measurement methods for determining the tubular braiding angle. Also, identifying the most effective and the appropriate method for measuring the braiding angle for this type of braid structure with the highest accuracy using the available facilities is another contribution of this paper.

2- Methodology

2- 1- Methods for calculating the tubular braid angle

According to the descriptions mentioned in the introduction, it is clear that the accurate calculation of the braiding angle value is very valuable. In the following section, some studies based on determining the tubular braiding angle using mathematical equations are presented.

Brunnschweiler was probably the first to start research on this structure. He indicated that half of the angle formed between two adjacent yarns is considered as a braiding angle (Fig. 2) [22].

$$q = \frac{x}{2}\sec\frac{\alpha}{2} \tag{1}$$

in which α, x, and q are the angle between the two adjacent yarns, the distance between the two tissues, and the length of one side of the single cell, respectively. Since the braiding angle (θ) is $\frac{\alpha}{2}$, so that:

$$\theta = \cos^{-1}\left(\frac{x}{2q}\right) \tag{2}$$

All the theoretical results of this study were obtained close enough to the experimental values. This means that Eq. (2) is helpful in prediction. Eq. (2) was one of the first geometric relations defined to calculate the braiding angle and can be used nowadays [22-24]. Although this is an advantage, in the cases where fine yarns are used or the braid structure is delicate, measuring the distances of a unit cell is complicated and associated with many errors. Therefore, when using this equation, it is better to use thick yarns in creating the braid structure.

Dabiryan and Johari [23] used the energy method and studied the braid deformation during its stretching to analyze the theory of tensile behavior of tubular braids and develop a predictive model for the young's modulus of the braid. To do this, they defined the unit cell of the simple braid (Fig. 3.) and Eq. (3) to determine the braiding angle.

$$\theta = \cos^{-1}\left(\frac{l_{ui}}{2l_y}\right) \tag{3}$$

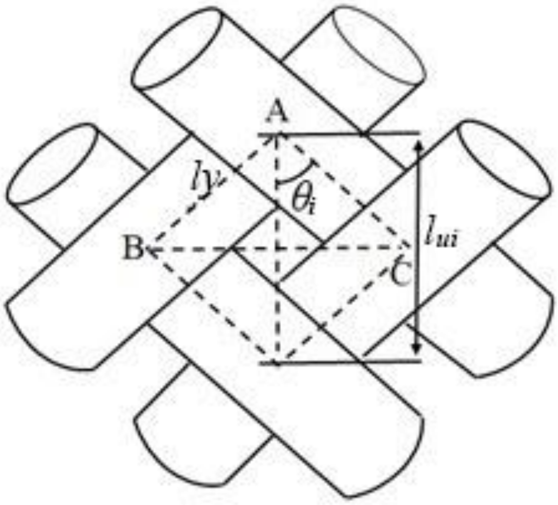


Fig. 3.The unit cell of a simple braid [23].

in which θ, l_{ui}, and l_y are braiding angle, length of the unit cell, and the yarn length in the unit cell, respectively. They evaluated their model on1/1 pattern braids and found that their generated model can predict Young's modulus of braids [23].

Although according to Eqs. (2) and (3), the pattern design of braided structures does not make a difference in how to measure the breading angle by using unit cell dimensions.

By identifying the location of a braiding yarn in the braid structure, it was found that the braiding angle depends on the lay length (L) and the circumference of the braid (Fig. 4).

$$\tan\theta = \frac{2\pi r}{L} \Rightarrow \theta = \tan^{-1}\left(\frac{2\pi r}{L}\right) \tag{4}$$

