Threats. There are difficulties associated with the use of research results. This is due to the fact that the application of the chosen calculation model of potential correspondence it is necessary to determine the number of departures and the number of arrivals in the transport system points. An occurrence of such state of the system, in which it will require transport enterprises to provide more volume of transport services, is possible.

8. Conclusions

1. Passenger transport correspondence between cities with different number of inhabitants is experimentally defined. The quantitative indicators of passenger transport correspondence are obtained. It is established that intercity passenger transport correspondence can be predicted. It is proved that gravity modeling of passenger transport correspondence is suitable for this system.

2. Theoretical and experimental data are compared. Static error of calculations is defined as a comparison results. Previously unknown parameters of gravity function are defined. This allows to predict the passenger correspondence in this system.

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МОДЕЛИРОВАНИЕ ПАССАЖИРСКИХ ТРАНСПОРТНЫХ КОРРЕСПОНДЕНЦИЙ МЕЖДУ ОБЛАСТНЫМИ ЦЕНТРАМИ В УКРАИНЕ

Исследован процесс предоставления услуг по перевозке пассажиров на маршрутах общего пользования. По полученным данным фактических корреспонденций было проведено исследование возможности применения известных методов к расчету пассажирских транспортных корреспонденций. Установлены параметры составляющих, при которых применение рассмотренных методов возможно в рамках исследованной системы.

Ключевые слова: транспортная система, гравитационная модель, пассажирские транспортные корреспонденции, междугородние перевозки.

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ANALYSIS OF ERRORS OF PROFILE TRANSFORMATION SCALE

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Проведено аналіз структури похибок при контролі форми пакувань хрестової мотки методом тіньової проекції. Отримані вирази для окремих складових похибки параметрів форми, що дозволяє обґрунтовано підійти до призначення допусків на взаємне розташування окремих елементів пристрою. Проведено аналіз пристроїв реєстрації зображень з точки зору можливості їх застосування в апаратному комплексі для реєстрації параметрів форми пакувань хрестової мотки.

Ключові слова: *форма пакувань, хрестова мотка, тіньова проекція, реєстрація параметрів, перетворення профілю.*

1. Introduction

Textile industry effectiveness is closely connected with the provision of the required quality for all technological steps. One of the most important processes in the textile industry is the winding process, which resulted in forming textile packages of various shapes. Defects of textile packages results in increased breakage in subsequent steps,

where the package is processed. Defective packages must be rewinding, which is associated with additional labor costs and an increase in the number of irretrievable loss of raw materials. One of the most important indicators of quality of textile packages is their deviation from a given shape. Development of inspection methods for packages in the production process is an urgent task. Features of ensuring the accuracy of the shape of packages by shadow projection method are considered in the article.

2. The object of research and its technological audit

The object of research is a device to inspect the shape of textile packages by shadow projection method for monitoring in real time.

Shadow projection method (Fig. 1) is used to measure the roughness of the slightly reflective surface more than 40 microns [1]. Shutter (S) is mounted above the testing surface for measuring by this method. It intercepts part of the light beam which is directed to the test surface from the light source, the optical axis O_1-O_1 of which is inclined at an angle α to the normal of the test surface. The shutter shadow falls on the surface and reproduces its profile. The shape and size of the cross section are determined by a visible image in the shadow in observation device. Its optical axis O_2-O_2 is directed at an angle β to the normal of test surface.
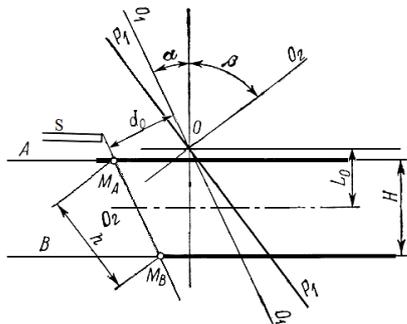
Fig. 1. The scheme of surface inspection by shadow cross section method

Unlike the methods using the surface scanning, shadow projection method doesn't require a long time to remove the primary image and allows monitoring in real time.

Well-founded choice of design parameters, providing the desired inspection accuracy, is necessary for use of this method in practice.