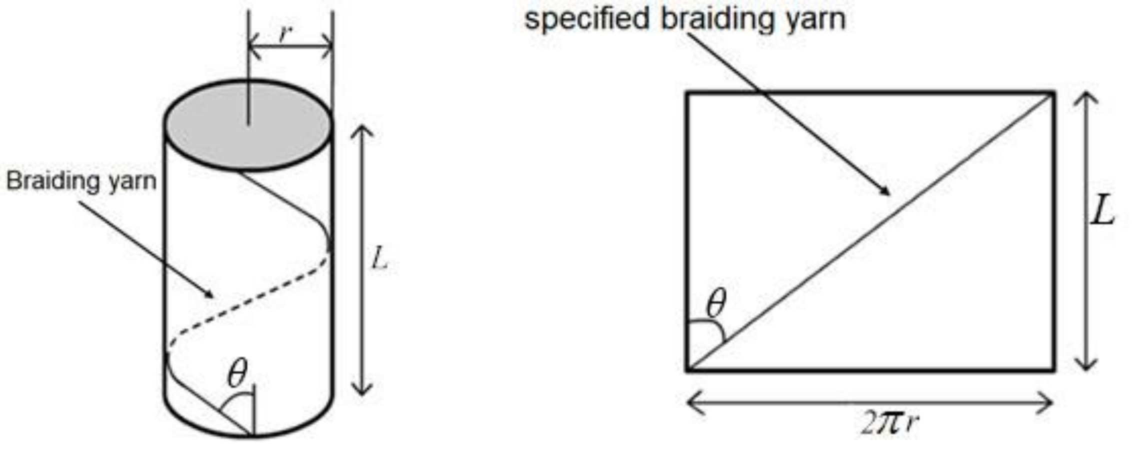
Eq. (4) used the geometry of a braided structure to calculate the braiding angle [25]. The basis of this equation is finding a braid yarn path and investigating the geometry of the braid. Therefore, the measurement of geometric characteristics must do accurately and correctly. This equation can be used by some researchers nowadays [24], and this is the advantage of this method, but in the case of small diameter braids, these measurements are difficult and will result in errors.

The rotation of the yarn carriers in two opposite directions forms the braid structure. Thus, the variable parameters such as the speed of carriers and take-up speed influence the braiding angle. The simplest form of this equation is given in Eq. (5), in which through this equation, the braiding angle is related to the braiding machine's speed. Also, this equation has been the basis of studies in different years [4, 18, 21].

$$\theta = \tan^{-1}\left(\frac{u_0}{v_0}\right) = \tan^{-1}\left(\frac{r\omega_0}{v_0}\right) \tag{5}$$

where r, v_o, and ω_0 are the radius of the cylindrical mandrel, the longitudinal velocity of the mandrel, and the angular rate of the spindle, respectively18]]. These parameters are shown in Fig. 5.

The advantage of this method is that even if access to the gears of the braiding machine is not easy, by having an accurate braiding machine catalog that has the gears' specifications, this equation can be used. However, one must be very careful in the measurements. Also, make sure that the



(a) Schematic of a braided structure

(b) Schematic of a cut and opened braid structure

Fig. 4.(a) Schematic of a braided structure, (b) Schematic of a cut, and opened braid structure [25].

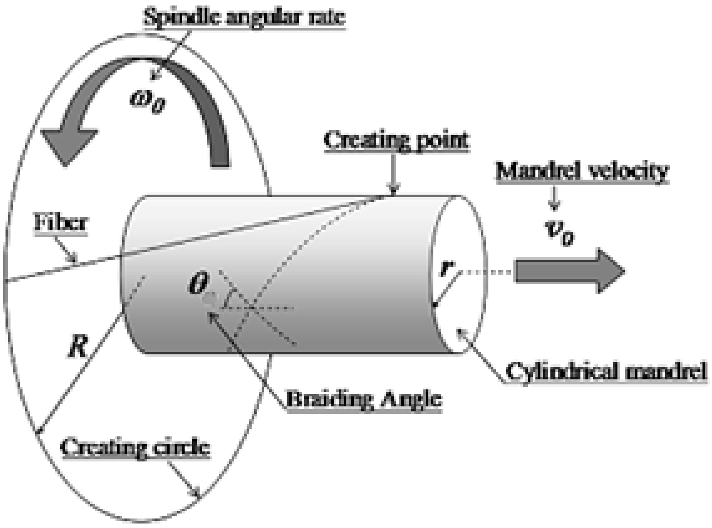


Fig. 5. The braiding mechanism in a simple model for tubular braid structure [21].

machine settings are done correctly and do not change during production.

According to Eq. (5), for changing the braiding angle, the longitudinal velocity ratio to the circumferential velocity should be altered. This equation is the basis for other studies in later years. For example, in 1994, Du and Popper [26] conducted a study to analyze of braiding complex shapes process, which led to the introduction of the Eqs. (6) to (8). These equations were used years later by Hunt and Carey [4] to calculate the braiding angle for 2D and 3D braids with complex mandrel shapes. These relations used the different braiding machine parameters such as radius of the mandrel (r), the track plate radius (R_g), the linear velocity of the take-up (v), and the rotational speed of the carriers (ω):

$$h(t)=\frac{v}{\omega}\frac{\sqrt{1-\lambda^2}}{\lambda}+\left[h_0-\frac{v}{\omega}\frac{\sqrt{1-\lambda^2}}{\lambda}\right]^{e^{\frac{\lambda}{\sqrt{1-\lambda^2}}\omega t}} \tag{6}$$

$$\tan\theta(z)=\frac{R_g}{h(t)}\sqrt{1-\lambda^2} \tag{7}$$

$$\lambda=\frac{r}{R_g} \tag{8}$$

where $h(t)$, t, and h_0 are the convergence point location, namely the axial location at which the fibers make contact with the mandrel, time, and the transition from the initial convergence point; respectively. Experimental results are presented for many cases, and they confirm the validity of the model [4, 26]. One of the limitations of using the group of Eqs. (6) to (8) is that it seems to increase the calculation time and make people want to use the calculator to prevent this.

Rawal [27] studied the different structures of braids in different years and showed that by using some of the specifications for the horn gears used in the braiding machine, Eq. (5) could be written in the form of the Eq. (9) to calculate the braiding angle:

$$\theta=\tan^{-1}\left(\frac{2\omega_h R}{N_h v}\right) \tag{9}$$

where ω_h, R, N_h, and v are the angular velocity of the horn gears around their center, a radius of the mandrel, number of horn gears, and take-up speed, respectively. These parameters are shown in Fig. 6.

He also predicted and simulated the yarns' paths on various 3D mandrels, including square pyramid, cylinder, square prism, and cones with circular and elliptical cross-sections concerning the braiding angle. These studies showed that the yarn paths' three-dimensional coordinates are related to the mathematical relationships with the braiding angle. Also, calculating the braiding angle according to the braiding machine parameters for different mandrel shapes can be calculated with a good approximation using Eq.9)). This equation is sufficiently accurate and to be used in various studies [15, 27-29]. The advantages and disadvantages of Eq. (5) also apply to this equation.

After changing the longitudinal velocity of the mandrel

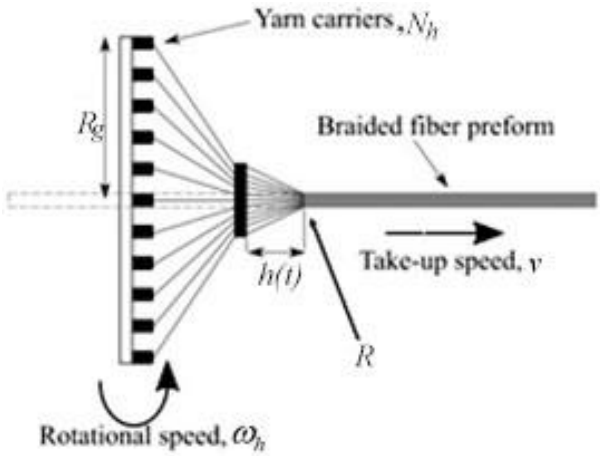


Fig. 6. Schematic of the braiding machine [4].

or the angular velocity of the spindle or both, i.e., the change in the amount of *u/v*, to change the braiding angle, the braid will not be formed with the new angle immediately. Altering the braiding angle would take place after a short time delay. This phenomenon is defined as a step response in the braiding angle. The reason for this naming is shown in Fig. 7 [21].

As can be seen, θ_i and θ_0 are the initial braiding angle and the target braiding angle, respectively. The initial braiding angle is the angle at which the braid is woven and formed, and the target braiding angle is the angle that is intended to form the braid from now on it. According to Fig. 7, which clearly shows the step response phenomenon, it is clear that the braiding angle's value can vary until the braiding angle reaches the target value [21].

Nishimoto et al. [21] conducted a study based on Eq. (5), which led to the presentation of a relationship to predict the braiding angle and its changes. They showed that the braiding angle's value could calculate when the change starts to reach the target value. So, the braiding angle can calculate at any time by using the following Eqs. (10) and (11):

$$T = \frac{\sqrt{R^2 - r^2}}{\tan\theta_0} \cdot \frac{1}{v_0} = \frac{\sqrt{R^2 - r^2}}{u_0} \tag{10}$$

$$\theta = \tan^{-1}\left(\frac{1}{\left(\frac{1}{\tan\theta_0} - \frac{1}{\tan\theta_i} \right)\left(1 - e^{-\frac{t}{T}} \right) + \frac{1}{\tan\theta_i}} \right) \tag{11}$$