3. The aim and objectives of research

The aim of research is to develop a technique of theoretical analysis of the scale errors of the textile package profile transformation and development of technique of well-founded choice of design parameters of the device, allowing to minimize them.

To achieve this aim it is necessary:

1. Identify the basic parameters of the device used to generate primary data about the shape of packages that affect the inspection results.

2. Prove the divergence of design parameters, providing the required transformation accuracy.

4. Research of existing solutions of the problem

Device in [2] is proposed to inspect the bobbin out-of-roundness. This device projects its image on the screen at certain points of which photocells are installed. The signals from the photocells are processed on a computer. As follows from the description, inspection of geometric dimensions in this device is carried out only at certain points, thus, because the bobbin image projection on the screen is analyzed, then information on the bobbin shaded areas is lost.

Device for inspection of the size and shape of the bobbin is proposed in [3]. It is used for automatic winding machine during the yarn winding. It is provided with a control head, installed in front of the bobbin board or in the zone of bobbin movement to the storage bin. The control head is equipped with a light source and a dispersing lens guiding the light beam onto a bobbin. The reflected light beams are directed to the host system of mirrors, where the beams are directed one-row photocells.

The beams pass through the focusing lens and arrive at the photocell corresponding to the determined diameter of the wending bobbin. Pulses of photocells are sent to the control electronic unit. Signals from this unit are sent to the drive unit of the winding head correcting a bobbin board rotation rate. A disadvantage of the device is that only one of the ends of the bobbin is inspected, wherein the bobbin out-of-roundness and diameter deviation are determined. Thus, the device doesn't allow for an integrated inspection of geometrical parameters of the winding body.

Device to inspect the shape of the bobbin is shown in [4]. This device is used on the winder for winding inspection and correct formation of the end face of bobbin. It is provided with a photoelectric sensor, which receives light rays reflected from the defective area of the bobbin. Light rays at the end surface bobbin are directed from the light source and pass through a dispersing lens. Signals are sent from photocell to the electronic noise-block of analyzing unit. The formed signal is applied to the amplifier and analog-to-digital converter coupled to the normalizing unit and the memory unit.

Described device, as the previous one, allows to inspect only one of the ends of the package that does not give full information about its shape. Unlike the previous device designed to inspect the out-of roundness of the end, this device allows to determine its out-of-straightness.

Some of the best results can be obtained by scanning the test winding body with a laser beam, as is done in inspection device of the bobbin winding [5].

The device is designed for non-contact determination of the lifting angle of the winding. Also this device, based on angle measurements, may adjust it within a predetermined range, which allows winding the bobbin of a regular shape.

The next step in the development of devices based on bobbin image scanning is the automatic inspection system of yarn packages [6, 7], which records the presence of broken yarns, stains and dirt, as well as inspection of package shape. System operation is based on an optical distance measurement that is independent of the gloss degree of inspected packages. The laser beam is used as a light source. It scans the package end surface, generally in the direction of its radius. The resulting linear profiles

are transformed into rectangular image. Reflected light from the package falls on the detector that captures not the amount of reflected light, and the location of the light spot. Location of the light spot is a measure of height. Since the detector operates independently of the amount of reflected light, device is suitable for scanning of natural yarn packages, partially oriented yarns and yarns obtained by texturing with extension.

Further development of the above-described system is a system [8], which allows to inspect:
– geometric parameters (diameter and saddle shaping and swelling);
– structural parameters (presence of the running end, roving winding, etc.);
– such parameters as yarn intersection, the presence of broken filaments, loops and fluff.

This system has a modular design and allows to define all characteristics or only some of them. Use of the laser technology makes available a fixation of very small defects of the bobbins, unseen by the human eye. The system is equipped with an automatic vehicle and robots, which provide bobbin reception, setting them in the inspection places and other activities related to the bobbin inspection. Throughout the inspection human hand doesn't touch the bobbin during the inspection. Time for bobbin inspection is ~9 seconds. The system monitors more than 400 bobbins per 1 hour. Systems that are based on the laser scanning of investigated area are quite complex and, consequently, costly, requiring specially trained personnel to operate them.

Similar results at a much lower cost can be achieved using the cameras and matrix photocells as receiver.

Device for quality inspection of the yarn bobbins of all sizes, colors and materials is shown in [9]. The principle of device operation is based on the image acquisition of the bobbins and their processing using the computer to determine the presence of defects.

Device comprises two racks on which the image sensors are installed, for example, matrix camera. Sensors scan the upper and lower ends of the bobbin, and its side surface. For this, they are moved along the rack by electromechanical drive. Image input unit, improvement unit, filter, image binarization unit, output characteristics unit and evaluation unit are used for processing of each image. Each input image is converted into two-color digital image. Specific image geometrical characteristics of each defect are detected in each image. These characteristics are compared to stored characteristics with predetermined values in the storage unit. This makes it possible to assess the existence of the defect or lack of it.

Inspected bobbins in the device [10] are moved through inspection camera equipped with devices for optical inspection of the bobbins. Test of every bobbin is carried out for their sorting. At the same time the full bobbins continue to move on the support conveyor to the place of removal. Defected bobbins are transferred to another conveyor, from which they are removed elsewhere.

5. Methods of research

Publications [11–20], which are devoted to shadow projection method, are used.

The following research methods are used: analysis of measurement error and geometrical optics.

6. Research results

Using the method of shadow cross section projection in order to calculate the height of the surface profile in the normal section, M scale of profile transformation is used. It is calculated for nominal values of the angles α, β and φ. The angle deviation from the nominal values will cause the scale error of profile transformation and, therefore, the error of surface profile measurement. It is known that the transformation scale depends on the angles α, β and φ. The angle φ varies with angular displacement of the axis of the inspected bobbin around the Z-axis. Angles α and β are changed in the case of [11–14]:
– linear displacement of the light source and the camera along the X and Z-axes while maintaining the substantive position of the point O;
– bobbin displacement along the X-axis and its rotation around this axis;
– angular displacement of the shutter and the bobbin axis.

According to [10, 11, 15], the error of the measured profile height can be determined by the following formula:

$$\Delta h'(\Delta\alpha, \Delta\beta, \Delta\varphi) = \frac{\partial h}{\partial \alpha}\Delta\alpha + \frac{\partial h}{\partial \beta}\Delta\beta + \frac{\partial h}{\partial \phi}\Delta\varphi, \quad (1)$$

where $\Delta\alpha$, $\Delta\beta$ and $\Delta\varphi$ – deviations of corresponding angles.

Substituting h' from the previous in (1), after differentiation we obtain:

$$\Delta h'(\Delta\alpha, \Delta\beta, \Delta\varphi) =$$
$$= \sqrt{H^2 + L^2}\left[\sin\left(\varphi + \arcsin\frac{H}{\sqrt{H^2+L^2}}\right)\frac{\cos\beta}{\cos^2\alpha}\Delta\alpha + \right.$$
$$+ \sin\left(\varphi + \arcsin\frac{H}{\sqrt{H^2+L^2}}\right)\frac{\cos(\alpha+\beta)}{\cos\alpha}\Delta\beta +$$
$$\left. + \frac{\sin(\alpha+\beta)}{\cos\alpha}\cos\left(\varphi + \arcsin\frac{H}{\sqrt{H^2+L^2}}\right)\Delta\varphi \right]. \quad (2)$$

Let's analyze the individual components of the transformation scale error caused by linear and angular displacements of the individual components of device to inspect the package shape. Because these components are independent variables, the error of the angle α can be determined by the formula [11]:

$$\Delta\alpha = \sqrt{\Delta\alpha_1^2 + \Delta\alpha_2^2 + \Delta\alpha_3^2 + \Delta\alpha_4^2}, \quad (3)$$

where $\Delta\alpha_1$ – deviation caused by a linear displacement of the light source position; $\Delta\alpha_2$ – deviation caused by the bobbin displacement along the X-axis; $\Delta\alpha_3$ – deviation caused by shutter rotation around the axis that is parallel to the X-axis; $\Delta\alpha_4$ – deviation caused by shutter rotation around the axis that is parallel to the Y-axis.

The deviation $\Delta\beta$ of the angle β is caused by linear displacement of the recording camera. The deviation $\Delta\varphi$ of the angle φ can be caused only by the angular deviation of bobbin position.