where R, r, v_o, and u_0 are the radius of the creating circle, the radius of the cylindrical mandrel, the longitudinal velocity of the mandrel (take-up velocity), and spindle velocity, respectively. The moment of applying changes in mandrel velocity or spindle velocity that changes the braiding angle is defined as the zero time. So, the time spent from this moment to the moment that the braiding angle changes is considered the variable t in seconds. T is a constant value obtained by using the Eq. (10) and is called a time constant. In physics and engineering, the time constant is the parameter characterizing the response to a step input of a first-order, Linear Time-Invariant (LTI) system and is the central characteristic unit of a first-order LTI system. Physically, the time constant represents the elapsed time required for the system response [21, 30]. It is clear that a larger radius of the creating circle, R, results in a more significant delay until the braiding angle reaches the targeted angle by using Eq. (11). It is possible to calculate the time spent to reach the target angle and the possibility of predicting the angle at any time. Finally, in order to validate

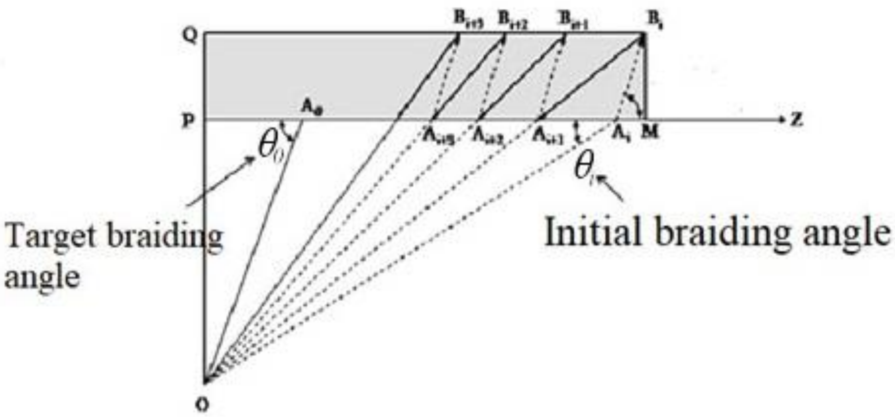


Fig. 7. The geometrical derivation of the braiding angle under changing the braiding angle [21].

Table 1. The comparison of the various mathematical methods

Number of Equation	Need to accurately measure Braid structure	Need to accurately measure Machine parameters	Ability to predict time in changing angles	In use
2	Yes	No	No	Yes
3	Yes	No	No	Yes
4	Yes	No	No	Yes
5	No	Yes	No	Yes
7	No	Yes	No	Yes
9	No	Yes	No	Yes
11	No	Yes	Yes	Yes

the new forecasting method, this paper compared the braiding angle on a cylindrical braid with 24 carriers in two different radii with experimental data. Matching the predicted and the calculated results showed that the model has been useful [21]. One of the advantages of using this equation is that if there is a need to change the braiding angle, can calculate how long it takes for the structure to start weaving at that angle. While knowing the spent time, the previous braiding angle, and the target braiding angle to calculate the braiding angle at any time is one of its disadvantages.

Various studies to calculate the braiding angle using each of the equations listed in this section have shown that the braiding angle calculation using mathematical methods can provide a reasonable estimate of the braiding angle value if each variable is measured very accurately. These studies also showed that the computational method with the least measurement error would lead to a very different result from the braiding angle's actual value. Therefore, computational methods are susceptible to errors in measurement, human error, and errors due to improper braiding machine settings 29 ,28 ,21-26 ,4]].

The comparison of the various mathematical methods is given in Table 1.

The braiding angle measurement in methods that have required accurate measurement of the braid structure should be done after production and accurate measurement of the required braid dimensions. While the braiding angle depends on the braiding machine parameters, it is also possible to measure during production. On the other hand, when using these methods, all the machine parameters should be accessible and easily measurable.

3- Experimental Setup

3- 1- Image processing technique for measuring the tubular braid angle

In general, the image processing technique for measuring the braid angle is a very user-friendly method and it is easy because of its application and accuracy of the measurement. Therefore, it seems that using image processing to calculate the braiding angle is much better and more accurate than mathematical measurements4]]. Using image processing to calculate the braiding angle reduces time and increases accuracy. Some of the studies devoted to different image processing techniques introduce in this section. The basis of this method, which is shown in Fig. 8, will be described as follow:

The microscope ophthalmic lens must be replaced with a single high-resolution scientific-grade area-scan camera. By using the camera, images take from the sample's surface, and their information saves into a file on a computer system that connects to a microscope. Finally, the information analysis is done by software in different ways:

In 2008, Li [31] introduced the detection of unit cell edges method for analysis of the image and calculation of the bridging angle. As shown in Fig. 9, each corner of the unit cell has a position on the *x-y* coordinate. The accurate position of these points computes an exact braiding angle. It is necessary to identify the unit cell and obtain an image such as Fig. 9, called the diagram of the braided angle.

In his analysis, after plotting the diagram of the braiding angle, the position of the corner points, i.e. ($x1$,$y1$), ($x2$,$y2$), ($x3$,$y3$), and ($x4$,$y4$), are put in Eq. (12), and thus the twice of braiding angle (Ψ) can be obtained. Then, by dividing Ψ into two, the value of the braiding angle (θ) can be calculated [31].

$$\psi = \arccos \frac{\left((x4-x1)^2 + (y4-y1)^2 + (x3-x1)^2 + (y3-y1)^2 - (x4-x1)^2 + (y4-y1)^2 \right)}{2\sqrt{(x4-x1)^2 + (y4-y1)^2} . \sqrt{(x3-x1)^2 + (y3-y1)^2}} \tag{12}$$

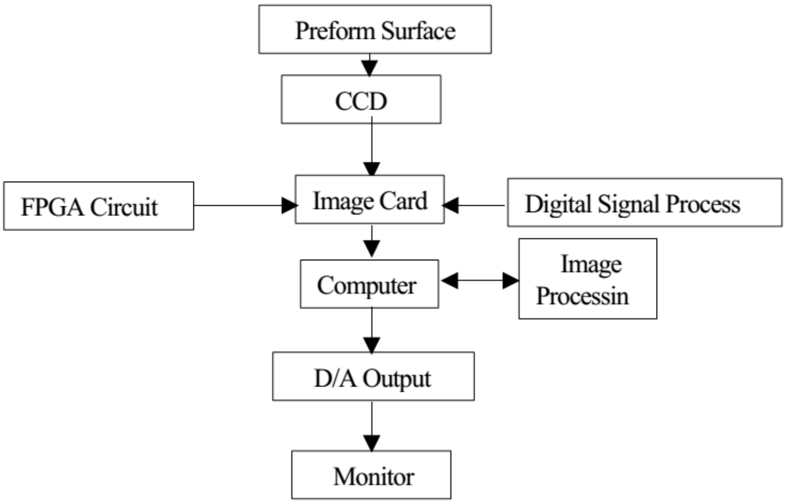


Fig. 8. The diagram of the image process technique [17].

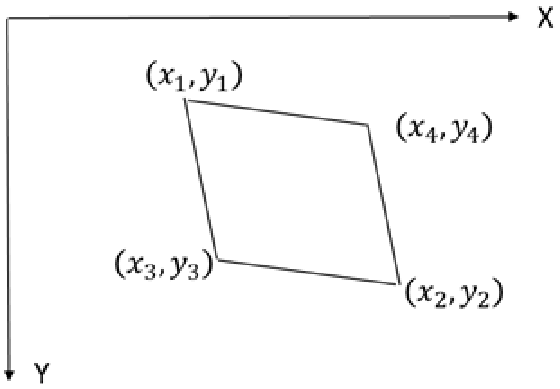


Fig. 9. The diagram of the braided angle [31].

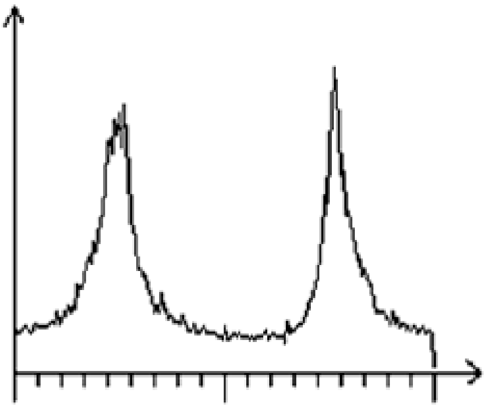


Fig. 10. The diagram of the extracted polar spectrum [17].

$$\theta = \frac{\psi}{2} \tag{13}$$

An algorithm based on this method was performed, then the performance of three-dimensional braided composite materials made of carbon fiber and glass fiber was evaluated. Parts of the results obtained from the 64 braided angles measured are listed in Table 2.