Let's estimate the deviations $\Delta\alpha_1$ and $\Delta\beta$ of the angles α and β, caused by the displacement of the light source and the camera at a fixed position of the point. According to Fig. 2, light source should be located at the point C, at a distance R_o from the point $O: OC = R_o$. However, its

coordinates are displaced by the magnitude Δx_o and Δy_o along the coordinate axes due to the errors.

Fig. 2. The scheme of estimation of the transformation scale error caused by the displacement of the light source

Let's estimate the value of the error $\Delta\alpha_1$ caused by this displacement. The distance between points B and C is determined by the formula:

$$BC = \sqrt{\Delta x_o^2 + \Delta y_o^2}. \tag{4}$$

Let's drop a perpendicular from point B on the line OC. It is obviously that the segment AB is inclined to OX axis at an angle α. The inclination angle of segment BC to OX axis is calculated as follows:

$$\psi = \operatorname{arctg} \frac{\Delta y_o}{\Delta x_o}. \tag{5}$$

Angle $BEF = \psi$ and it is external to the triangle DEB, so it is equal to the sum of the angles BDE and DBE. Then the angle $DBE = \psi - \alpha$. Therefore, from the triangle ABC:

$$AB = BC \cos(\psi - \alpha),$$
$$AC = BC \sin(\psi - \alpha). \tag{6}$$

From the triangle OAB get:

$$\operatorname{tg} \Delta\alpha_1 = \frac{AB}{AC + OC}. \tag{7}$$

Substituting (4), (5) and (6) in (7) and accept that $\operatorname{tg}\Delta\alpha_1 \approx \Delta\alpha_1$ taking into account that angle $\Delta\alpha_1$ is small, define:

$$\Delta\alpha_1 = \frac{\sqrt{\Delta x_o^2 + \Delta y_o^2}\cos\left(\operatorname{arctg}\dfrac{\Delta y_o}{\Delta x_o} - \alpha\right)}{\sqrt{\Delta x_o^2 + \Delta y_o^2}\sin\left(\operatorname{arctg}\dfrac{\Delta y_o}{\Delta x_o} - \beta\right) + R_o}. \tag{8}$$

Arguing in the same way, it can define $\Delta\beta$ as:

$$\Delta\beta = \frac{\sqrt{\Delta x_c^2 + \Delta y_c^2}\cos\left(\operatorname{arctg}\dfrac{\Delta y_c}{\Delta x_c} - \beta\right)}{\sqrt{\Delta x_c^2 + \Delta y_c^2}\sin\left(\operatorname{arctg}\dfrac{\Delta y_c}{\Delta x_c} - \beta\right) + R_c}, \tag{9}$$

where Δx_c and Δy_c – deviations in the position of the camera, respectively, in the X-axis and Y-axis; R_c – the distance from the camera to the point O.

Influence of angular deviations of the bobbin on the conversion scale is estimated by the formula (2) taking into account (3). Let's estimate the impact of displacement of the bobbin axis on the transformation scale error (Fig. 3).

Analyzed device is designed to record the profile of textile packages, so the surface of A and B can be considered as flat only under the survey of the flat ends of the package. A and B surfaces are cylindrical or conical surfaces upon registration of side surface of the package profiles. Fig. 3 shows the bobbin with the center O_1 in the nominal position with the center O_2, displaced by a certain amount x_b [16–20].

Fig. 3. The scheme of estimation of the transformation scale error caused by the displacement of the bobbin

As it follows from Fig. 3, the displacement of the bobbin along the Y-axis will change the position of the point O. Change of the angles α and β is not going to happen, so transformation scale error of the profile at the same time is not observed.

Displacement of the bobbin axis by the x_b leads to a change of angles α and β by the same value $\Delta\alpha_2$. Moreover, if the angle α increases, than the angle β decreases. Thus, the sum of the angles $\alpha + \beta$ remains unchanged. The value of angle errors caused by the bobbin displacement can be determined as shown in Fig. 3 according to the formula:

$$\Delta\alpha_2 = \frac{\Delta x_b}{R_b}, \tag{10}$$

where $R_b = O_2O$ – bobbin radius

The angular deviation of the shadow on the test surface is taken place at the angular displacement of the shutter from the nominal position. In Fig. 4, a, the shutter is deviated from its nominal position by rotation by an angle ψ_x relating to ξ_x axis. As a result, the edge of the shutter will occupy the positions shown in Fig. 4, a by the points a and b. Accordingly, the edge of the shadow, which, in the case of parallel arrangement of the shutter relative to the planes A and B are the points M_A and M_B, will move to the point and M'_A and M'_B.