The Experimental results show the high accuracy of this method and its practicality [31]. Because the corners' coordinates are accurately calculated using image processing, the calculated braiding angle will be more accurate. However, to use this method and the need for equipment such as a camera, the user must also specialize in image processing and coding in software such as MATLAB.

Fourier transform was used to determine the braiding angle value of the triaxial braided glass/urethane composites by image processing in the year 2000. The excellent agreement shown between the results of this study led to the introduction of the Fourier transform for image analysis and braiding angle determination. This transform still uses to analyze the images captured from the surface of the braid [32].

Wan et al. [17] used an algorithm developed based on Fourier transform to estimate the braiding angle of three-dimensional braided composite in 2006. They claimed that this research was a new development for measuring the braiding angle of three-dimensional braided composite materials and laid the foundation for establishing a test standard in China. In this method, after the polar image is processed, the diagram of the extracted polar spectrum is obtained with two peaks, as shown in Fig. 10:

Two peaks in the x-axis are named ω_1 and ω_2, respectively.

Table 2. Part of the braided angles of carbon composite material (Unit = degree)

	1	2	3	4	5	6	7	8	Average Value
Measured by algorithm	32.73	31.18	32.11	32.21	31.60	32.45	32.85	32.83	32.25
Measured by protractor	32.1	32.2	32.1	31.4	31.5	31.5	31.7	32.08	31.8
Measured by PC-image software									32.1

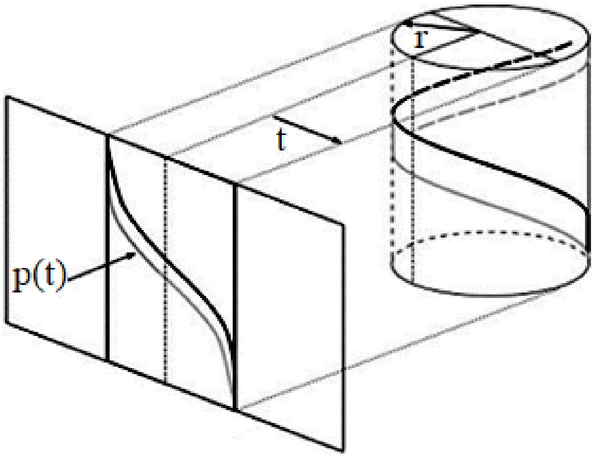


Fig. 11. Illustration of the yarn path on a 2D plan [4].

The braiding angle is calculated by using Eq. (14).

$$\theta=\frac{\left|(\omega_1+90)-(\omega_2-90)\right|}{2} \tag{14}$$

The algorithm, developed by Wan et al. [17] was tested on both carbon and glass braided composites. They have claimed that the research is a new development for measuring 3D braided composite, and the work will lay the foundation for establishing a test standard for 3D braided composite.

Using Fourier-based coding increases the accuracy of angle calculations but requires more equipment and expertise.

Xiao et al. [33] suggested a method based on the local edge of a unit cell for biaxial braided preforms by using the algorithm presented in the Wan article. This method has been evaluated on biaxial regular braided carbon fiber preforms. Experimental results showed that this method performs measurements of braiding angles with reasonable accuracy [33, 34]. Also, this algorithm is used to estimate the braiding angle of three-dimensional braided composites made of carbon and glass fibers. Experimental results showed that this method performs precise braiding angle measurement [34, 35].

Hunt and Carey [4] introduced the helical yarn path as an efficient method for calculating the braiding angle without user interference. In this method, a helical yarn path was identified on the braid and displayed onto a 2D plan by using the parameters, which are shown in Fig. 11.

In the next step, the image of the yarn path is divided into small sections so that each section, is considered as a straight line.

However, the slope of each small section relative to the horizontal position of its start and endpoints can be calculated. Then, the slope of each small section is the tangent value of the braiding angle calculated according to Eq. (15).

$$p(t)=c.r.\arcsin(\frac{t}{r}) \tag{15}$$

In this, c, r, t, and p are the line's slope, the radius of the tubular braid, the transverse distance from the mandrel centerline, and the longitudinal position yarn path; respectively.

By plotting the helical path's angle relative to the horizontal position of the image relative to the centerline (Fig. 11), a similar diagram, as shown in Fig. 12, will obtain. The peak of this diagram represents the braiding angle.