This will cause additional rotation of observed shadow by an angle $\Delta\alpha_3$. The length of the segment ab can be calculated using the formula:

$$ab = L \operatorname{tg} \psi_X. \tag{11}$$

Fig. 4. Scheme: *a* – estimation of the transformation scale error caused by shutter rotation around the axis ξ_x parallel to the *X*-axis; *b* – beam path to estimate angle $\Delta\alpha$ of the shadow rotation

Schematic beam path to estimate the shadow rotation angle $\Delta\alpha$ is shown in Fig. 4. It can be seen that $cb' = ab$. Then from the triangle *cdb'*:

$$cd = cb'\,\mathrm{tg}\,\alpha = L\,\mathrm{tg}\,\psi_X\,\mathrm{tg}\,\alpha,$$

and from the triangle *def* get:

$$de = H\,\mathrm{tg}\,\alpha. \tag{12}$$

Angle $\alpha + \Delta\alpha_3$ can be determined from *dcf* triangle as:

$$\alpha + \Delta\alpha_3 = \mathrm{arctg}\,\frac{cd+ed}{H} = \mathrm{arctg}\,\frac{\left[\mathrm{tg}\,\alpha\left(H + L\,\mathrm{tg}\,\psi_X\right)\right]}{H},$$

where finally there is:

$$\Delta\alpha_3 = \mathrm{arctg}\,\frac{\left[\mathrm{tg}\,\alpha\left(H + L\,\mathrm{tg}\,\psi_X\right)\right]}{H} - \alpha. \tag{13}$$

Let's consider the effect of shutter rotation by an angle ψ_Z relative to ξ_Z axis (Fig. 5, *a*).
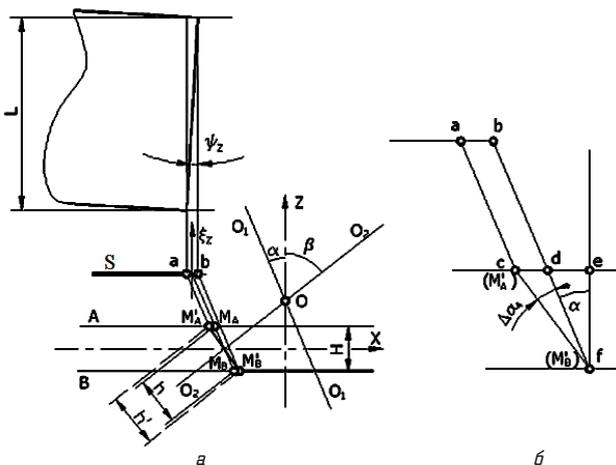
Fig. 5. Scheme: *a* – estimation of the transformation scale error caused by shutter rotation around the axis ξ_Z parallel to the *Z*-axis; *b* – beam path to estimate deviation of an angle $\Delta\alpha$

Edges of the shadow are displaced in the planes of the shutter and occupy positions designated by the points *a* and *b*. The length of the segment *ab* can be calculated according to the formula $ab = L\,\mathrm{tg}\,\psi_Z$. Beam path scheme for deviation estimation of $\Delta\alpha_4$ angle is shown in Fig. 5, *b*. Segment $cd = ab$, then from the triangle *fce* taking into account (12):

$$\alpha + \Delta\alpha_4 = \mathrm{arctg}\,\frac{cd+ed}{H} = \mathrm{arctg}\,\frac{\left[\mathrm{tg}\,\alpha\left(H + L\,\mathrm{tg}\,\psi_X\right)\right]}{H}.$$

Finally, there is:

$$\Delta\alpha_4 = \mathrm{arctg}\,\frac{\left[\mathrm{tg}\,\alpha\left(H + L\,\mathrm{tg}\,\psi_X\right)\right]}{H} - \alpha. \tag{14}$$

Lenses, particularly with high magnification, distort the image in such a way that a straight line on the object is transformed into a line that is curved at the edges of the image [9]. Profile image is curved at the edges, and only in the central zone of the field of view is observed with no distortion. Fig. 6 shows the profile image in the object plane $P_1 - P_1$ of the camera lens without distortion (1) and with distortion (2).
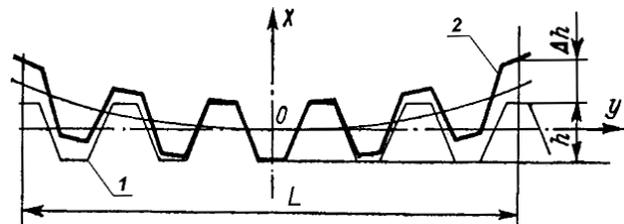
Fig. 6. Scheme of estimation of the transformation scale error caused by the shadow image curvature: 1 – without distortion; 2 – with distortion

The curved average line of the profile in the adopted system of coordinates can be approximated by a parabola of the form:

$$y = ax^2, \tag{15}$$

where a – empirical coefficient. Lines of projections and depressions – parabolas of the form:

$$y = a_1 x^2 + h/2 \quad \text{and} \quad y = a_2 x^2 + h/2.$$

Then, assuming that the coefficients $a = a_1 = a_2$, the maximum absolute error in the height of the profile at the edge of the observed image will be:

$$\Delta h_c = aL^2/4. \tag{16}$$

Let's experimentally define the value of the coefficient a. To do this, flat plate is mounted instead of the bobbin, and shadow image of the shutter edge is photographed on a flat surface. Such image is shown in Fig. 7.

If there is no lens distortion, the shadow edge should be a straight line. However, as shown in Fig. 7, it is not so. The image is distorted near the boundaries of the field of view.

To quantify the error, caused by this curvature, the shadow image is placed in the AutoCAD program window

in an enlarged view. After that, by means of this program the coordinates of a shadow boundary in steps of 1 cm are defined. These data are approximated by a parabola. As a result, for used lens, coefficient $a = 3{,}28 \cdot 10^{-4}$.
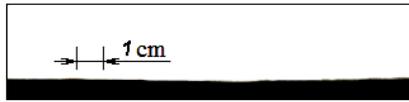
Fig. 7. Shadow image for projection of the shadow edge on the plane

The error associated with the curvature of the image due to optical imperfections is a systematic error that can be eliminated by the introduction of correction for data processing. These corrections are calculated using the formula (15). The required amendments have been taken into account in the development of software complex.

7. SWOT analysis of research results

Strengths. Inspection of shape deviation in real time enables timely excluded the effective packages from the process and thereby increases an efficiency of textile production.

Weaknesses. Installation of inspection devices on winding equipment requires additional costs.

Opportunities. Further studies should be able to debug the equipment using the proposed quality inspection method for bobbins.

Threats. External factors that negatively affect the application of the proposed method are the presence of foreign-made analogues, which have a much higher cost.

8. Conclusions

1. It is found that the main parameters of the device used to generate primary data about the shape of packages that affect the inspection results are:

– Angles determining the position of the light source and the camera relative to the normal to the package.

– Displacement of the light source and the camera in the tangential direction to the package.

2. Permissible variations of design parameters are proved on the basis of knowledge of the general expressions for the total measurement error of the package profile. These variations ensure the required transformation accuracy. Overall error can be set at the level of 5 %, as is customary for technical measurements. After that, on the basis of formula (2), taking into account the members of its expression, it can be distributed over the individual components on the basis of the requirements of equal accuracy.

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АНАЛИЗ ПОГРЕШНОСТЕЙ МАСШТАБА ПРЕОБРАЗОВАНИЯ ПРОФИЛЯ

Проведен анализ структуры погрешностей при контроле
формы паковок крестовой намотки методом теневой проекции.
Получены выражения для отдельных составляющих погреш-
ности параметров формы, что позволяет обоснованно подойти
к назначению допусков на взаимное расположение отдельных
элементов устройства. Проведен анализ устройств регистра-
ции изображений с точки зрения возможности их применения
в аппаратном комплексе для регистрации параметров формы
паковок крестовой мотки.

Ключевые слова: форма паковок, крестовая намотка, теневая
проекция, регистрация параметров, преобразование профиля.

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