Hunt and Carey [4], in order to validate their proposed method for determining the braiding angle, using aramid fibers at three braid angles 30, 45, and 55 degrees produced tubular braided preforms on a 36-carrier maypole braiding machine with a constant take-up speed of 280 mm/min. Comparison of experimental results with the theoretical method in this study

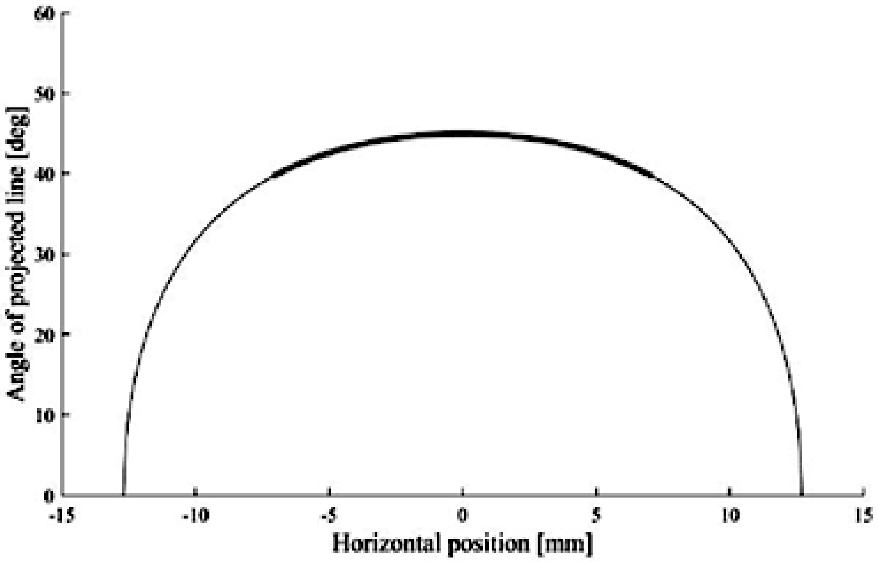


Fig. 12. The angular distribution is obtained by following the yarn path [4].

Table 3. The characteristics of the different image processing methods

of Equation	Need to equipment	Need to expert	In use
13	Yes	low	Yes
14	Yes	high	Yes
15	Yes	medium	Yes

showed that determination of the frequency spectrum by Fourier transform and investigation of the braid's geometry could reduce the human error in measuring the braiding angle.

The results of these studies showed that the image processing technique is an effective and accurate method. In this method, using image processing, the path of the yarn and the characteristics of the unit cell in the braid structure can be obtained to an exact extent. Therefore, it can say that the image processing method is more accurate than analytical methods. Since in this method, the necessary calculations are performed by analyzing the image. Therefore, the available errors were minimized. It seems that the use of an image processing technique when the braid is produced to detect any changes in the braiding angle can be effective. Also, by equipping the braiding machine with the appropriate and required equipment, these changes can be eliminated [5, 8, 26-29, 33]. For people without coding knowledge to be able to use the image processing technique, there is software such as Image-J. By importing the image taken from the braid surface to Image-J software, the braiding angle can measure with high accuracy.

Table 3 shows the characteristics of the different image processing methods for determining the tubular braiding angle.

4- Conclusion

In this study, different methods based on mathematical equations and image processing to calculate the tubular braiding angle were investigated and evaluated. The calculation of the tubular braiding angle using mathematical methods has many errors, including measurement errors. In this case, a braid with a more delicate structure not only increases the challenges about the measurements but also increases the error. If the gear information is not available, it will not be possible to calculate the speed of the braiding machine. Therefore, when using this method, to provide a reasonable estimate of the braiding angle value, not only high accuracy in measurement but also access to machine specifications is required.

The use of image processing techniques in any way, despite the extra equipment it requires, such as a camera, provides accurate measurement of the braiding angle value. Because the analysis of this method performs on the image taken from the braid structure there is no such thing as measurement error and human error anymore. An error in the braiding machine settings may occur during production. However, the use of the image processing techniques leads to detect changes in the braiding angle and equipping the braiding machine with the appropriate and required equipment; these changes can minimize. Also, Image-J software can use in image processing without the need for coding information.

All the methods presented in each category, if used correctly, show remarkable, impressive, and satisfactory results. Therefore, neither of them is inherently superior or better than the other. Nevertheless, the conditions and facilities that the manufacturer is dealing with determine which method determines the angle value faster and more accurately.

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